RJD: A Cost Effective Frackless Solution For Production Enhancement In Marginal Fields

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Abstract: With the worldwide trend of low oil prices, high maturity of oil fields, excessive cost of horizontal and fracking technologies, and necessity for green drilling applications, radial jet drilling (RJD) technology can be a cost effective and environmentally-friendly alternative. RJD is an unconventional drilling technique that utilizes coiled tubing conveyed tools and the energy of high velocity jet fluids to drill laterals inside the reservoir. In recent years, rapid advances in high pressure water jet technology has tremendously increased its application in oil and gas industry not only in drilling operations to improve drilling rate and reduce drilling cost, but also in production to maximize hydrocarbon recovery. In addition, RJD can be used to bypass near wellbore damage, direct reservoir treatments/injections, improve water disposal and re-injection rates, and assist in steam or CO2 treatments. This paper highlights the theoretical basis, technological advancement, procedures, applications, and challenges of high pressure water jets. Several worldwide case studies are discussed to evaluate the success, results, pros, and cons of RJD. The results show that nearly an average of four to five fold production increase can be obtained. The present paper clearly shows that radial jet drilling is a viable and attractive alternative in marginal and small reservoirs that still have significant oil in place to capture the benefits of horizontal drilling/fracking and to improve productivity from both new wells and/or workover wells that cannot be produced with the existing expensive conventional completions.

Index Terms: Drilling, completion, radial jet, laterals, horizontal, coiled tubing, impact force, hydraulics.

1 Introduction

Recently, the oil and gas industry has witnessed a steady increase in the use of short-radius horizontal drilling operations to enhance well productivity. The trend is expected to continue in the future as oil and gas industries become increasingly aware of the benefits associated with it while targeting thin reservoirs and oil reserves, which are pocketed and scattered. Horizontal drilling and new completion techniques have helped increase production in fields that may be uneconomic with traditional completions. However, these traditional techniques are still expensive and may not be suitable in marginal oil/gas reservoirs. Developing small and marginal fields with traditional techniques is expensive and economically unviable. For example, the cost can range from 1.0 to 10.0 million US$ to drill and complete one well. With increase in oil usage and demand, the need for finding new reserves has very high importance. Only new discoveries cannot compensate the rate of exhaustion of resources. As 60% of world's production is from matured fields, a better strategy for extend the production life of existing assets is crucial. Therefore a new technique like Radial Jet Drilling, RJD can be quite helpful in improving recovery, especially from marginal fields where the hydrocarbons reserves may not justify the high cost of horizontal drilling and hydraulic fracturing. Abrasive water jet cutting of material involves the effect of a high-pressure velocity jet of water with induced abrasive particle. It is a recent non- traditional machining process, and it is widely used in many industrial applications such as mining, shipbuilding, automotive, etc. [1]. The concept of water jet was first introduced in the 1960s and the initial applications were limited to cleaning and unblocking drains. With the development of new technology and availability of high pressure pumps, water jetting gained importance and was used on commercial scale to cut soft materials such as cardboard and rubber.

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Many efforts were made in late 1960s to use water jetting in petroleum industry to drill sub-surface reservoir rocks, but favorable results could not be achieved because of deficient abrasive injection techniques [2]. Drilling fluids pumped at ultra-high pressures can enhance drilling performance while maintaining conventional rig operating procedures and safety. The impact of the high velocity fluid stream can significantly assist the mechanical action of the rock bit allowing penetration rates of 2 to 5 times over conventional systems in comparable drilling conditions [3]. In 1993, Dickinson et al reamed a large in casing and pushed 1¼-in. CT between 25 to 150 ft into formation for production enhancement (2 – 10 folds). Currently, RJD has been proven to enhance production rates, to reduce decline rates, to reduce near wellbore damage, and to recover more resources from stripper wells [4 – 7]. Radial Jet Enhancement has made it feasible to enhance production from more than 1.7 million wells that would otherwise be cost prohibitive to recover. This represents a total potential untapped market of more than $50 billion. Using RJD technology, horizontal channels up to 300 feet can be drilled out from an existing wellbore in any direction, with 1 – 2 in. diameter using high pressure fluid. In North and South America, RJD technology is oriented toward existing oil and gas wells at depths of 4,500 feet and shallower for productivity improvement [8].

2 What is RJD?

Abrasive water jet cutting is one of the non-traditional cutting processes capable of cutting wide range of hard-to-cut materials. Radial Jet Drilling is a process of drilling radials of small bending diameter horizontal perforations using water jets at very high pressure in different directions. The diameter of these radials is approximately 1 - 2 inches and lengths up to 300 ft. These radials can be drilled in multiple layers through a same well, Fig. 1. Abrasive water jet process includes large number of parameters, which affects the quality of cutting surface. These parameters include hydraulic pressure, traverse speed, stand-off distance, abrasive mass flow rate, abrasive materials, nozzle length and diameter, orifice diameter, abrasive shape, size and hardness [9, 10].

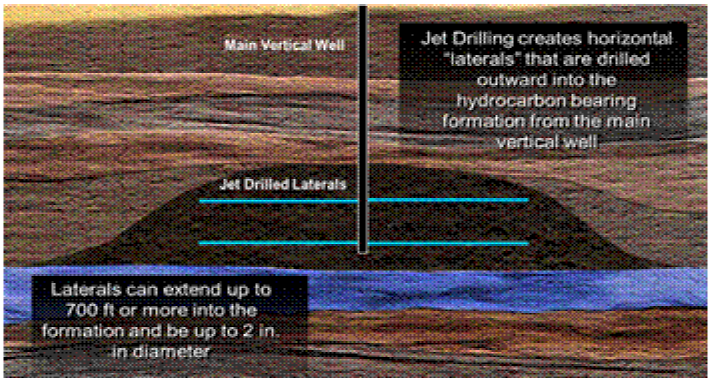

Fig. 1: *Radial jet drilling (Courtesy of Buckman Jet Drilling)*

This drilling process encompasses a wide variety of systems and concepts ranging from down hole tools to be added to a conventional rotary system to the use of surface pressure intensifiers with a parallel high pressure flow path to completely new rigs designed specifically for jet-assisted drilling. Abrasive waterjet systems cut when the abrasive is accelerated above a critical velocity and the abrasive particles begin to chip out pieces of the target material upon collision. The higher the velocity, the more effective the cutting becomes [11]. When jet impact pressure and nozzle type is fixed, hole depth and rock breaking volume increases, and then decreases with the increase of standoff distance. The optimal standoff distance is 12.0 mm in the experiment [12].

3 RJD Process

RJD is a low-cost way to drill small-diameter horizontal completions. Instead of being drilled with a conventional bit and drilling mud, RJD uses high-pressure water, diesel, or acid to be expelled through a high-pressure hose and a nozzle to drill into the formation. The nozzle has orifices that face forward to cut the rock, and orifices that face backwards at a 45-degree angle to push the nozzle forward into the formation and to widen the hole behind the nozzle. The hose is delivered down the hole via a coiled tubing unit (CTU) [7]. Figs. 2 and 3 outlines RJD procedure. The first step of the drilling process is to remove the production equipment from the well and rig up the CTU. The end of the coil tubing (CT) is equipped with a 90-degree deflector shoe that points sideways into the formation when lowered downhole. This deflector shoe is essentially a 90-degree elbow. The CT is then lowered down the well until the deflector shoe reaches the target formation. In a cased hole application, a special cutter is lowered into the well by CTU until the cutter reaches the casing. The cutter is then energized to perforate the casing and cement. After the casing is penetrated, the high-pressure hose with the jet nozzle can be lowered downhole inside the CT. Once the nozzle has reached the formation, the drilling fluid is pumped through the high-pressure hose and exits the nozzle, which both jets the lateral and advances the nozzle and hose into the formation. The jet of fluid exits the nozzle at very high speeds, erodes the reservoir, and drills the lateral. At the end of the process, the pressure in the hose is decreased as the hose is removed from the jetted hole, which circulates out any remaining cuttings left behind. If only one lateral is being jetted, the procedure is complete. If more laterals are going to be completed, then the process is repeated as many times as desired]7, 13].

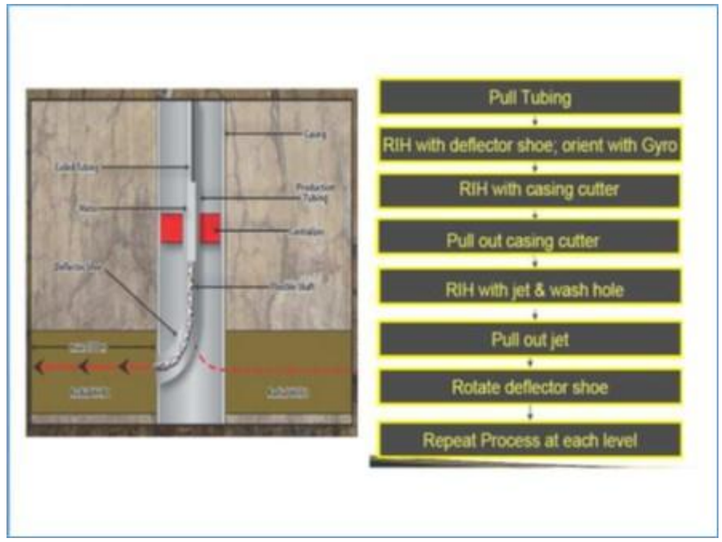

Fig. 2: *RJD procedure (Courtesy of RadJet).*

Different firms offer this service commercially, so procedures vary depending on the operators and their proprietary equipment. Some firms mill the casing and then jet the hole; others mill the casing, turn the deflector shoe, mill another hole in the casing, and then jet the holes out into the formation. Others use abrasive sand in the jetting fluid, allowing them to eliminate the use of a cutter and use this sand to cut through the casing instead. Fundamentally, these procedures follow the same essential pattern of milling the casing and jetting the hole [8].

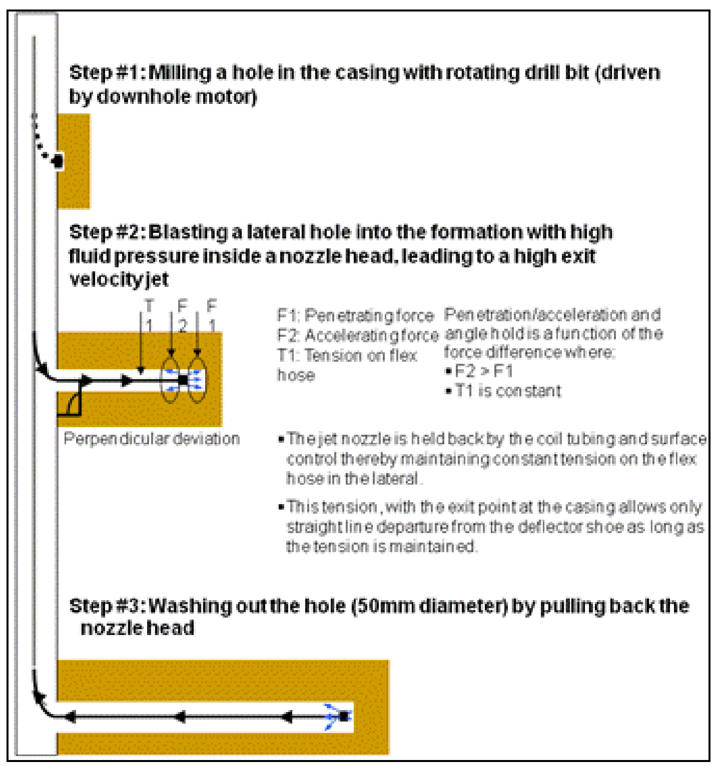

Fig. 3: *RJD procedure (Courtesy of RadJet).*

4 RJD MECHANISM

The basic cutting mechanism is by using an array of nozzles in a drill head. Each nozzle has jetting fluids with necessary additives running through it with very high velocities of 1000 fps exit velocity and creating a drawdown of 10,000 psia. These high pressure jets cut through the formation employing various penetration mechanism include superficial erosion, failure resulting from pore-elastic tension, and cavitation. As shown in Figs. 4, 5, and 6, due to the distribution of nozzles in drill head, enough force is available to let the drill head slide into the lateral perforation created by water jets. There are four forces affecting on jet nozzle and flexible hose; fluids pressure on the forward surface of jet nozzle, $F_{p\text{-}out}$, friction force between wellbore and deflector, F_{df}, friction force between wellbore and flexible hose, F_f, and ejecting force generated by fluid jetting from orifices and acting on rocks, Fj. The pulling force along the x-axis is then can be written as:

$$F_{pull} = F_i - F_{p\text{-}out} - F_f - F_{df} \quad (1)$$

F_{df} is insignificant when compared to other forces and therefore it is neglected. This reduces the above equation to:

$$F_{pull} = F_j - F_{p\text{-}out} - F_f \quad (2)$$

The remaining forces are defined as follows:

$$F_j = \rho {v_0}^2 A_0 - \sum \rho {v_i}^2 \cos\varphi_i \, A_i \quad (3)$$

$$F_{p-out} = \frac{\pi}{4} p_{out} \, {d_o}^2 \quad (4)$$

$$F_f = f \rho_{hose} \, g l_{hose} \quad (5)$$

As long as the pulling force is positive, the well can extend forward. This continues until the friction forces increases at a certain well length, l_{dh} which results in a zero value for pulling force. At this point the well cannot extend anymore and the well has reached its maximum length [14, 16].

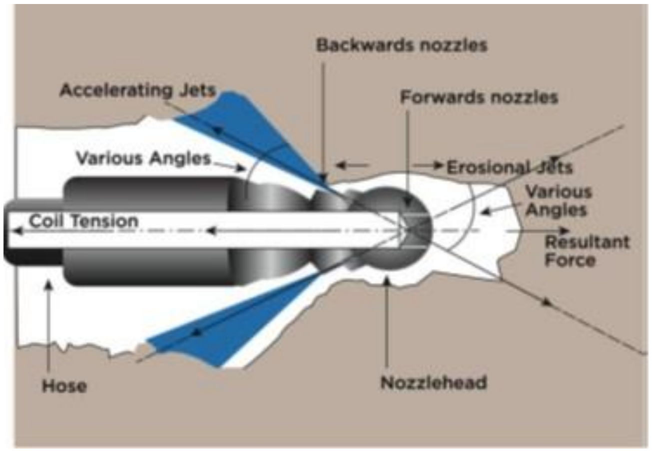

Fig. 4: *Sketch of the Nozzle*

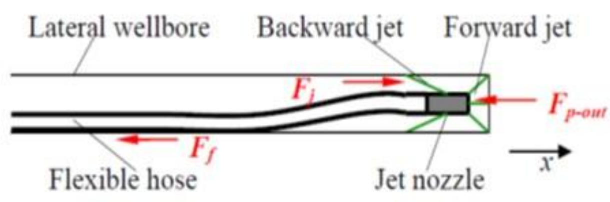

Fig. 5: *Force Analysis of RJD System.*

5 RJD TOOLS

The casing cutter itself is typically a burr mill run by a mud motor. The jetting nozzle, on the other hand, has several orifices that face forward, and several that face backward at a 45-degree angle. The forward orifices cut the rock, while the backward-facing orifices enlarge the hole and push the nozzle forward into the formation. The overall nozzle diameter typically varies from 0.5 to 0.75 inches and is approximately an inch long. Fig. 6 shows the nozzle and the lateral, demonstrating how the forward spray cuts the formation while the rearward spray accelerates the nozzle's progress into the rock and circulates cuttings from the hole [16, 17].

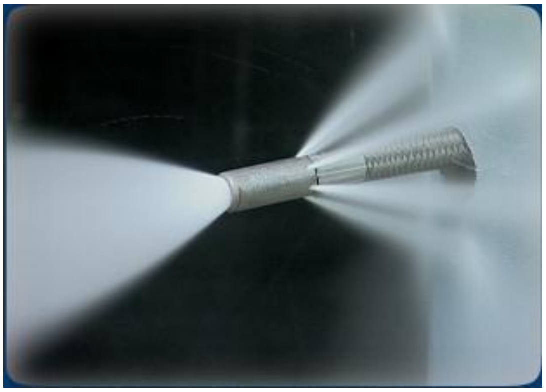

Fig. 6: *RJD procedure (Courtesy of RadJet).*

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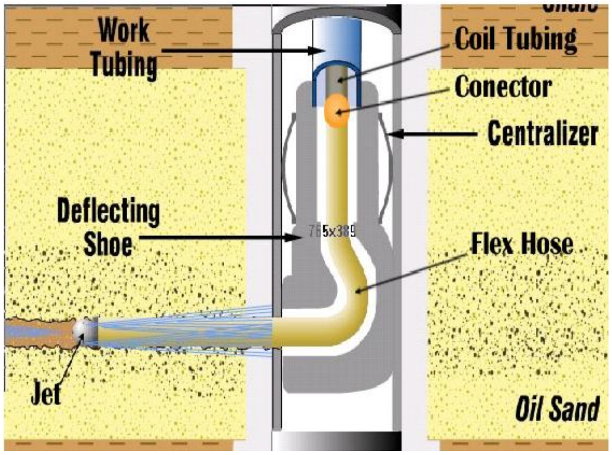

Fig. 7: *RJD Dwonhole equipment*

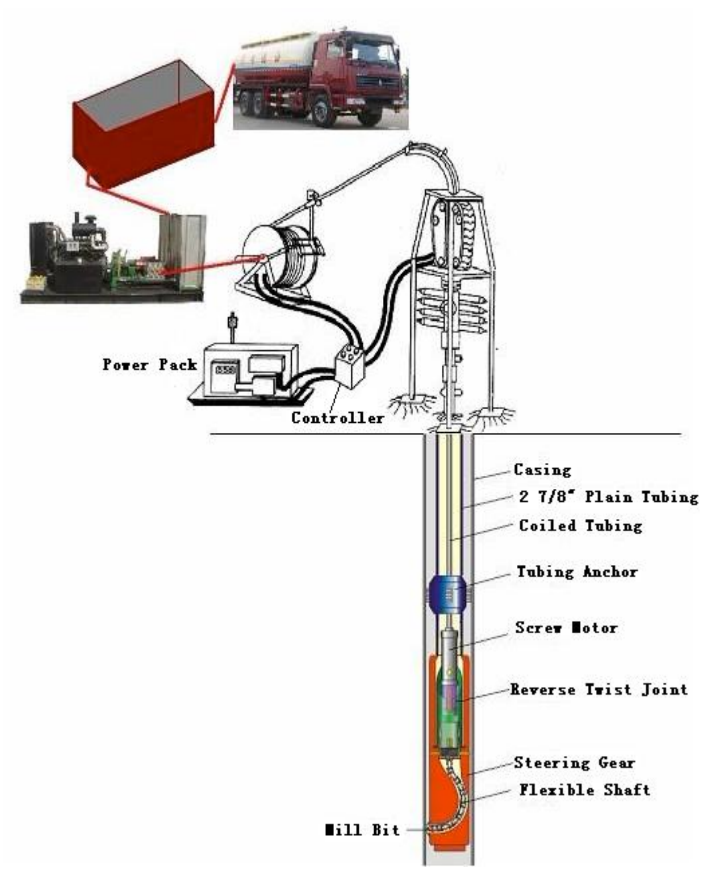

Fig. 8: *Equipment connection diagram.*

7 RJD FLUIDS

In RJD process, fluids with abrasive particles, or grains, are circulated against the surface so that each particle cuts away a small bit of material. The fluid generally, has an important indirect role. It stores and transfers the energy required to accelerate abrasive particles, guides the abrasive particles and focuses impacts within a small spot, flushes debris and abrasive particles away from the working zone, and ensures that fresh surface material is always exposed. Also, it provides some lubrication between the particle and formation, reduces frictional heating, and provides an effective convection cooling medium, where heat generated during deformation is immediately extracted from the formation [11]. Various fluids are pumped through the high pressure hose to the nozzle and they vary depending on reservoir lithology and formation fluid properties. In most cases, water is sufficient as it has obvious advantages as an RJD fluid. It is a cost effective fluid, readily available, easily disposable, and with no HSE issues. However, in water-sensitive formations, diesel fuel may be used to drill the radials. Diesel fuel also has solvent properties that may be advantageous for waxy reservoir fluids; it aids penetration by cutting paraffin in the formation and does not emulsify as water might. In carbonate formations, hydrochloric acid is an advantageous drilling fluid; combining the effects of pressure and dissolution of carbonates. Finally, abrasiveness occurs as a result of proprietary blast-sand, which utilizes the effects of water pressure and sand-blasting to physically erode the casing and formation. The use of abrasives can eliminate the need for a separate cutter to penetrate the casing [20, 21].

8 APPLICATIONS OF RJD

The ability of an abrasive assisted water jet to cut through rocks and metals has potential applications in the oilfield. In oil and gas industry, the abrasive water cutting technique know as radial jet can be used to increase the drainage surface area and enhance oil production. In drilling, the high- pressure jet-drilling system can dramatically reduce the torque and thrust required for drilling, thereby increasing reliability, drilling rate of penetration (ROP), and lateral reach which eventually reduces drilling. In general, the main application of RJD is to provide a fast and economical method to recover the remaining hydrocarbons form marginal or mature oil and gas fields. RJD has been proven to enhance production rates, reduce decline rates and prolongs the productive life of wells and fields, reduce near wellbore damage and/or by-pass damaged zones, allow connection with vertical permeability channels. It is also a viable alternative for traditional perforating to extend beyond near wellbore damaged zone, when other stimulation techniques are not applicable, an alternative for layered formations and when close to water contact [15, 16]. This technique can be applied in different disciplines in oil well industry such as:

- Well completions
- Well stimulations
- Directed reservoir treatment
- Improve water injection
- Improve vertical cleaning
- Reduce water coning
- New wells instead of standard completion methods
- Water disposal and re-injection
- Steam applications in heavy oil and tar sands.

9 ADVANTAGES OF RJD

Radial Drilling characterizes by small footprint and minimizes the formation damage and it can be used as a replacement for well stimulation through laterals and also for cost reduction by minimizing the logging expense. RJD is economical: it can be a cost effective method to complete vertical wells to perform like an open hole horizontal completion. In addition and based on what have been performed on some worldwide fields, the radial drilling methods have some economical and technical benefits such as [4, 17].

- Radial drilling penetration greatly exceeds conventional (perforation) penetration and can reach

substantially beyond the damaged area of the well-bore.
- Laterals can be jetted through-tubing, eliminating the need for pulling the production tubing.
- Reach beyond the damaged area of the well-bore. It can penetrate up to 300 feet, in up to 16 different directions.
- No need for large, expensive rotary rigs.
- Does not require mud pits that can damage the environment.
- No casing milling requirement, therefore no need to circulate mud back to the surface.
- No additional stimulation required.
- The process is fast, average operation duration is two days per well (can drill up to 8 laterals in only two days), so no big loss in production.
- No logging expense required.
- No need to change well-bore configuration.

10 Limitations of RJD

RJD principal application to date has been in marginal and mature fields with low productivity and shallow wells. At present, this method can only be applied in vertical or near vertical wells. Its application in deviated and horizontal wells is still under investigation. Based on the previous operations using radial drilling all over the world, there are some limitations and challenges in applying such technique in oil and gas wells. Among these limitations are [7, 22]:

- Difficulties of penetration under porosity of 3 to 4%.
- Maximum working depth about 4000 - 9000 ft.
- Bottom hole temperature not to exceed 120°C (248°F).
- Maximum wellbore inclination 30° and no more than 15° at the zone target depth/zone of interest.
- Maximum tensile strength 100,000 psi.
- There is no way to complete the lateral with a liner.
- Reentering the lateral after it has been drilled could be very tricky.
- There are no surveillance options inside the lateral.
- Standard logging tools likely will not fit into the lateral.
- Directional control of the lateral is also very difficult.
- Laterals can prematurely terminate due to fractures, faults, or other reservoir heterogeneities.

11 Simulations Results

A simulation study was carried out on wells with different scenarios to accommodate a variety of reservoir permeability from high to low permeability values as shown in Figs 9 and 10 and forecasted different folds of increase and enhanced productivity index with different number of laterals drilled and different permeability [7].

12 Case studies

12.1 Case Study #1: The Donelson West Field

The Donelson West field is about 1,200 acres reservoir of fine crystalline limestone in Cowley County, KS, with an average permeability of 1- 10 millidarcies and an average porosity of 15 – 20%. The net pay varies from 6 to 10 ft. The field commenced the production in 1967 and in 1968, it produced 83,000 bbl from 13 wells, after which production quickly began to decline. During 1973, the field produced only 14,858 bbl. Over the last 10 years, production from the field has been very low. From 2000 to 2009, the field averaged 1,033 bbl per year, with a maximum annual production of 1,701 bbl per year during 2009.

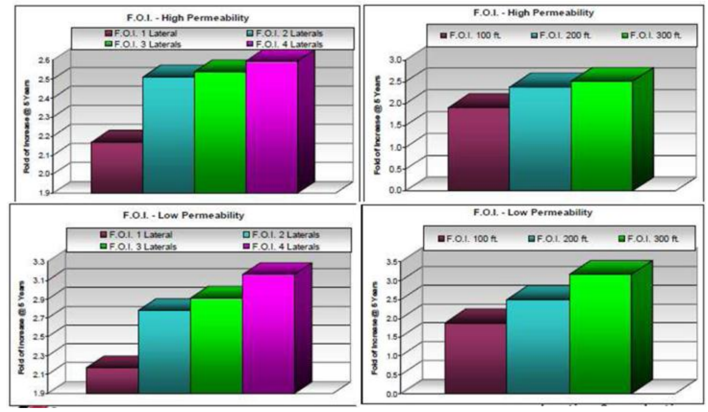

Fig. 9: *Fold of Increase, FOI for Low and High Permeability Reservoirs*

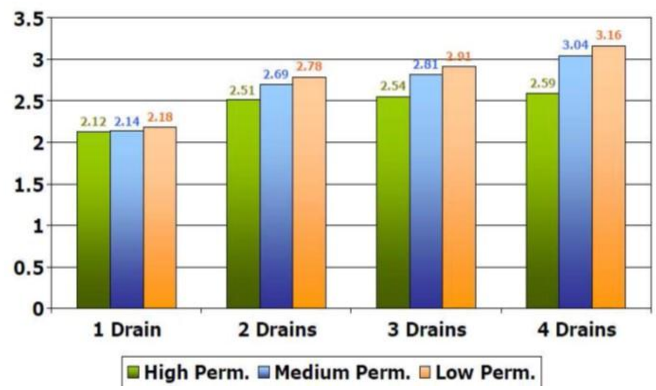

Fig. 10: *Fold of Increase, FOI for different number of laterals*

Development Plan: A new development plan consisting of stimulating the existing wells and initiating an infill drilling program was adopted and then was completed in several phases. The initial phase consisted of recompleting and stimulating eight existing wells and drilling two new wells in the lease, each well was completed with RJD laterals. After the laterals have been completed, each will be hydraulically fractured with 15,000 gallons of acid and 250,000 Mcf of nitrogen. The laterals were drilled over a period of several weeks. Two of the wells were jetted on the same day. Each of the remainder of the wells took a full day to jet. The old wells were completed with four different 600 ft laterals that each required 500 gallons of acid to drill. The new wells were also completed with four different 600 laterals but with 400 gallons of acid for each lateral. After the jetting, each well was stimulated with a 15,000 gallon acid frac followed by 250,000 Mcf of nitrogen. After fracturing, the wells were put on production.

Results: Both of the new wells came on strong with flush production, and seven of the existing wells came on, with one of the existing wells never coming back online. The well that never came back to production is located on the far western edge of the lease. The formation generally thins to the west, and the indicators are that the combination of thin pay and low pressure are such significant that the well simply won't produce. However, despite the one well that never came back to production, the overall success of the ten well programs was excellent. Table 1 summarizes total monthly field production prior to the workovers, as well as total monthly field production after the workovers. The step change in production after the RJD and acid fracturing is evident. Prior to the RJD, the wells struggled to reach an average of 160 bbl per month. Afterwards, production reached nearly an average of 938 bbl per month with a maximum of about 1100 bbl/month. The data clearly indicates that the filed is producing more oil overall, and on average, despite losing one well. In conclusion, the overall RJD/acid fracturing campaign was a success with well production doubling afterwards [8].

***Table 1 –** Pre-Workover and Post-Workover Production*

Before RJD		After RJD	
Year	bbl/month	Months After	bbl/month
2002	11	1	1100
2003	62	2	974
2004	125	3	976
2005	106	4	961
2006	85	5	789
2007	70	6	790
2008	133	7	1124
2009	142	8	797
2010	197	9	803
Average:	**157 (last 3 yr)**		**938**

12.2 Case Study #2: Belayim Land Field
The filed is located in the Central part of the Gulf of Suez, along the coast of the Sinai Peninsula and it is a multilayer field with separated reservoirs with interbedded shales and anhydrite intercalations.

Development Plan: Radial drilling pilot tests were performed in three wells. In the first well (Well #1), 6 lateral drains were jetted at two main depths; three of them at 7460 ft and the other three were at 7450 ft. Five laterals were 160 ft long and the last one was 330 ft long. In the second one (Well #2), 7 lateral drains, 160 ft long were jetted with between 7650 and 7700 ft depth. For the third well (Well #3), 4 laterals, 160 ft long each were drilled; two at a depth of 7500 ft and the other two were at a depth of 8080 ft.

Results: Well #1 showed an increase in production rate from 470 to 820 BOPD (about 350 BOPD gain) while there was no change in water cut. For well #2, RJD drilling was not as effective as in case of well #2. It only showed a slight increase in production from 233 to 246 BOPD. For well #3, there was no increase in production rate and this is believed due to the sand production problems. Well #3 has a history of sand production problems, which may plug laterals after being drilled. Well #2 and #3 were drilled in unconsolidated sandstone with a history of sand production and fines migration. This is one of the drawbacks of RJD as it is not recommended for application in unconsolidated sand [7, 15].

13 What is next?
RJD, however, is a relatively recent technology in the oil and gas and still needs a lot of investigation and research to overcome its limitations and to explore new applications. For example, further research and testing of the jet nozzle penetration mechanism are required in order to identify the optimal nozzle configurations. New techniques are recommended to maintain the increase in production rate, especially in unconsolidated formation. Other areas for improvement from the author point of view includes improved jet bits (most crucial), high strength materials and tubular goods, fluids and application of drag reduction concepts, alternative methods to clean laterals from cutting after jetting process.

14 Conclusion
Despite its limitations, RJD can be an effective tool for production enhancement and completions for both new wells and workover wells with radials up to 1,000 ft long. It is a very viable, cost effective alternative for fracturing in marginal fields. However, candidate selection is a crucial parameter in RJD success. Petrophysical studies, in situ stress magnitude/distribution and rock cutting mechanics are necessary before well intervention to maximize benefits from RJD. In addition, further investigation is recommended to overcome RJD limitations and to explore new applications.

Nomenclature

A_o	=	Hose inner area
A_i	=	Nozzle area
d_o	=	Outer diameter of oil tubing
f	=	Well friction coefficient
F_{df}	=	Friction force between wellbore and defelctor
F_f	=	Friction force of well to high-pressure hose
F_j	=	Ejecting force generated by fluid jet
F_{p-out}	=	Static ambient fluid pressure on forward surface of the jet bit
F_{pull}	=	Pulling force of the high-pressure hose and the jet bit
g	=	Gravitational acceleration
l_{hose}	=	Length of the high-pressure hose
P_{out}	=	Ambient fluid pressure around the jet bit
v_o	=	Speed in the hose
v_i	=	Speed in the nozzle
ρ	=	Fluid Density
ρ_{hose}	=	Weight of high-pressure hose per meter
φ	=	Angle of the nozzle

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