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Radial Jet Drilling Improves Injectivity & Conformance in High Permeability Layered Sandstone Reservoir Across Mangala, Bhagyam & Aishwarya Onshore Fields in India

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Abstract

Poor conformance & injectivity sustenance is a major concern of Mangala, Bhagyam & Aishwarya (MBA) fields. The presence of high permeability streaks or thief layers between injection and production wells typically results in pre-mature water breakthrough, high water cut and deficient volumetric sweep. As a result, significant oil volumes in the reservoir may not be contacted by the injection fluid. Another concern is of low VRR (Voidage Replacement Ratio) in some of the layers due to reduced injectivity in those sands. Consequently, it has led to poor recovery from those sands. It is also a growing problem with the polymer deposition taking place in the wellbore particularly Mangala (undergoing full-field polymer flooding), leading to challenging wellbore cleanup operations.

Several methods have been used in the past, both mechanical and chemical to improve the treatment fluids during stimulation. In this paper, we introduce a novel technique; Radial Jet Drilling (RJD) for Injection & Conformance Improvement which is practical & effective and has resulted in injection improvement of greater than 100% and at-least 3x sustained treatment result over conventional techniques performed earlier. The technique involves running in hole the RJD deflector shoe on jointed pipe (typically 2-3/8") to the target depth & correlated. This is followed up with high pressure coiled tubing to rig up over the jointed pipe string and perform operations in two steps:

1. Milling to establish Casing exit
2. Jetting to create lateral of desired length (30 to 100m)

Both operations require separate runs with different downhole assemblies on coiled tubing. The setup allows the operator to jet with fluid of choice depending upon the geological & well fluid understanding. The selection of depths to create desired laterals depends upon sand thickness, formation dip, sand continuity, well deviation, cement quality & few other factors which shall be discussed in this paper. As a result

of the created laterals, the injection fluid experiences low pressure drops and bypasses damaged zones/ permeability barriers; which ultimately results in improved injection & conformance leading to better sweep efficiency. The other advantage of the technique is the relatively easy integration of tool with existing infrastructure i.e. small horsepower rigs.

This paper will document the physics behind the technique, treatment design considerations and implementation for stimulations performed across the fields using Radial jet drilling. Particular attention is paid to multiple injector well stimulation case studies from these fields, the challenges faced, the solutions implemented, results & inferences drawn using post job surveillance. The results observed across the field w.r.t injection & its sustenance performance is consistently greater over conventional methods used earlier.

Introduction

The quest to discovering Mangala, Bhagyam & Aishwarya field in Northwestern part of India (Figure 1), started with a few small discoveries made in southern Barmer Basin. But the development accelerated in 2004 with the discovery of large shallow tilted fault-block reservoirs in Fatehgarh sandstones in northern area of the basin (Compton 2009; Kothari et al. 2014). The Mangala (original oil in place (OOIP) 1,300 × 10^6 bbl), Bhagyam (500 × 10^6 bbl) and Aishwarya (300 × 10^6 bbl) Fatehgarh fields are collectively referred to as MBA.

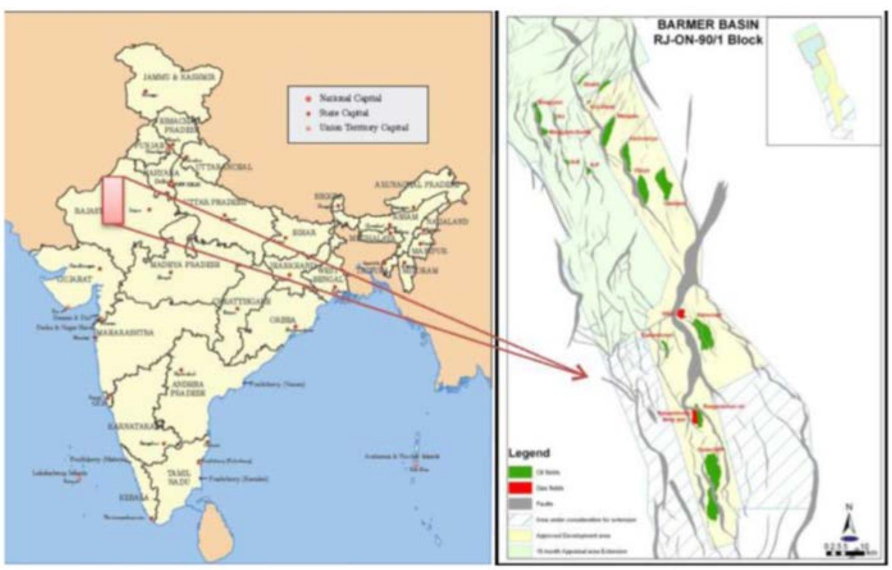


Figure 1—Geographic Location of RJ-ON-90/1 Block in India

MBA Fatehgarh sandstones have excellent reservoir properties, with porosities of 20-35% and high permeabilities that range up to 20 darcies or more (Beliveau 2007). Regionally, the Fatehgarh can be roughly divided into a lower section dominated by multistory braided streams and an upper section dominated by single-storey meandering streams.

The Upper Fatehgarh (UF) and Lower Fatehgarh (LF) can be further split into members based on detailed stratigraphy; for example, at Aishwarya, the UF is split into FA1, FM2 while LF is split into FA3, FA4, and FA5. In terms of reservoir quality, Bhagyam has the highest overall net-to-gross (NTG) and some of the highest core permeabilities in the basin, followed by Mangala and Aishwarya (Shankar et al. 2019). It is not surprising that Fatehgrah properties degrade slightly as depth increases from Bhagyam to Mangala to Aishwarya.

From a fluid perspective, the MBA Fatehgarh oils have some unusual properties that lead to a few developments with respect to north production and injection challenges. The oils are lacustrine-sources, and thus very waxy, with average viscosities in the main oil columns of 7-30 cp and Wats are a few degrees lower than their respective reservoir temperatures, which range from 50 to 75 deg C. Other properties are tabulated as per Table 1.

Table 1—Key Properties by field

Key Properties by Field	Aishwariya	Mangala	Bhagyam
OOIP (million bbl)	300	1,300	500
Depth (m)	1050–1350	750–1150	425–625
Reservoir temperature (°C)	65–75	55–70	50–57
WAT (°C)	~65	~55	~50
Pour point (°C)	40–45	40–45	~45
Gravity (°API)	27–32	20–28	21–30
Viscosity (cp)	7–25	10–50	15–500
Biodegraded zone thickness (m)	<5	~25	~50
Gas/oil ratio (scf/bbl)	160	185	100
CO_2 content (mole)	~25%	~7%	~1%

The MBA fields were developed with waterfloods using various combinations of patterns and edge line-drives (depending on the specific field and reservoir member). It is important to re-emphasize that all the injection water is heated above reservoir temperature to minimize potential for any wax dropout in-situ. In order to overcome adverse mobility ratio and improve sweep efficiency thereby increased oil recovery, the potential for chemical enhanced oil recovery (EOR) had been recognized from an early stage in the field development, with polymer flooding identified for early implementation, with a follow up plan of stage wise implementation of Alkaline-Surfactant-Polymer (ASP) injection especially for Mangala.

Over past two years, the Mangala field polymer injectors have displayed multiple injectivity issues. In addition, the Aishwarya and Bhagyam fields are dealing with low Void Replacement Ratios (VRR) for their ongoing water injection, which if not rectified could adversely affect recovery. While various types of injector stimulations are being used, injectivity increases are short lived. On the other hand, the Mangala & Aishwarya field producers have observed increasing polymer concentration in producer wells and have found to create ‘polymer debris deposition’ (Mittal et al, 2018) - inorganic scale debris agglomerated with polymer and waxy oil making debris; which sticks at tubing walls, inside ESP/Jet pumps and at sand face effecting the productivity as well as injectivity of some polymer injection wells. Further details on the challenges regarding injection and conformance across the fields are available in the reference paper (Nagar et. al 2020). It also details the typical well completion for injectors across the fields along with various water quality and polymer mixing factors that impact injection performance particularly in fields undergoing polymer injection. A combination of the detailed factors leads to the complete loss of injectivity over certain volumes of injection or sustained deep NWB damage. As a result, debris build-up within the tubulars and well stimulations are challenging in such environments. There were wells which did not yield desirable stimulation results over time particularly conventional treatments. Even for unconventional techniques such as Sand Scouring (Nagar et al. 2019), the results better than conventional treatments were observed but increased sustenance period lasted 2.5-3.5 months over conventional stimulation results. In order to achieve a longer sustenance period of stimulations, it was decided to compare conventional hydraulic fracturing for high permeability systems and radial jet drilling technique by fundamentally bypassing the damaged zone.

For high permeability systems, a good fracturing performance can be achieved by bypassing the damage and hence short and fat fracture (Tip Screen Out) resulting in high fracture conductivity should serve the purpose. Similarly, a radial if generated around the wellbore with capability of jetting out laterals ranging from 50-100m with each radial at least 1"-2" in diameter would also help achieve the objective. However, during this time it was realized that a hydraulic fracturing treatment for the candidate wells would require longer execution lead times, similar resource support (w.r.t rig requirement) & higher costs as compared with Radial Jet Drilling. Since the completions were 7" monobore or selective completions, a workover was required even for hydraulic fracturing, bringing the overall hydraulic fracturing costs higher than radial jet drilling. The above reasoning allowed us to move forward with a pilot execution of radial jet drilling in MBA reservoirs to evaluation its impact on improvement of injection performance.

Radial Jet Drilling & Its Evolution

Radial Drilling technology is a modified coil tubing system that uses high-pressure fluids combined with hydraulic erosional forces to penetrate the reservoir rock. This is achieved by the design of the jet technology which is such that forces are directed both forward and rearward at certain flow volumes and patterns. The forward flow and patterns allow erosion to the point that the jet moves forward. Forward movement becomes a function of the percentage of the hydraulic forces available at the jet as thrust, to propel the jet forward. This is achieved from circumferentially arranged rearwards jets.

High-pressure fluid is generated in the surface unit and conducted to the jet thru a specially designed high pressure, small OD coil tubing arrangement, and a flexible high-pressure hose for the part of the system that enters the formation. The coil tubing remains in the vertical (or angled) part of the wellbore whereas the flexible hose is guided thru a preset radius deflector system allowing the change from vertical to horizontal inside casing or in open hole. The system utilizes existing production tubing to surface. The RJD deflector shoe is run on the bottom of the production tubing to target depth, and the RJD coil and bottom hole assemblies are conveyed through the production tubing to the RJD deflector shoe.

Evolution of RJD

A quick view of the originally designed RJD System and the adaption over the years helps us understand the impact of the technology that the industry has realized and how its capabilities is shaping as per industry's demands. Originally the technology was designed for shallow low producing wells with a standard simple well design (Table 2):

Table 2—Evolution of RJD technology

S.No	Parameter	Original Criteria	Current Evolved Criteria
1	Maximum Depth	4000 ft	14000ft
2	Minimum Casing Size	5.5”	4.5”
3	Maximum Casing Grade	J-55	P-110
4	Temperature Limitation	80 Deg C	150 Deg C

Due to success and demand the technological feasibility of RJD has over the years, upgradation of RJD systems were required in order to be make it feasible in deeper, higher pressured and hotter wells. In particular, the evolution had kicked off with the increase in the coil size to ½" from 3/8", then to 5/8" to enable higher volumes with lesser pressure loss and higher yield strength to allow for deeper applications. To further allow the system to be capable to jet through carbonates and near wellbore $CaCO_3$ damage environments, the surface system was designed to safely and effectively use various types of acids along with optimized jetting with re-designed the jet configuration to an optimized erosion pattern & addition of the "reverse" cleaning runs by adjusting the reverse jets angle and orifices. Along with these major improvements, improvement in power & hydraulic system, downhole BHA capabilities & azimuth control as well as several engineering & design services were introduced to the technology of radial jet drilling.

The focus of the technology today is towards adapting the technology for offshore deployments particularly in harsh environments. Some of the recent developments with the objective of complementing existing technologies and other application as below:

- Development of milling & jetting downhole tools for 45-degree exit and horizontal well applications. – this enables penetration into multiple layers with low vertical connectivity.
- RJD for Frac enhancement & Optimization for interbedded tight formations.
- Development of Surface & Downhole equipment for Geothermal applications – for increased temperature ratings of equipment.
- Development of Turbine and Rotary jets – with the aim to jet clean-holes in Shales.

Presently over 2000 wells have been jetted in formations ranging from Carbonates to Clastics as well as in coal bed, salt leaching and geothermal applications (Buset el. al. 2001) (Raul et. al. 2007) (Marcelo et. al 2007) (Ragab et. al 2013) (Adel et. al., 2013) (Jiuquan et. al 2014) (Al-Jasmi et. al. 2018). When the suitable criteria for RJD is fulfilled with correction geological and reservoir-based understanding, successful campaigns over multiple cases have been delivered. The mechanical & reservoir criteria are summarized in Annexure A.

Typical RJD set-up is shown on Figure 2 and it includes the following:

1. Bottom Hole Assembly (BHA) - Deflector shoe, 2 each spring-pad de-centralizer
2. Milling BHA - PDM Assorted weight bars, Flex Shaft, Bit
3. Jetting BHA-Nozzles, High Pressure Jet Hose
4. Full Coil Tubing unit to deliver all tools & power.
5. Coil Straightener or Hydraulic Injector system.
6. Pack-Off

Figure 2—Typical Deflector Shoe BHA for RJD Operation (left), Cut section of Deflector show & Picture demonstrating Flexibility of Flexshat (Top Right) & Close up of Jetting Nozzle (Bottom right)

Jetting Principle & Nozzle Configuration

Compared with traditional jet bit design, the jets used in Radial Drilling have specially designed forward and backwards directed nozzles, arranged at specific angles and sizes depending on application as shown on figure 3. As a result, the present types of jetting bits can generate both, forward and backwards jet impact. The forward jet nozzles can be swirling or straight from several nozzles with the main function to break and erode the rock creating an opening from a few inches to greater size opening depending on jet bit size and angle of the nozzles. The overall principle borrows from the Bernoulli equation and has been well addressed in (Buset et al. 2001).

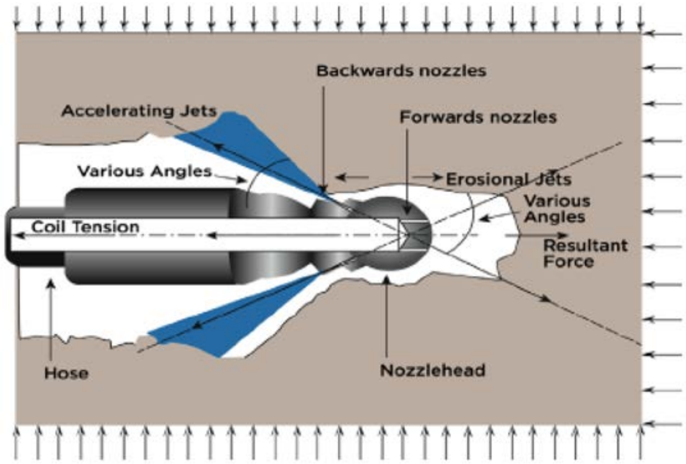


Figure 3—Mechanics of Jetting Action in RJD

The function of the rearwards jet nozzles is to increase the pulling force of the jet bit and to clean the jetted radial from the erosion debris resulting from the forward jetted materials as well as slightly enlarge the jetted radial during the forward movement and allow for slow back pull once the radial is completed to further clean, enlarge and chemically treat the radial.

The backwards jet nozzles produce a reverse trust whose vectoral components are part of the horizontal pulling force into the radial direction. These components are in balance, the resultant forces being "zero" provides for a "centralization" of the jet bit in the radial bore. With the jet bit in the center of the radial hole and the resultant forces, gravity and buoyancy of the jet bit balanced at zero, the resultant rearwards vectoral forces make the hole trajectory control less difficult and assures a relative straight horizontal radial bore jetted perpendicular or at a chosen angle from the main original wellbore.

Circulation-pressure loss, jet bit pressure drop, jet-bit ejector force can be estimated using detailed hydraulics-calculation model presented in (Wang Bin et al. 2016) and it has been used to estimate expected rates & pressures and to optimize hydraulics during the pilot in MBA.

Well Selection & Job Design Basis

The RJD pilot campaign completed 5 wells including a producer well with formation damage due to workover activity, 2 injectors with poor conformance and 2 polymer injectors, which were shut more than 6 months due to zero injectivity. Well candidates selected considering productivity / injectivity decline trend, conventional treatment effectiveness, cement bond quality, sand continuity, formation dip and RJD limitations, such as well deviation, casing size and sump availability. The limitations of the lengths of the lateral are based upon the sand continuity, dipping nature and worst case "Potential Strike Zone’ GIS based study. A Potential Strike Zone (PSZ) is defined as the 3-dimensional subsurface space around the initiation point which could see the physical growth of the radial flow paths as the radial drilling operations is conducted. Since there is no direct control on the direction of flow path during radial drilling, effectively the PSZ would be the sphere of uncertainty (Figure 4) with its radius equal to the maximum possible length of radial flow paths.

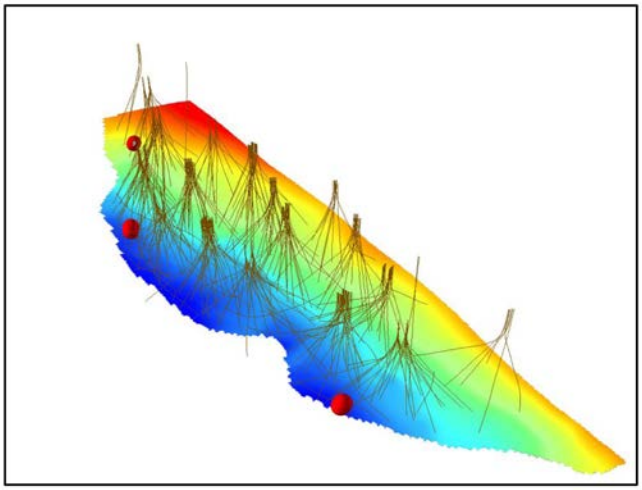


Figure 4—3D Subsurface with several PSZ (red spheres)

The objective of the initial workflow adopted on GIS platform is to evaluate the risks associated due to the uncertainty in the trajectory of radial drilling flow paths. The primary objective of this exercise is to identify all cases of possible intersection of radial flow paths with existing wells around the candidate well particularly when there are over 300 wells across MBA fields. The key issue being that lateral lengths of the radial flow paths from the initiation points can be designed to extend from 50 to 100 meter; due to pad based drilling and very tight well spacing (~70 m) at the reservoir level for Mangala, Bhagyam & Aishwarya wells, this may result into radial flow paths intersecting through the existing nearby wells, placing the well Integrity and the environment at risk. To evaluate the possibility of intersection of radial flow paths with nearby wells, a suitable software was used to map well trajectories on the Geographic Information System (GIS). While evaluating risks for MBA field, all the existing and planned well trajectories in the field were populated on GIS, followed by generating PSZ for all the planned radial drilling stages with initiation points at their respective 3D coordinates.

- Populate the well trajectories of all wells drilled through the target formation of subject well
- Populate PSZ for 50 m radius for all planned initiation point
- Filter all offset wells which cuts through the planned 50 m PSZ, (Figure 5)
- Repeat the exercise by populating PSZ for 100 m radius for all planned initiation points
- Filter all offset wells which cuts through the planned 100 m PSZ

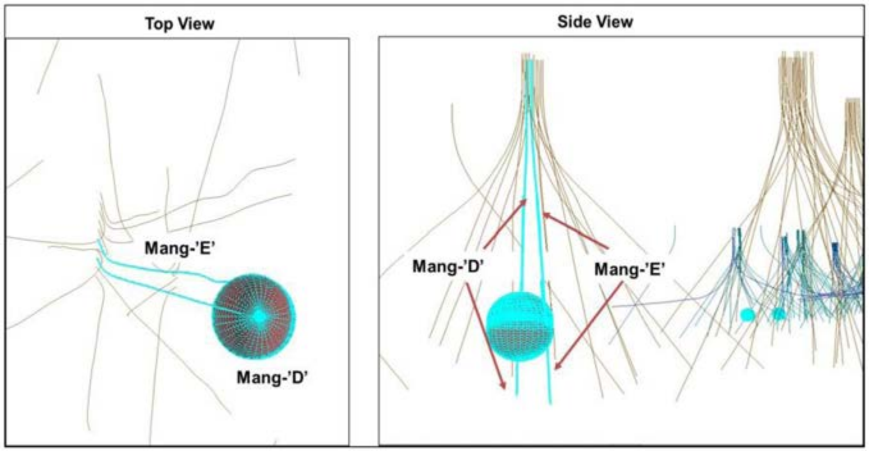


Figure 5—PSZ based on GIS base study in candidate Mang - 'D'

As a result of above exercise conducted on all candidates, the intersection of nearby wells with the PSZ of 50 & 100 m radius resulted in some wells to have planned restricted lateral lengths below 50 m/75m to minimize the risk of intersection with existing wells.

Aish – 'A' – Water Injector with poor injectivity and conformance

Well History & Performance. Aish 'A' is a water-leg injector with average rate of 2200 bwpd @1300 psi that requires frequent well interventions due to continuous decline in injection rates. Injection conformance is poor and most of injection is taken by top layer. Post restoration of water injection with surfactant & acid treatment in 2017, the well has been regularly treated with sand scouring followed by acid treatment. These treatments resulted into improved injection rates up to 3500 bwpd @ 1300 psi, however the sustainance of results was limited by 2-3 months and no improvement in conformance observed.

The well is 4.5" monobore injector with maximum deviation about 30 deg. The quality of the cement between casing and formation has been assessed with CBL & CAST logs and found good at the target depths. The clearance of 120 meters from the deepest lateral depth till last held up depth obtained during slickline intervention was available to allow the jetted debris to settle beneath the deflector shoe.

Subsurface design. The formation is a meandering fluvial sandstone reservoir in which sandbody channels are interbedded with floodplain muds as it has shown on cross-section C-D and A on figure 6. The average petrophysical parameters: net to gross ~ 36 %, porosity ~ 23 %, permeability ~ 1-3 D and water saturation ~ 7 %. The well contains four sands with thickness of 3-4 meters among which the top and the bottom sands are considered as main targets due to better petrophysical properties. Lateral depths are decided to target maximum number of sand packages assuming the jetting action in perpendicular to well trajectory, preferably at the middle of the sand. However, it was not always possible due to the necessary clearance required between lateral and casing collar depths to be at least 2 meters to eliminate any milling risks. The average formation dip is about 11 deg towards East. Therefore, azimuths within a range of 30 – 170 deg North were not recommended as jetting upwards is not likely to be achieved. Azimuth directions C – D on figure 6 (180 & 0 deg North) are aligned across formation strike while azimuth directions A & E were chosen to jet through shale layers towards oil bearing zones. Aish "A" does not have any wells with 100 meters range as per PSZ study, hence planned lateral lengths were only limited by sand continuity.

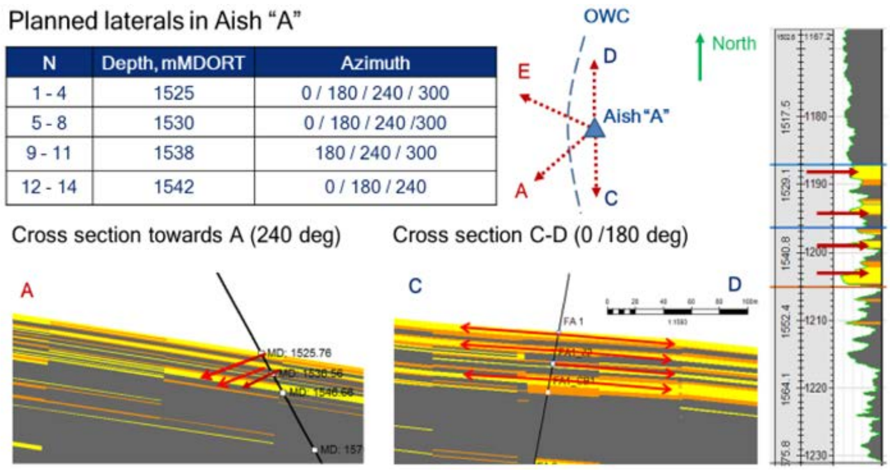


Figure 6—Subsurface design of RJD in candidate Aish-'A'

Bhag – 'A' – Polymer Injector with zero injectivity

Well History & Performance. Post conversion from PCP producer to polymer injector in Sep. 2017, the well has a poor injectivity even in water phase. Several acid & chelant-based stimulations were completed without much improvement & marginal improved results sustained less than 14 days. The well was revived in Feb.2018 with Sand Scouring followed by acid treatment for ~ 60 days (34 days with polymer) with rates 800-900 blpd @ 1000 psi. Due to low result sustenance, 'Rescouring' was repeated with oxidizer (Jun. 2018) and with acid (Nov.2018) treatments but the same results observed. Bhag 'A' had been shut due to zero injectivity for a year prior to RJD stimulation.

Bhag 'A' had an upper completion with 4.1/2" tubing and lower completion with 7" VTA packer that had to be retrieved prior to the stimulation. The deviation at the zone of interest ~ 45 deg which is close to upper limit of RJD stimulation. The system relies upon gravity to set deflector shoe and this deviation is close to upper limit of RJD. The overall quality of the cement between casing and formation has been found from good to moderate with 25 meters of poor cement quality, refer to figure 7. The lateral depths with poor cement quality and casing collar depths are excluded. Perforations were partially covered with sand and it was decided to clear debris/fill prior to RJD in order to create enough sump for debris created while jetting.

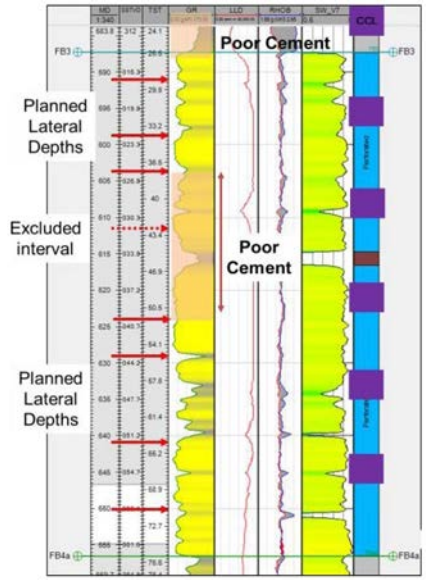


Figure 7—Planned lateral depths in Bhag-‘B’

Subsurface design. The formation is stacked braided fluvial sands with high net-to-gross ~ 90% and porosity ~ 26%. The sandstone consists of loose unconsolidated sand grains, fine to medium grained. The average permeability and water saturation are 5-6 D and 4 % respectively. Lateral depths are placed at the middle of sand packages to increase the chance for lateral to stay within the sand despite of lack of directional control. The well is in geologically complex area, very close to Main Bounding Fault and Scoop faults on West. The jetting through faults is uncertain but it is known that petrophysical properties are worse in zones adjacent to the fault. In pilot well, Aish ‘A’, jetting through shale sections was attempted, however no desired length achieved. Hence, the permeability contrast must be avoided as much as possible. Average formation dip is 15 deg towards East. The preferred azimuth directions were chosen in range from – 30 deg to 210 deg North including interval across the strike & towards the dip. Lateral lengths were limited within 50 meters due to the presence of other well within 60 meters from Bhag-‘A’.

Bhag – ‘B’ – Producer

Well History & Performance. Bhag-‘B’ is a PCP Producer that has been producing ~ 1400 blpd @ 93 % WC since workover activities in Jan. 18 when rates dropped from 2100 blpd @ 85 % WC to 1100 blpd @ 92 % WC. Right after the workover, stimulations with Terpene based solvent and EDTA bullheading were conducted but only minor improvement in rates was observed. RJD is considered for PI improvement in the well.

Bhag ‘B’ has an upper completion with 4-1/2" tubing and lower completion with 7" VTA packer that had to be retrieved prior to the stimulation. The deviation at the zone of interest ~ 50 deg that is the highest deviation taken during this pilot campaign. Well was not tagged prior to the stimulation, hence WBCO was planned till Bridge Plug installed @ 758 m MDORT to isolate bottom sands. The cement quality was found good at all target depths.

Subsurface design. The formation is sand-dominated stacked braided fluvial system as Bhag-‘A’, however bottom sands are frequently interbedded with thin mudstones and siltstones. The sandstone consists of loose unconsolidated sand grains and has good petrophysical properties as permeability ~ 5D, porosity ~ 27 %, NTG ~ 69 % and water saturation ~ 9%. Three sands with thickness 20, 10 & 7 m are to be targeted with RJD.

The well is located in crestal zone. There is main bounding fault on West and scoop fault are suspected South but only southern scoop fault is within planned lateral length of 50 meters, please refer to figure 8. Therefore, the jetting is not recommended towards South direction to avoid potential intercept with fault zone. Also, it is highlighted that jetting towards East may be difficult because the formation dip is 15 deg towards East and jetting upwards is not likely to be achieved. Lateral lengths were limited within 50 meters due to the presence of other well & scoop fault within 60 meters from Bhag-'B'.

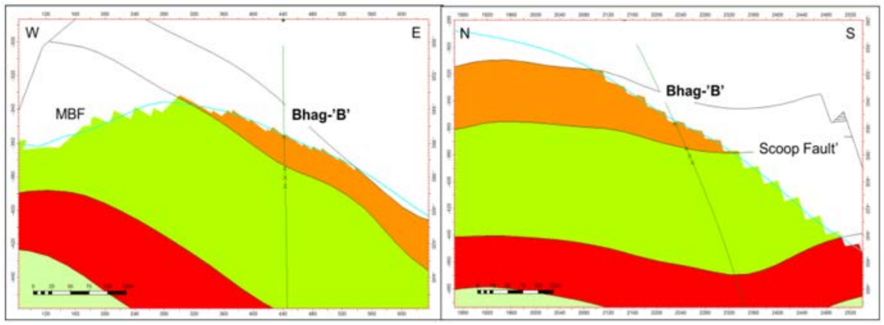


Figure 8—W-E & N-S cross sections for Bhag-'B'

Mang – 'A' – Polymer Injector with zero injectivity

Well History & Performance. Mang - 'A' is polymer injector with zero injectivity. The well has had a history of low injectivity since it was brough online in 2015 with injectivity index ~ 1-2 bpd/psi. Repeated stimulations were required to revive the well from zero injectivity, including acid bullheading (Nov'16), high rate water flush above frac pressure (Jun'17) and sand scouring (Sep'18) both followed by acid treatment. All of them restored injectivity to 1 bpd/psi but results did not sustain more than 50 - 60 days. Injection conformance was poor and most of injection was taken by top layer. Mang 'A' had been shut due to zero injectivity for more than a year prior to RJD stimulation.

The well is 7" monobore with 25 deg deviation. The cement has found to be from moderate to good with patchy cement and potential liquid channels at 1225 & 1238 m MDORT, therefore the potential milling issues were expected at the depth. In addition, 15 meters of perforation were covered with sand left post sand scouring stimulation done in Sep'18, hence WBCO was required to ensure 10 meters sump above the bottommost lateral depth.

Subsurface design: the depositional environment is a braided fluvial system with possible sheet flood deposits. Formation consists of stacked sandstone with minor shale sections that reflects in high NTG ~ 96 % and exceptional petrophysical properties: porosity ~ 27 %, permeability ~ 5 D and water saturation ~ 1.5 %. Well is 20 meters from Main bounding fault on West. The performance lower than expected was observed in the well located in the vicinity of the fault area despite of good petrophysical properties as per log data. Due to low deviation and relatively low formation dip ~ 10 deg, the azimuth was only limited towards East due to the presence of fault. The lateral length was limited as 50 meters to avoid any potential intercept with nearby wells.

Mang – 'B' – Polymer Injector with good injectivity and low conformance

Well History & Performance. Mang - 'B' is polymer injector with good injectivity ~ 4-5 bpd/psi but low conformance. Prior to 2017, reduction in injectivity had been the main concern and 5 acid treatments had been done to improve injectivity to 4 – 5 bpd/psi showing that the well responds good to acid treatments. However, all injection had been taken by the top two layers for last 3 years. Acid treatment with salt diverter was done in Mar'18 to address both injectivity and conformance issue but no improvement in conformance observed.

The well is converted polymer injector with 3.1/2" tubing upper completion and lower completion with 7" VCA packer. The completion had to be retrieved prior to Radial Jet Drilling stimulation. The deviation at the zone of interest is ~ 25 deg that is favorable for RJD. The cement quality has been from poor to moderate with patchy cementation and liquid channel present behind the casing, therefore issues were expected while milling the window in the casing.

Subsurface design: the depositional environment is a meandering river channel and the sandstones are interbedded with floodplain muds. There are multiple sands with various thickness from 3 to 12 meters, N/G ~ 51 %. The rock has exceptional petrophysical properties: permeability ~ 9 D, porosity ~ 27% and water saturation ~ 2.6 %. The well is a candidate for conformance improvement and the most of laterals (5 of 8) are planned into the sands that do not contribute into current injection profile. Formation dip (7-10 deg East) and sand continuity were considered to avoid jetting upwards and ensure jetting within the sand. Lateral length was limited from 45 – 75 at various depth due to the presence of other wells.

Jetting & wash back fluid selection – All Laterals. The selection of the jetting fluid is based upon the compatibility with clays & mineralogy for the target layer with contingent provision to switch to 10%-15% HCl to help dissolve scale depositions particularly in the early penetration scenario in the near wellbore region. Mineral acid is selected as the contingent fluid basis the established scale deposition as shared in earlier sections of the paper. Typically, certain formation clays can be prone to swelling (mainly smectite clays like montmorillonite) when they are in contact with incompatible invading fluids, especially fresh water. This can reduce the pore throat size and the effective permeability. To mitigate the swelling problems, given the high percentage of Kaolinite & low percentage of swelling clays across Fatehgarh sands across MBA (figure 9), clay inhibited water using 2% KCl was considered as primary jetting fluid. The fluid is heated to ensure no congealing of crude oil takes place in the deflector shoe or NWB given the nature of oil in MBA reservoirs

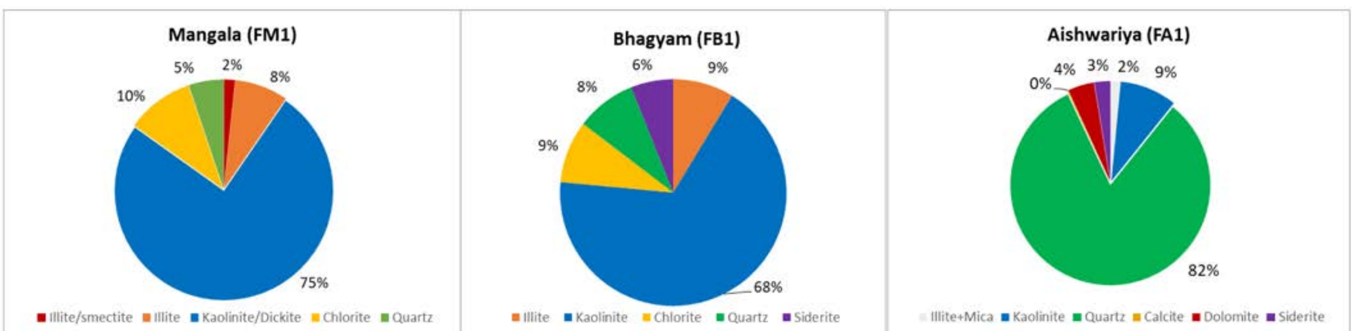


Figure 9—Clay content in FM1, FB1 & FA1 sands for Mangala, Bhagyam & Aishwariya respectively

Since most of the treated injectors have presence in the oil leg of the reservoir, it is expected that upon penetration further away from the wellbore, oil will be contacted and given the nature of crude, may congeal or provide undesirable pressure drop impacting injection performance. Therefore, in addition to the fluid being heated, once the forward jetting is completed with 2% KCl and the jetting bit at the desired depth of lateral, prior to commencing pull back the coil is displaced with wax solvent (terpene based) and the jetting hose is pulled back while continuously jetting till inside the deflector shoe. For jetting attempts which were not successful achieving the required target lateral lengths, the process was still executed irrespective; keeping in mind that a few meters would still impact injection performance particularly in a high permeability system. Another key point to capture is that fluid must be filtered down to 10 micron and any additives should be in liquid form so that the fluid laden debris/chemical doesn't clog up the nozzles during the operation.

Operational Sequence & Implementation

Milling Function Test

"Seeing is believing" means that if you see something yourself, you will believe it to exist or be true, even though it may feel unusual or unexpected. With the same thought, function test for both jetting & milling is required. We were not able to arrange the logistics for jetting test which required a sophisticated lab setup provided in Houston but decided on performing the milling function test once unit is mobilized to field location. The milling setup was arranged as depicted in figure 10. A stand was fabricated using which a supporting 6 ft 4-1/2" VT 12.6 ppg tubing was secured using slickline SUPA75 wire (appropriate clamps or chains can be arranged as well). Using the crane, the prepared 4-1/2" deflector shoe was lowered inside the pup joint on a 2-3/8" EUE joint. This is followed up by lowering of the milling BHA on the 5/8" CT and lining up of milling fluid, in this case fresh water. Initially, there were clear indications of when the bit stalls as the gooseneck/CT frame was not well secured leading to changes in weight on bit during the function test. Once put back on bottom with frames secured, the milling continued uninterrupted for about 45 mins, resulting in the visible confirmation of the bit crown on the other side of the tubing and milling fluid exiting from the milled hole. Finally, after additional 45 mins, a clean hole of about 1.5" was obtained as visible in the figure 11 (a).

Figure 10—Milling Function Test - Set-up

Figure 11—Milled 1.5′ window post milling function test (a) and broken confirmation ring (b)

Please note that during downhole execution, the casing milling timeframe takes 3-4 hours with milling of casing and cement. It is to be noted that the confirmation of successful milling on surface can be indicated with the help of the following:

- Difference between final and initial on and off bottom pumping pressure. If the same is found to have a difference of 150-200psi it can be considered as an indication of good milling attempt.

- In wellbore conditions, typically the bit meets the cement behind the casing to ensure clean hole in communication with the formation. This contact can be established once the bit is pulled out of hole to surface using phenolphthalein solution. Since cements are typically alkaline in nature, the bit if in contact with cement (note that this would work only if the well kill weight brine is less alkaline ph < 8), will turn purple on tested with few drops of phenolphthalein solution to serve as an indicator of a good milling attempt since the bit was able to mill through the casing & establish contact with the cement.
- Another critical indicator is the ‘confirmation ring’ that is a brass ring installed just behind the milling bit as can be seen in the figure 11 (b). This is an indicator that the bit during milling has travelled the bit length and during pulling out of the milled hole, the brass ring gets damaged; serving as a confirmation of milling. This indicator serves with a probability of confirmation for good milling as observed in the executed well campaign.

With the above visual confirmation using a function test setup as above, helped proceed mobilization to well location to commence the campaign.

Spotting & Rig Up

The typical setup of Radial Jet Drilling unit can be moved on two trailers in one go. Once on the well site, the unit needs to be spotted in a manner that allowed the rig to mast up comfortably over the well with most of its auxiliary equipment (tanks, pumps etc.) on the adjacent sides. This allows access to the RJD unit to be spotted and rigged up perpendicular to the well; which is the most preferred orientation given the nature of spooled small size coiled tubing & the high-pressure hose.

The setup after spotting shall be depicted as in figure 12. Please note that in case the water/jetting fluid is being supplied in tankers, the tankers must be spotted close to the main unit. Since the volumes required per lateral stage are typically 5-6 bbls, a gravity feed mechanism can be established into the 1000L tanks inside the RJD unit. Hence, it is prudent to ensure that the enough height from the tanker to feed in directly is available or a platform is created where separately fluid from the tanker is filled into the tote tanks and kept at an elevation on the platform for this purpose. It is to be noted that typically solvent and acid pumping will need their own precautions to be considered, in our case, acid was hooked up directly to the high-pressure pump while solvent was taken into a separate 200L tank inside the RJD unit.

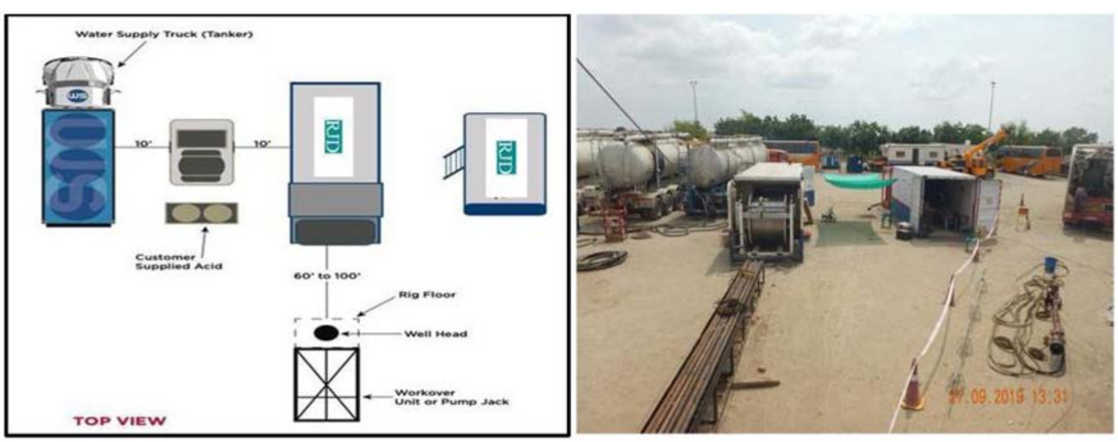


Figure 12—Scheme of typical surface setup of Radial Jet Drilling unit (a) and actual picture (b)

It is important to note that meanwhile the unit is spotted & preparations are ongoing for RJD unit, the Workover rig must be towards conclusion of pull out of hole of completion (required if a non-monobore well) and the wellbore cleanup. Following operations were completed prior to the RJD unit being ready for operations:

- Pre-job well performance surveys i.e. injection logging for conformance & fall-off test for skin and permeability estimates.
- Establish tag depth of well prior to WBCO & sample the held-up depth (even if in the sump)
- Removal of injection lines, Nipple down of Christmas Tree & Nipple up of BOP.
- Retrieval of completion string in non-monobore well completions only.
- Thorough wellbore cleanup using scrappers & magnets.
- Establish tag depth again of well prior to RJD operations & sample the held-up depth (even if in the sump).

Once the above operations are completed, the deflector shoe of required casing size is run in hole on 2-3/8" EUE tubing and stationed across the bottom most depth of required lateral. Wireline is run in hole through the 2-3/8" tubing and depth correlation is performed to ensure the correct depth is achieved. Upon pull out of hole, a gyro run can be performed to ensure that the lateral depth initiated is in the preferred azimuth direction basis maximum horizontal stress direction or a direction to avoid geological feature or a well. In our case, gyro run was performed only on the first well of the campaign that shall be illustrated in detail later in the paper, with the decision driven by factors of cost and time. In the case of orientation of shoe without gyro, a simple rig floor mapping and rotation of string in direction of 90 Deg or 180-degree turns depending upon number of laterals on a depth is performed.

Once the deflector shoe is on depth and aligned to preferred orientation, the string was made to rest its weight on the slips and the rig up upon the rig floor is performed as depicted in figure 13. The coil is fed over the goose neck and through the coil straightener. The Coil Straightener is purely mechanical and is only used for the initial RIH of the first 500 feet of coil. Once gravity takes over it is not required. The riser is an independent structure for guiding the coil. The coil straightener attaches to the riser. The coil is then fed through the straightener into the pack-off or oil saver. The oil saver is rated to 3000psi and allows to contain well pressure by packing off against the coil during the job. Please note it does not serve as a barrier if coil is unstabbed from the oil saver. It is therefore important to keep a kill line provision along with FOSV sub/Kelly valve in the string accessible on surface to ensure required barriers are present during the operations. Once the riser is made up and milling or jetting BHA made up, ensure a quick function test for either of them are performed as on figure 14. Although it is important to mention that the jetting function test must be performed only a reduced pressure i.e. 2000-3000psi only to ensure that the nozzle is clean and jetting action is achievable.

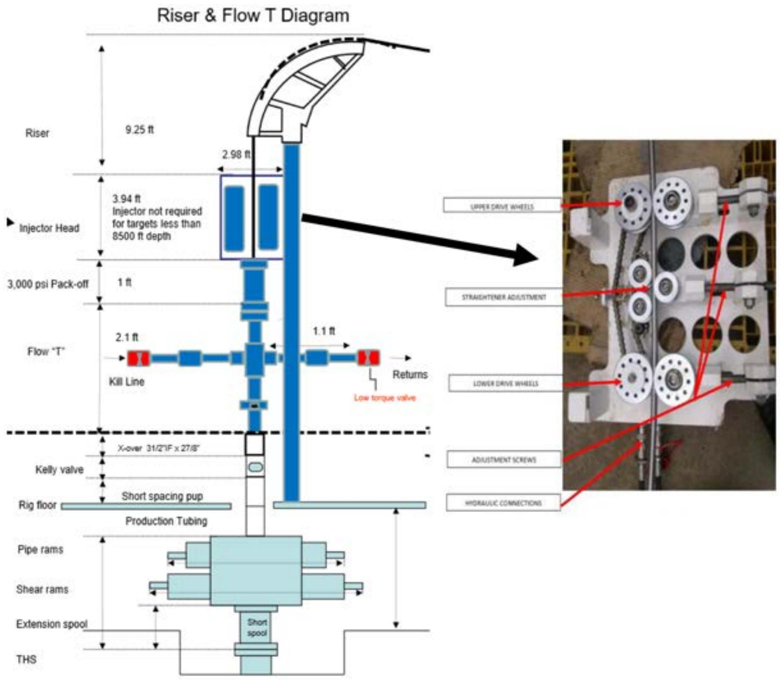


Figure 13—Surface Rig Up of Radial Jet Drilling Pressure Control Equipment

Figure 14—Actual Function test of Jetting at High (left) pressure & Low(right) pressure

Typically, one may be tempted to test the setup at 10000 psi on surface, but extreme caution needs to be taken in such a case and only if it is necessary. After the function test, pressure test the riser against BOP & FOSV by closing off the oil saver with a stabbed coil piece to 3000 psi. Upon a positive pressure test, bleed off pressure and commence the run-in hole of milling or jetting assembly. This may need to be performed once unless the stack is required to be broken up to exercise the string. Please note the sequence of lateral creation involved first the milling followed by the jetting run.

Milling procedure and challenges observed

Post orientation and depth correlation, milling is conducted to mill 22 mm diameter window in the production casing. The procedure takes at least 3 to 4 hours excluding RIH & POOH time. The evaluation of milling success is a critical part of operation as the job will not proceed to jetting stage unless convinced that milling done. During the pilot campaign, 80 % of 54 milling attempts were successful and only once the jetting attempt was done without broken confirmation ring when the right decision was made based on secondary indicators.

Milling process is affected by multiple factors, such us deviation, cement quality, deflector shoe orientation on high side and fluid quality. Unsuccessful milling leads to increase in well downtime and even impossibility to place lateral at the target depth. In case if milling is not confirmed, it is required to either re-enter the same window (75 % success rate during the pilot), rotate to other azimuth at the same depth (40 % success rate during the pilot) or proceed to the next lateral depth.

Bhag - 'A' was the most challenging well from milling point of view with only 10 successful attempts out of 18 (56 %). The reason behind is both high deviation (~ 45 deg) and poor cement bond quality between formation and casing. Two lateral depths in the well were placed on the edge of interval with poor cement and milling was unsuccessful at the depths even after multiple deflector shoe rotation. In addition, the issues while milling were faced due to improper mixing of friction reducer. Please find below the table 3 with summary of all milling attempts done during the campaign:

Table 3—Milling Summary over the RJD Campaign

Well Name	Aish-'A'	Bhag-'A'	Bhag-'B'	Mang-'A'	Mang -'B'	Overall
Milling Attempts	11	18	8	5	12	54
Successful attempts (%)	10 (91 %)	10 (56 %)	7 (88 %)	4 (80 %)	12 (100 %)	43 (80 %)
Re-entry for Milling	1	3	0	0	0	4
Successful attempts (%)	1 (100%)	2 (67 %)	-	-	-	3 (75 %)
Re-entry post rotation by 30	0	3	1	1	0	5
Successful attempts (%))	-	0 (0 %)	1 (100%)	1 (100 %)	-	2 (40 %)
Attempts without confirmation ring broken	0	1	0	0	0	1
Successful attempts (%)	-	1 (100%)	-	-	-	1 (100 %)

In other wells, no serious milling issues observed despite of the high deviation in **Bhag- 'B'** (~ 50 deg) and poor cement quality at the most of lateral depths in **Mang-'B'**. No clear correlation between milling success rate and cement quality or well deviation was observed during the pilot campaign. Hence, it is believed that milling success is dependent on multiple factors including deflector shoe orientation that cannot be validated in wells completed without azimuth orientation.

Jetting procedure and challenges observed

Once milling BHA is retrieved, jetting BHA is run into milled window to drill the lateral up to 100 meters using high pressure hydraulic jet. A flexible high-pressure hose with nozzle is only part of the system that enters formation, it is cut as per desired lateral length and coil is flagged to know the actual lateral propagation. The time taken while jetting is dependent on downhole condition and varied from 2 to 5 hours during the campaign, excluding RIH & POOH time.

Radial jet drilling is low-rate high-pressure stimulation with expected pressure in coil tubing up to 8000 - 12 000 psi @ 3-5 GPM rate. RJD operator is continuously monitoring the pumping parameters to ensure that pressure does not exceed the hydraulic hose burst limit of 12 000 psi. If propagation stops before desired length achieved, it is usually tried to jet at higher pressure and repeat the jetting after pullout by 1-2 meters. Due to the low penetration observed, RJD operation have been optimized by switching the jetting fluid to acid and providing soaking time when penetration stops. As a result, it has significantly improved the performance of RJD in Bhag & Mang wells.

Multiple issues while jetting have been observed during the pilot, including hose getting burst, nozzle getting cracked or lost & coil tubing puncture. The possible reasons behind these low success ratios are difficulties to jet through formation heavily plugged with scale, jetting through unconsolidated sand, fluid filtration quality or lack of directional control. Only Aish-‘A’ job was done using Gyro survey and it mitigated the risks related to jetting in direction of shale / faults or jetting high side. It should be highlighted that all fluids pumped through the system are to be filtered up to 10 microns because even small particles can plug the jet opening casing a rapid increase in pressure.

The significant drop in pressure at the same rates is a signature of possible hose burst, nozzle cracked / lost or coil tubing integrity issue. Despite of burst pressure rating as 12 000 psi, hose bursting was observed multiple times at pressure below the burst limit, please refer to figure 15. The reason of it may be a material fatigue due to continuous attempts to propagate while jetting. Hose bursting leads to laterals shorter than planned or extra jetting run for re-entry (improvement was observed in 63 % attempts). If hose bursting is suspected due to upside jetting or permeability barrier, re-orientation of deflector shoe may help but additional milling & jetting runs will be required. The situation when nozzle lost in the hole may lead to the significant time loss if nozzle is not recovered to waste pit by re-circulation because it would require the complete retrieval of RJD BHA along with tubing string to the surface to verify that nozzle is not left in deflector shoe.

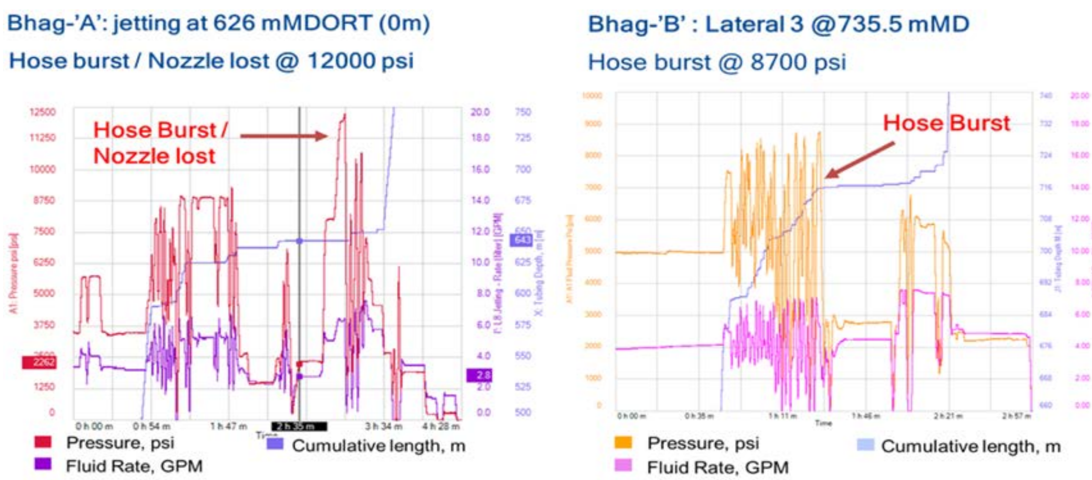


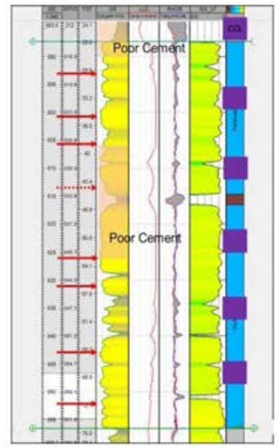
Figure 15—Plotted graph Depicting Hose burst/Nozzle lost event using Jetting Surface Pressure, Fluid rate & Cumulative Length during Jetting Operation in Bhag-‘A’

Aish - ‘A’ is a pilot well for the campaign. Initial plan included jetting across the strike as well as jetting through the shale sections and sand packages to improve sweep efficiency placing laterals towards producer wells. However, high pressures (up to 8000 psi) were observed and desired lateral length not achieved in other directions other than + - 20 deg across formation strike. It has proved that jetting through shale / shaly sand can be a challenge for RJD and laterals are to be placed within the sand to avoid any permeability contrast. Directional control plays significant role in wells consisting the sands interbedded with shale sections like Aish – ‘A’. In all following wells, RJD was conducted without gyro, hence there is a high uncertainty in lateral direction. The job was planned in the way that the first lateral is done without any directional control, then the rig floor is marked in case of success or tubing string is rotated by 90 or 180 deg clockwise in case of failure.

Most of the laterals were jetted with shorter length than expected in **Bhag – ‘A’**, please refer the table 4, despite of the clean sand without interbedded shales. The quality and sand continuity are very good at the most depths, but the sandstone is unconsolidated that could be the reason of low penetration. Jetting of unconsolidated formations may cause washouts which impedes forward progress of the jetting assembly. Only 2 laterals 90 deg apart were jetted @ 602 m MD with 50 meters length, and sand continuity and petrophysical properties are getting worse with shallow depths. Also, it should be highlighted that other factors, such us high deviation, lack of directional control and possible intercept with sub seismic and scoop faults, could play a role in low jetting efficiency.

Table 4—Lateral Summary in Bhag-'A'

Lateral #	Depth, mMDBRT	Number of laterals		Rotation prior to milling, deg	Length of laterals	Sand Continuity
		Planned	Actual		Actual (Planned = 50 m)	
1	652	2	2	0	10	Very good
2				90	8	
3	643	2	2	0	5	Very good
4				180	6	
5	631	2	2	0	12	Very good
6				180	4	
7	626	2	1	0	11	Very good
No lateral jetted	606	1	0	Multiple rotations	Milling was unsuccessful	Good
8	602	1	2	RIH Deflector shie	50	Good
9				90	50	
10	593	1	1	0	10	Moderate

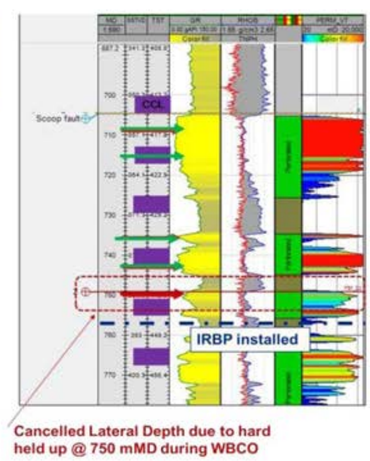


The performance of laterals @ 631 and 626 m MD was affected by improper mixing of polymer-based friction reducer that caused nozzle plugging followed by hose burst & nozzle crack. These are operational issues and to be considered separately.

Sandstone in **Bhag - 'B'** is also loose unconsolidated sand, however sands are frequently interbedded with shale sections that make it like the top layers of Bhag - 'A'. Initially, the high pressures and low penetration were observed even while jetting acid. Then, tubing string got rotated by 180 deg clockwise and desired lateral lengths were achieved, indicating that highly likely the first attempt had been done towards unfavorable dip. Table 5 shows lateral depths and lengths completed in Bhag-'B', the jetting with 2 % KCI had shown low penetration ~ 2-4 meters and all lateral were completed post soaking or jetting acid.

Table 5—Lateral Summary in Bhag - 'B'

Lateral #	Depth, mMDBRT	Number of laterals		Rotation prior to milling, deg	Length of laterals	Remarks
		Planned	Actual		Actual (Planned = 50 m)	
1	743	1	2	0	12	3 m with KCI. Rest with acid.
2				180	40	Overpull while POOH observed.
3	735.5	2	2	0	50	2 attempts to jet. 6 m propagation with KCI / Acid. 50 meters propagated with Musol
4				90	50	4 m with KCI, rest with Acid
5	716	1	1	0	50	2.5 m with KCI, rest to 50m with Acid
6	709	1	2	0	2	Only 2 m with KCI, switched to acid. No success
7				270	50	1 m with KCI, then 1 m with acid. After that, 48 m with KCI.



The job in **Mang-'A'** is limited to 5 jetting attempts in order to have a sufficient time for additional well in Mangala and try RJD on well with conformance issue (table 6). Only 3 laterals at three different lateral depths have been placed during the job. Again, the penetration is achieved only post pumping acid. Pressures while jetting observed in Mangala wells were up to 10 500 psi which are the highest pressures among all wells treated during the campaign. It resulted into lower than expected lateral length and significant downtime due to multiple hose burst, nozzle cracked and CT puncture issues (40 % attempts for Mang-'A' & 50 % attempts for Mang – 'B'). Formation damage caused by polymer & inorganic scale is considered as primary reason for this pressure response.

Table 6—Lateral Summary in Mang-'A'

Lateral #	Depth, mMDBRT	Number of laterals		Rotation prior to milling, deg	Length of laterals	Remarks
		Planned	Actual		Actual (Planned = 50 m)	
1.1	1244	2	1	30	0	1st Attempt. Could not initiate jetting. Nozzle lost in hole. Pinhole in CT. POOH Deflector shoe.
1.2				NA	5	Hose burst. Re-entry was called off due to multiple held ups.
2	1233	2	1	0	50	Jetted ~4.5m with KCl, switched to acid and made progress
3.1	1225	2	1	0	4.5 m	1st attempt. Hose burst and found debris.
3.2				0	50 m	2nd attempt to jet at the same milled window. Jetted with acid
5	1221.5	2	0	-		Job called off to make time for priority candidate Mang-196-01
6						

In **Mang – 'B'**, planned lateral length was achieved only @ 1052.5 mMD whereas other 11 laterals were in range of 1 to 6 meters due high pressure observed while jetting, please refer to table 7. Laterals were placed with 90 deg phasing to eliminate the risk of jetting upwards or towards shale sections. However, no improvement in length was observed even jetting and soaking acid. As most of the laterals were not successful, it was decided to place additional lateral depth @ 989 mMD targeting the same sand as lateral depth @ 982 mMD (most of injection taken by this sand in the well).

Table 7—Lateral Summary in Mang-'B'

Lateral #	Depth, mMDBRT	Number of laterals		Rotation prior to milling, deg	Length of laterals	Sand Continuity / MPLS comments
		Planned	Actual		Actual (Planned = 40 -60 m)	
1	1052.5	1	1	0	60	Moderate. It used to get injection (10%)
2	1045	1	2	0	3	Good. It used to get injection in the past (10%)
3				180	1.5	
4	1011.5	1	1	180	2	Good.
5	1025.5	2	3	0	4.5	Good. Up to 70 % injection in the past. Pre-job contribution ~ 3-5 %.
6				90	5	
7				90	6	
8	982	1	2	90	5	Good. 97 % of pre-job injection.
9				90	2	
10	970	1	1	90	1	Good sand but top of FM1.
11	989	1	2	90	3	Good. The same sand as 982 mMD ~ 97 % of all injection taken by this sand.
12				90	1.5	

The summary of all jetting attempts done in the campaign is presented in table 8. 34 out of 53 jetting attempts (64 %) were done without those problems and only 16 attempts (30 %) were completed with length more than 50 % of planned lateral length. Hose burst, CT puncture and nozzle lost issues were observed in 29 %, 10 % and 6 % jetting attempts respectively. Re-entry with Jetting BHA at the same milled interval had shown improvement in 63 % attempts (in 83 % excluding Mang-'B' with all unsuccesful attempts) but it is risky if there is no confidence in the position of the delfector shoe. Rotation post unsuccesful jetting improved results in Bhag-'B' & Mang-'A' indicating that previous attempt failed due to lack of directional control rather than other issues.

Table 8—Jetting Summary over the RJD Campaign

Well Name	Aish-'A'	Bhag-'A'	Bhag-'B'	Mang-'A'	Mang-'B'	Overall
Jetting Attempts	13	12	8	5	14	52
Successful attempts* (%)	10 (77 %)	9 (75 %)	7 (88 %)	2 (33 %)	6 (43 %)	34 (65 %)
> 50 % of planned length (% of all attempts)	6 (46 %)	2 (17 %)	5 (63 %)	2 (33 %)	1 (7 %)	16 (31 %)
Nozzle lost	0	2	0	1	0	3
% Nozzle recovered	-	2 (100 %)	-	0 (0 %)	-	2 (67 %)
Puncture in CT (% of all attempts)	1 (8 %)	2 (17 %)	1 (13 %)	1 (17%)		5 (10 %)
Nozzle cracked or Hose burst (% of all attempts)	2 (15 %)	3 (25 %)	1 (13 %)	2 (40 %)	7 (50 %)	15 (29 %)
Re-entry for jetting	3	1	1	1	2	8
Successful attempts** (%)	2 (67 %)	1 (100 %)	1 (100%)	1 (100 %)	0 (0 %)	5 (63 %)
Rotation post unsuccessful attempt (% attempts with better results)	Gyro used	3 (0 %)	2 (100%)	2 (50 %)	5 (0 %)	12 (25 %)

* No hose burst / nozzle cracked / pin hole
** Re-entry is considered as successful if there is an improvement in compare with the first attempt

Key Operational Considerations & Contingencies

Given the criticality of the operation, it is important to be prepared with possible contingencies that may arise during radial jet drilling execution. It is to be noted that during our campaign none of these contingencies were exercised.

The coil is must always maintained in tension given the small size. The max overpull for the 5/8" CT is 4000Ib over hang-off weight. If the coil kinks on surface we will initially clamp the coil, and close the oil saver to review the situation. If damage is severe, cut coil and pull the piece hanging off out of the well with the reel. The unit has 12000' of coil on the reel so operations would restart immediately. There is also spare coil.

During milling operation, the entire CT & milling BHA remains inside the tubing and the deflector shoe. Therefore, the PDM is always inside the work string/2-3/8" tubing. It can be fished when required by retrieving the tubing with the shoe. Similarly, if flex shaft becomes stuck, the unit can pull to the max overpull of the coil. If continues to be stuck, the work string/tubing & deflector BHA can be reciprocated to release and retrieve on surface. The worst case would be the deflector shoe after milling or jetting being stuck at a given depth, the maximum pull as per 2-3/8" production tubing (or the tubing being used as work string).

During jetting operation, if jetting hose is stuck in the formation and does not release despite overpull and switching of fluid types downhole, the final option would be to turn the deflector shoe on surface cutting the hose. This will result in most of the hose inside the formation and rest in the tubing if any. This can be followed by another lateral placed as close as possible to the old one. It is to be understood that only the jet-hose enters the formation. The coil tubing cannot pass the shoe and therefore always stays in the work string/tubing.

Data acquisition during the treatment also plays a key role which helps in understanding different desirable and undesirable events w.r.t depth wise lithological change, cement quality or deviation.

Pre- & Post-Operation Results

Following section is related to stimulation results and its sustenance. Injection profile logging and Injection Fall-Off (IFO) surveys had been conducted in injector wells prior & post RJD operation to estimate RJD impact on injection conformance and skin. MBA producers are sub-hydrostatic and not able to flow without artificial lift support, therefore performance evaluation of Bhag - ‘B’ done based on change in rates and WC post treatment.

The treatment results of the new technique had to measure upon the following factors:

- Improvement/Increase in Injecitivty Index
- Improvement in conformance
- Improvement in Sustenance days for the Stimulation technique.

The reason being that the previous techniques have been statistically logged and understood over the other techniques & therefore, helps understand if the new technique in the true sense is effective over the current solutions that have been executed.

Aish – A: Water Injector

The well is a candidate for conformance and injection improvement. Right after RJD stimulation, not significant improvement in injectivity observed, II improved only from 1.58 to 1.82 bpd/psi, and conformance remained the same that seen comparing injection logging done prior to the job (0) and right after (1) on the figure 16. However, the increasing trend in injection (II improved up to 2.2 bpd/psi) had been observed after Injection logging / IFO survey and post high rate water flush injectivity has improved up to 3.7 bpd/psi. In this pursuit, one critical operation which is conducted once the laterals are jetted and rig released; is what we term as "High rate flushing". This came about as a learning from the post job results that were observed on the wells particularly the first treated well (Aish ‘A’) and became a practice for all the wells in which radial jet drilling was executed. Aish ‘A’ prior to the radial jet drilling was injecting above theoretical frac pressure at 15m3/hr. The same was validated in the pre RJD operation IFO with a linear slope indicating frac of 24m half length.

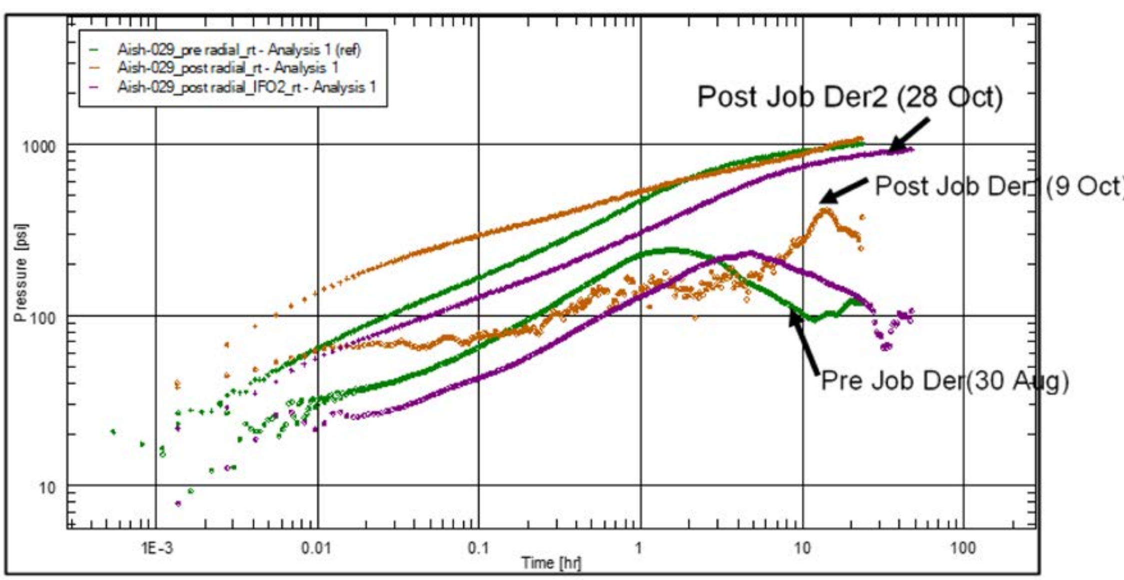


Figure 16—Timelapse IFO Pressure Transient Analysis indicating increasing fracture half length pre & post RJD treatment

This well immediately post the RJD operation was found to have similar injection performance as in pre RJD on the injection header. This was interpreted as a ‘damaged’ lateral as can be understood with the Injection fall-off test interpretation as shown in figure 16 with erratic pressure derivative trend and an increasing slope. Interestingly, the well performance improved over sustained injection period and the injection performance doubled. At this stage, another IFO survey was conducted and the reason for improved performance was the increase in effective half-length to 40m. It is to be noted that along with pre job IFO & the two-post treatment IFOs; injection PLT's were also conducted. Like the no change in injectivity index for pretreatment and immediately post treatment, there was no improvement in conformance as well. Though it did improve marginally once a 2x improvement in injection was observed with some bottom sands taking marginally improved injection.

Given these observations, there were two possibilities. The topmost section which was taking the most injection even prior to the treatment, is still dominating injection, while the transient behavior is showing only an effective length of 40 m given the laterals have been jetting for an average of 75m. The pressure derivative trend is like a damaged frac indicating either the laterals have collapse or a possible fluid incompatibility. Henceforth it is thought that if the laterals are fracced with high rate water, this may allow better ‘opening’ of the lateral and connectivity as well as flush off a possible source of damage if any. Along with the same, a high rate (~ 15-20 bpm) injection will allow fluid to divert from the dominant fluid injection section to the other perforations, due to the back pressure generated as a result of perforation friction. This shall help in opening of the laterals which have a ‘restricted’ injection.

As can be observed from figure 17, post the water frac/high rate flushing, the bottom perforation with laterals started taking fluid and the injection performance improved further with more details in the results section. With this result, it became prudent to analyze the result on each well immediately once after the radial jet drilling has been conducted & compare the same. The same must be followed by a high rate flush operation to ensure that the laterals get effectively opened and distributed across the reservoir section. It is worth mentioning that the injectors were not flowed back for cleanup suspecting any possible damage inside the laterals primarily because there is a high chance of the laterals collapsing upon drawdown.

Figure 17—Time-lapse Injection Logging Shows improvement in conformance particularly after High rate flushing Operation post RJD Treatment

After high rate water flush, injection trends were relatively stable for 90 days with injectivity index decline of 0.01 bpd/psi/day that is better than average decline rate in Sand Scouring jobs conducted previously. However, faster decline rate ~ 0.015 bpd/psi/day was observed after planned Processing Terminal shut down, probably, due to debris from injection lines. Overall sustenance was ~ 240 days that is significantly higher than any other stimulations completed in the well as it is shown on figure 18.

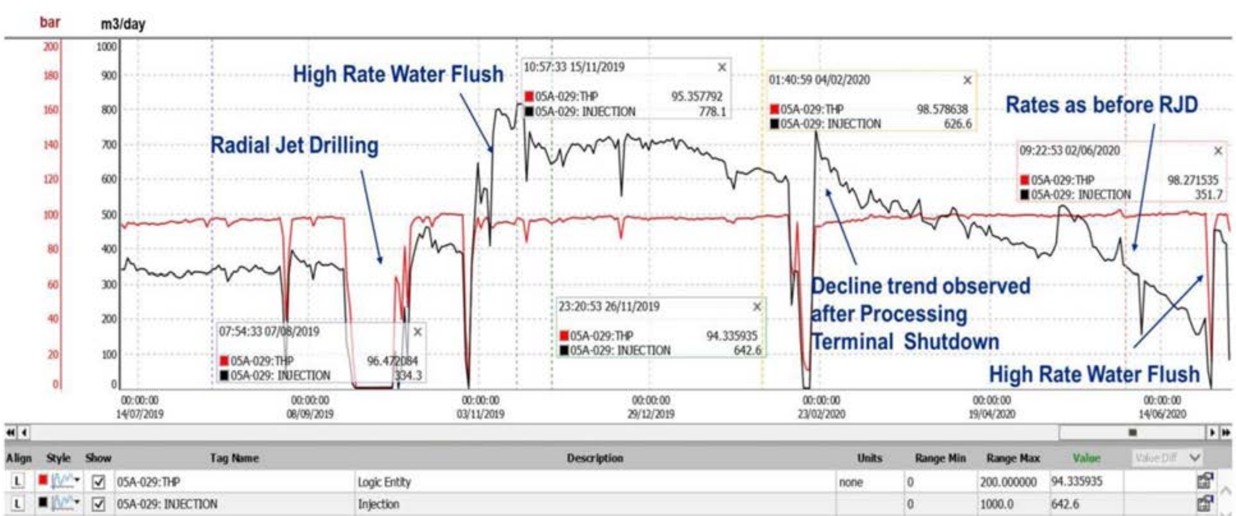


Figure 18—Injection Trend of Aish-'A' Water Injector before and after RJD Treatment

Bhag – A: Polymer Injector

The well is a revival candidate with zero injectivity @ header pressure. No injectivity was observed post RJD operation, hence it has been brough online with help of high rate flush improving from 0 to 0.78 bpd/psi on water injection, please refer figure 19 for injection trend. The main objective of the well revival is to facilitate polymer injection in the well, however the injectivity has shown a rapid declining trend on polymer. Hence, the well is currently shut-in after 62 days of sustained injection including 12 days of polymer injection.

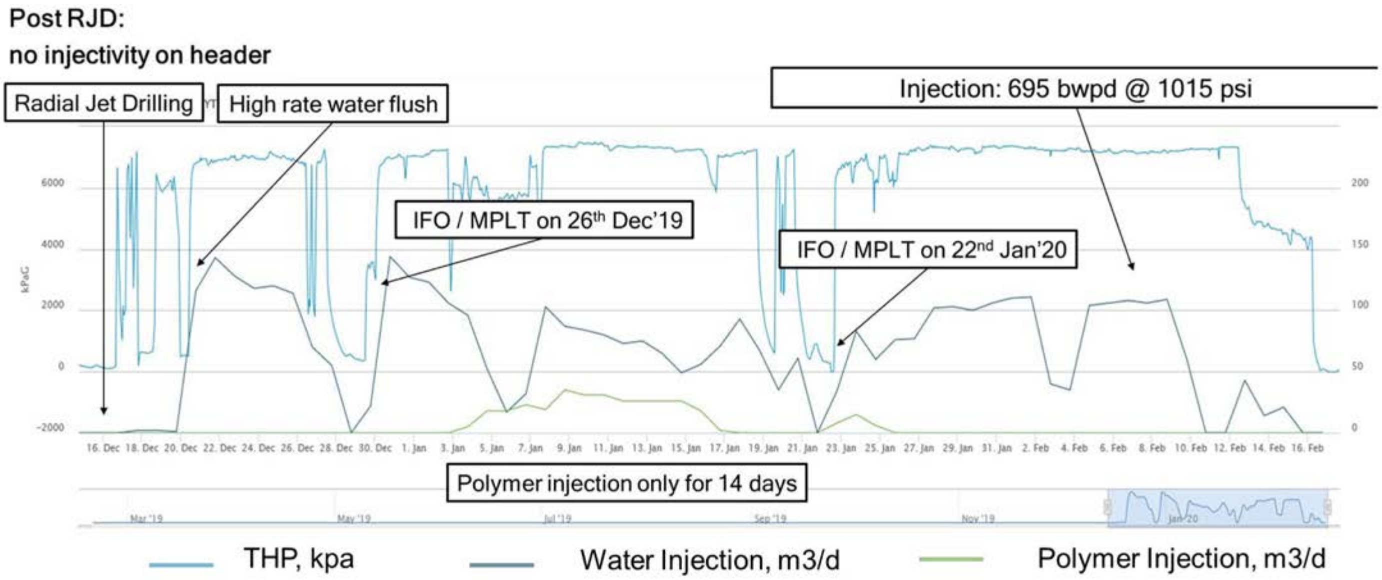


Figure 19—Injection Trend of Bhag-'A' Polymer Injector before & after RJD Treatment

Post job IFO (1) interpretation comparison with base line IFO (0) has shown drastically reduction in skin factor from 40 to 0, as per Figure 20 (a), with short fracture half-length ~ 4 meters that may reflect 8 laterals jetted with length of 4-12 meters. Also, late time region response may be a result of intersecting fault or nearby producer that is quite possible as the well is in fault section.

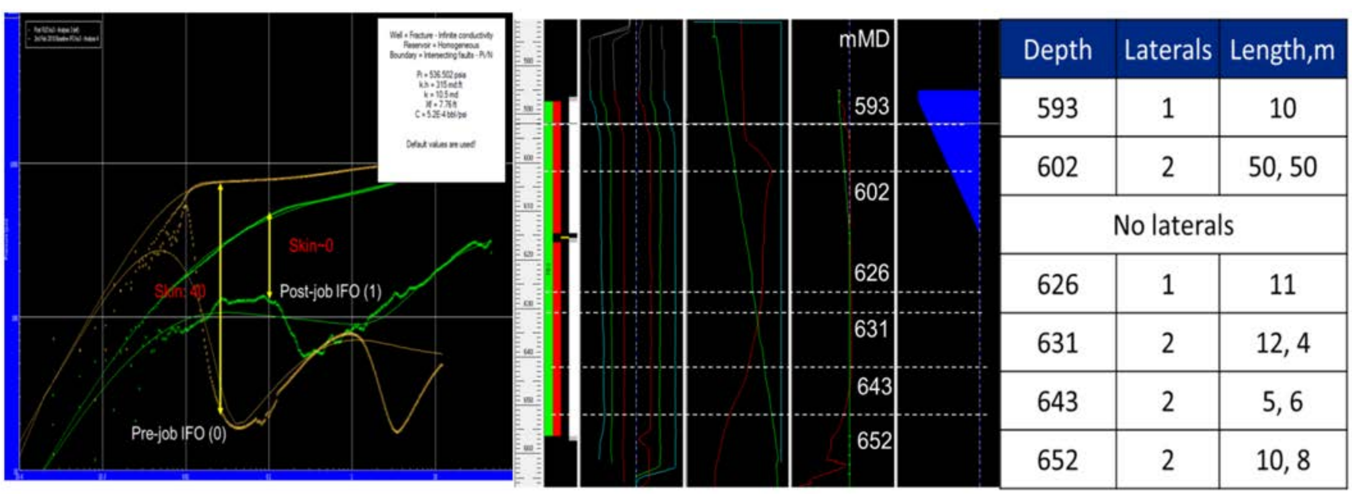


Figure 20—(a, left) Pre & Post IFO Pressure Transient Analysis indicating reduction in Skin, (b, right) Lateral summary and Injection Logging indicating Injection in topmost zone with Injection Revival in Injector: Bhag'A'

Post-job injection log provides qualitative analysis due to poor quality spinner response and no match achieved between output interpretation rate and actual rate. Spinners show the deflection only at the topmost depth @ 593 mMD (1 lateral of 10 m) while temperature survey shows clear deflection at 602 mMD (2 laterals of 50 m). No spinner or temperature deflection observed at the depth below 602 mMD, figure 20 (b).

The well has been deliberately chosen to justify the feasibility of RJD to revive the dead wells that have showed low performance since the beginning. Overall performance of RJD is similar to Sand Scouring stimulations conducted in the past with II improvement up to 1 and low sustenance ~ 60 days. The low performance of the stimulations may be attributed to the faults in the vicinity of the well that affect connectivity between sand packages as well as have a negative impact on rock petrophysical properties. In addition, Bhagyam is reservoir stacked with poor consolidated sands and original low-pressure support that might have a significant impact on lateral stability over time.

Bhag – B: PCP Producer

The well is only producer taken in the campaign with formation damage post workover suspected. Post stimulation, minor improvement in rates ~ 19% and no change in WC have been observed resulting into 20 bopd oil gain. Considering stable water cut, it can be concluded that the improvement is attributed to skin reduction rather than to involvement of upswept oil into production. The result sustenance is ongoing and has already been more than 120 days, please refer to the trend on figure 21.

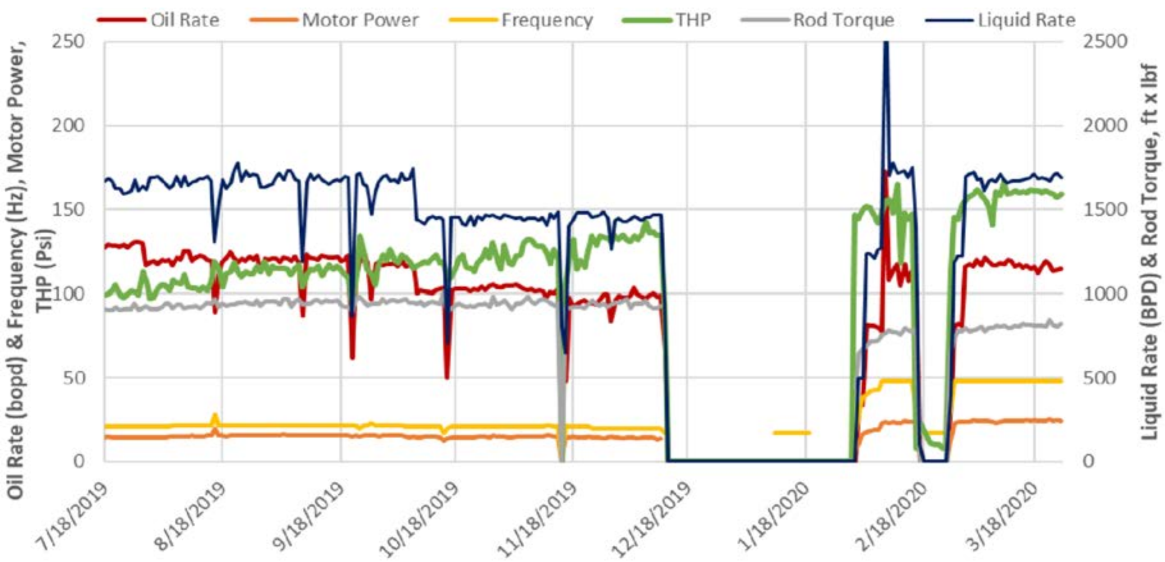


Figure 21—Production Performance Pre & Post RJD Treatment with marginal increment in Liquid and Oil production in Bhag-'B'

The results are compromised by several operational issues not directly related to RJD operation:

1. The bottommost sand had been found covered and lateral depths were re-arranged to target top 2 sands only. Several attempts to clear interval with WBCO BHA on 2.3/8" pipe failed.
2. Post high rate water flush, the casing leak was found during pressure test of lower completion packer. The well had been exposed to completion brine for 37 days before it was brought online. Due to sub-hydrostatic pressure in the well, deep invasion of kill weight brine might have resulted in formation damage
3. The second-high rate water flush was conducted through stator with pressure / rate limitation to avoid an elastomer erosion. This attempt failed to reach frac pressure and did not serve the purpose.

Mang – A: Polymer Injector

The well is the second revival candidate in the campaign with zero injectivity and historically poor injection performance. As it is shown figure 22, injectivity has improved to 0.65 bpd/psi post RJD showing the stable injection trend, then further improvement up to 1.5 bpd/psi is observed post high rate water flush.

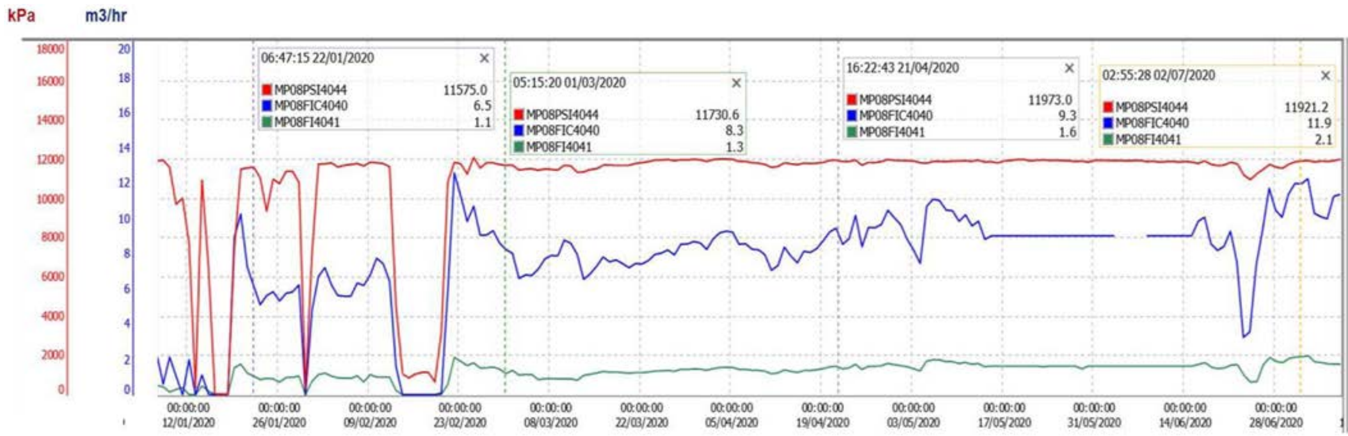


Figure 22—Injection Performance Pre & Post RJD Treatment in Polymer Injector Mang-'A'

Injection log obtained right after RJD is shown on Figure 23. Only qualitative analysis can be done with the data due to poor spinner response caused by polymer. The interpretation suggests that all injection is taken by the top layer with one 50 m lateral @ 1225 mMD while no clear response observed @1233 mMD (50 m lateral) & 1244 (5 m). No injection log was recorded after high rate water flush to verify if improved injection is attributed to better conformance.

The stable injection trend is being observed in the well and ongoing sustainance has passed a milestone of 200 days so far. This result is significantly higher than for any other stimulations completed in the well previously showing the effectiveness of technique in bypassing the damage zone of near wellbore to reach original reservoir condition.

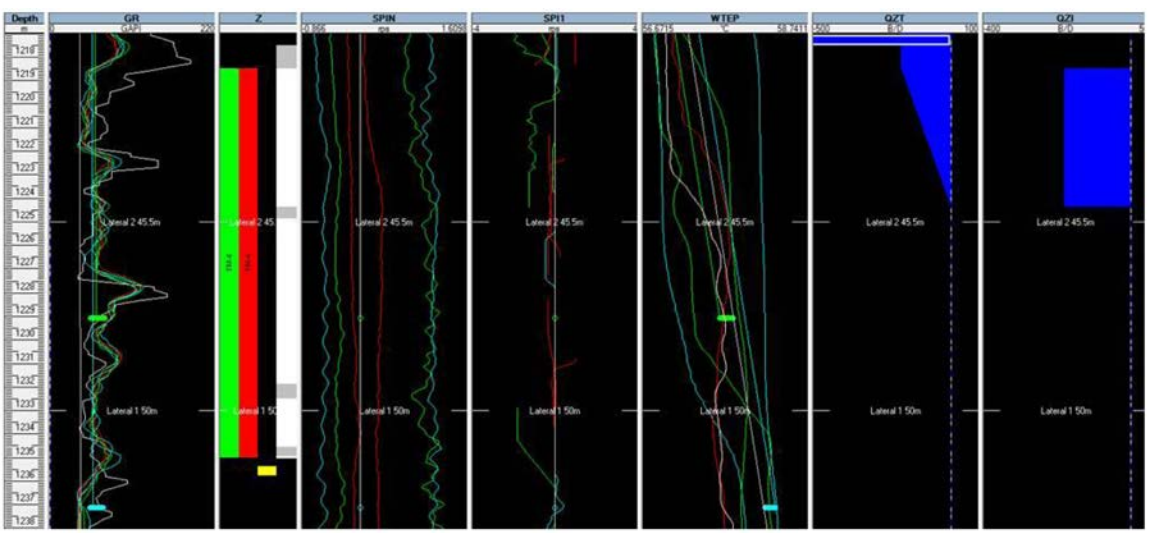


Figure 23—Injection Logging in Mang-'A' indication Injection revival with Injection only in Topmost section

Mang – B: Polymer Injector

The well is a candidate with good injectivity and poor conformance. Despite of the fact that most of laterals are less than 6 m length, injectivity has improved from 4.75 to 7.1 bpd/psi and then stabilized at 5.7 bpd/psi as shown on figure 24. The well parameters are being stable even after 130 days of injection with slight reduction in II over the time. Polymer injection has been ramped up by 32 % due to reduction in backpressure post RJD.

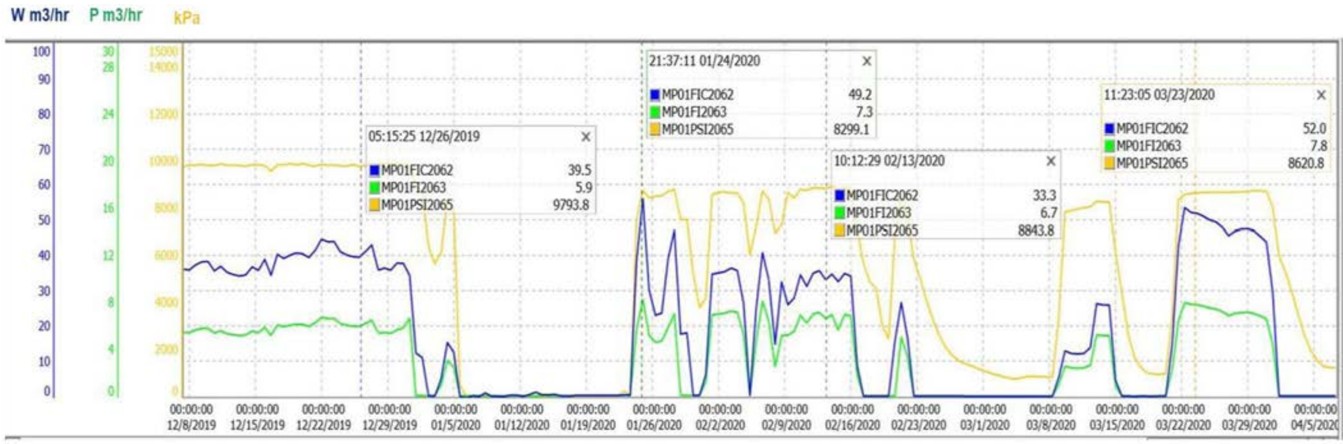


Figure 24—Injection Performance Pre & Post RJD Treatment in Mang-'B' Polymer Injector

The IFO survey interpretation confirms skin reduction and half fracture length extension post RJD treatment, please refer figure 25. However, conformance improvement is still uncertain. Pre-job Injection log (0) show that all injection is taken by top two layers @ 970 mMD, 982 mMD and 989 mMD: and 7 laterals out of 12 are placed in the sands contributing less than 10 % of injection profile. Spinner response are heavily affected by wellbore condition in these surveys and only qualitative analysis is possible to be done. Spinner response has been improved after wellbore clean-out resulting in higher quality injection logging data post RJD. This interpretation suggests worse conformance than before RJD and all injection is still taken by top sands. It should be highlighted that the injection log has been recorded not in ramp-up condition @ 34.5 m3/hr while injection rates prior to survey is about 49 m3/hr. Such a difference in injection is caused by just 4 bar change in ITHP. No linear relationship between ITHP and Injection rates may indicate a contribution of bottom sands into injection profile.

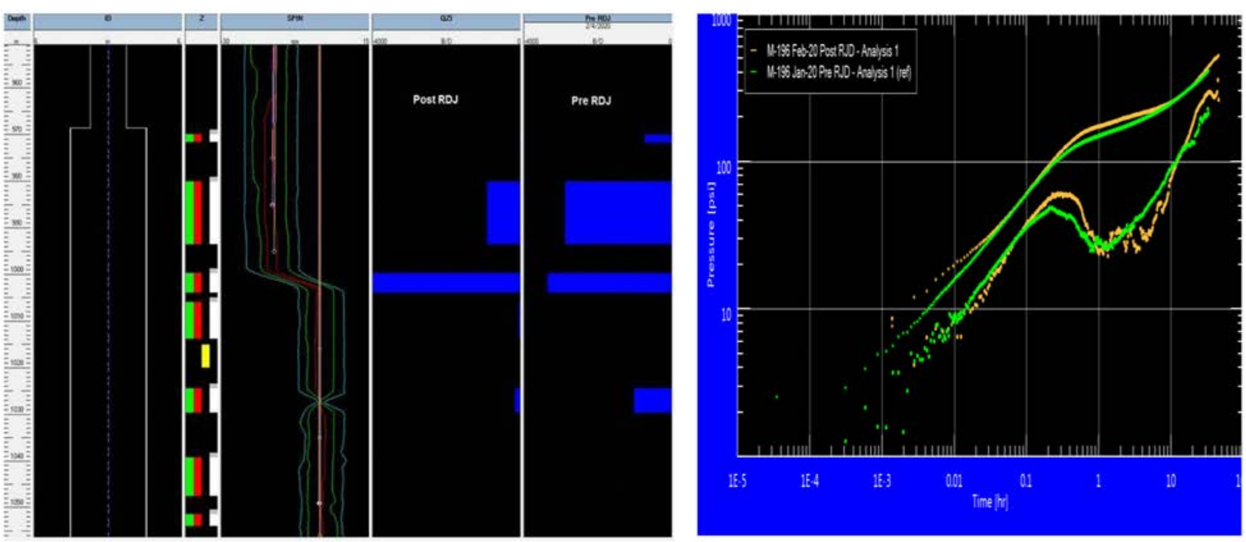


Figure 25—(Left) Injection Logging shows Improvement in Conformance along with improvement in Injectivity Index. (right) Pre & Post IFO Pressure Transient Analysis indicated marginal reduction in Skin.

Results Summary

The campaign results are summarized in tables 9 & 10 for injectors and producer respectively. The well performance is evaluated based on three major parameters including improvement in Productivity / Injectivity, Conformance and Result Sustainance in comparison with other stimulations done before. The positive change in injectivity / productivity has been observed in all 5 treated wells including 2 wells with zero injectivity prior to the job. It confirms that RJD is efficient tool to bypass near wellbore formation damage and reduce backpressure while injection.

Table 9—Injection Monitoring Parameters for RJD Treated Injectors over the Campaign

Well Name	Pre-job Parameters			Post Job Parameters			Current Status (26th July 2020)			Sustenance	Still sustained?	Conformance improved?
	ITHP, psi	Injection bpd	II bpd/psi	ITHP psi	Injection bpd	II bpd/psi	ITHP psi	Injection bpd	II	Days	Yes/No	Yes/No
Aish- 'A'	1435	2265	1.58	1363	5060	3.71	1421**	2830**	2**	240	No	Yes
Bhag - 'A'	1000	0	0	1000	1000 (220 P*)	1	0	0	0	60	No	Not confirmed
Mang - 'A'	1600	0	0	1400	2100 (300 P)	1.5	1740	2113 (350 P)	1.22	208	Yes	Not confirmed
Mang - 'B'	1420	6580 (891 P)	4.83	1200	8530 (1100 P)	7	1346	7359 (960 P)	5.46	150	Yes	Not confirmed

* P – Polymer injection, bpd

** After repeated High Rate Water Flush in Jul'20

Table 10—Production Monitoring Parameters for RJD Treated ONLY Producer well over the Campaign

Well Name	Pre-job Parameters			Post Job Parameters			Current Status (26th July 2020)			Sustenance	Still Sustained?
	THP, psi	Oil Rate, bpd	Liquid Rate, bpd	THP, psi	Oil Rate, bpd	Liquid Rate, bpd	THP, psi	Oil Rate, bpd	Liquid Rate, bpd	Days	Yes/No
Bhag-'B'	140	100	1400	160	120	1670	143	105	1530	140	Yes

Conformance improvement has been justified only in Aish-'A' while it is difficult to make conclusion on how conformance change in Mang'A', Mang-'B' and Bhag-'A' due to various reasons mentioned above. The synergistic effect of the high rate water flush on conformance & injectivity is confirmed in 3 wells. The technique demonstrates significantly higher result sustainance and less decline rate in comparison with conventional stimulations in all wells excluding Bhag - 'A' in which RJD shows the similar results as Sand Scouring stimulation. Results are still sustained for Mangala wells that demonstrate stable well parameters with minor reduction in II over time and Bhag-'B' producer that is currently on decline trend observed.

Way Forward

The promising results of the pilot campaign allow us to consider the second pilot of RJD on MBA wells. Lessons learnt during the first pilot will be used and further improve planning & execution workflow to increase the number of wells taken during the upcoming campaign. Having the proven record of injectivity improvement, several revival wells and wells which required II enhancement are considered as candidates. In addition, more candidates for conformance improvement to be tried to confirm the impact of RJD on injection profile. These stimulations will be clubbed with time-lapsed injection logging to estimate how conformance improves / degrades over time.

One well is not enough to confirm the RJD efficiency in producer wells. Therefore, more producers with low productivity index and large volume of unswept oil nearby are to be taken, especially in Aishwariya and Mangala fields in which only injectors were stimulated during the first campaign.

For the further design & planning improvement, there are a few questions that can be addressed with only with additional data points:

- Optimum number of laterals and lateral depths

- Cost-benefit analysis of lateral orientation with Gyro
- Synergy effect of Acid Stimulation / Sand Scouring on RJD performance
- Correlation & Impact of geology / rock properties / clay content on RJD performance
- Further innovation in RJD to measure and control lateral length & direction
  - Azimuthal control and casing exit with gyro
  - Lateral length limited by GPM and pressure loss in the coil system. Reviewing higher GPM in various coil sizes.

Conclusion & Way Forward

- RJD can be considered for revival / incremental improvement of the injection performance in injectors with history of zero or poor / degraded injectivity.
- Conformance improvement is validated only for Aish-'A' with injection profile logs. Data acquisition for other treated wells to validate conformance improvement is planned; in addition to more candidates to treat conformance issues in the next campaign.
- Significant improvement in sustainance period of improved injection results of RJD treated candidates over conventional stimulation techniques for the same wells
- Directional control mitigates risks of jetting towards shale zones, faults or upside of the casing
  - It has been proved in Aish-'A' that the jetting through shale section is hard to achieve. All lateral with planned depths were jetted across the formation strike
- High jetting pressures were observed in Mangala wells due to formation damage caused by polymer that resulted into high hose burst frequency.
- High Rate Water Flush has significantly improved the performance of the RJD laterals in most of the wells, with respect to conformance and injection performance
- No clear relationship between milling performance and deviation or cement quality was established for the executed wells in the campaign.

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ANNEXURE-A

Mechanical Factors:	
Casing Size	The current radial drilling equipment can operate in production casing sizes of 4-1/2" OD or greater.
Multiple Casing Strings	The radial drilling configuration presented in paper could only penetrate single strings of casing and overlapping casing strings could not be milled. However, multiple strings penetration has been recently tested and achieved and is being available on market as an application
Casing Grade	The tungsten carbide bits used to mill casing exits are limited to casing grades of P-110 or less.
Casing Wall Thickness	The maximum casing wall thickness able to be milled is .45" (11mm) in single cut. Thicker wall can be cut with a second run and new bit.
Casing Cementation	In order to successfully initiate a casing exit, the radial drilling equipment requires a good cement bond between the casing and the formation. A poor casing bond generally results in difficulty or failure in jetting operations. The competence of the cement bond is generally assessed by CBL.
Wellbore Inclination	Since the system relies upon gravity to seat the radial drilling equipment, the well inclination should not exceed 50 degrees from vertical for the system shared in paper. The new high angle system has been developed to jet out of high angled and horizontal wells and has been successfully tested in field.
Wellbore Depth	The present system is designed to operate at a maximum depth of 12 000 feet (3500 m). A unit specifically designed for Geothermal applications with a reach of 4300 meters (14,000 ft) has been developed and deployed in field and it has supported the operational capability of the present technology to that depth. Further research is being done to eventually exceed the 14,000-depth capability.
Wellbore Rathole	A rathole of 35 feet (10 m) is required to allow the jetted debris to settle beneath the deflector shoe.
Bottomhole Temperature	BHT should not exceed 120 C^{o} (250 deg. F). The high temperature system can handle wells up to 150 C^{o} (320 deg. F).
Reservoir & Geological Factors	
Dipping Formations	Steeply dipping formations are generally not suitable for radial drilling operations, particularly where there are porosity differences between adjacent formations.
Unconformities	Facial changes, pinch-outs and unconformities generally result in a stalling or stoppage of the jetting process.
Mineralization	Calcitic or siliceous mineralization in carbonates and sands can result in zero porosity which renders the well unsuitable for radial drilling
Cavernous and Vuggy Formations	Since the forward penetration of the jetting system relies upon some lateral constraint, cavernous and vuggy formations are not generally suitable for radial drilling operations.
Unconsolidated Formations	Jetting of unconsolidated formations generally causes washouts which impedes forward progress of the jetting assembly.
Evaporites and Amorphous rocks	Salts, gypsum, anhydrite and Chert's, flints, bounders and brecciated remnants are generally not penetrable by jetting action