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Jet Drilling Tool: Cost-Effective Lateral Drilling Technology for Enhanced Oil Recovery

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Abstract

The paper describes a new coiled tubing conveyed drilling technique, were several new well bores are jet-drilled perpendicular from the mother well and into the reservoir formation. This technology is targeted for Enhanced Oil Recovery (EOR) in both existing and new field developments. The objective is to improve the production profile around the mother well, by penetrating the damaged skin zone, and connecting to possible hydrocarbon pockets left behind in the reservoir.

The Bottom Hole Assembly (BHA) is configured to jet-drill several slim laterals, all in one coiled tubing (CT) run. This through tubing operation has the potential to create up to ten, 50 m long, and 1-2 in. diameter laterals at the exact desired depth in the mother well. The BHA consists of two main parts; a casing drilling machine and a high-pressure hose and jet-nozzle. The hose is spooled from the BHA as the lateral is drilled into the formation.

The main issues presented in the paper are:

1. The new jet tool functional characteristics
2. The theoretical aspects of jet drilling; penetration mechanisms and self-induced nozzle pull force
3. Laboratory experiments (confirmation of theoretical models)
4. The jet drilling effect on improved well production (production simulations).

The technology is an attractive substitute or supplement to acid and proppant fracturing, perforating services and conventional sidetrack drilling.

Introduction

An important issue when stimulating a producing or injection well is to control the exact placement and direction of the treatment. This may represent a challenge in conventional fracturing and acid stimulation methods. Stimulating low productivity zones exposed together with good productivity zones represent in many situations a problem, since the treatment is improperly diverted into the low productivity zones. The stimulation fluid tends to flow into the good zones, which in many cases were not the target for the stimulation. Furthermore, fractures may open pathways along the casing wall, causing zonal isolation problems in the well. A variety of diversion techniques have been developed in the industry today, in order to achieve improved stimulation control. The success of these techniques varies.

This paper describes a technology that provides means for improved control of the EOR treatment. The technology provides real time signals, which acquires exact measurements of tool depth and direction. No pre-treatment activities, like pulling tubing (dependent on size), section milling and/or under-reaming is required prior to the jetting operation.

The tool will be a valuable supplement or substitute to conventional services like:

- Perforating
- Matrix Acidizing
- Fracturing
- Conventional sidetrack, slim hole drilling.

The Jetting Technology Development Project – Definitions and Functional Descriptions

The tool is a coiled tubing conveyed electrical bottom hole assembly, designed and developed to create a number of laterals perpendicular to the mother well in one CT run. The laterals remain barefoot and are created by means of the jet-impact generated when pumping fluid at high pressure through the nozzle-head. The energy created when the fluid exits the nozzle-head is also providing the required forward force to pull the high-pressure hose into the lateral.

The main design criteria for the development were:

1. Provide 4-10 laterals radially from the mother-well, each 1-2 in diameter and up to 50 meters long
2. The entire treatment performed in one CT run
3. Temperature and pressure rating; 120^0C and 690 bar
4. Function in both live and dead wells

5. Function in sour environment
6. The data acquisition system should provide real time indication of tool position and lateral exit direction, as well as positive indication on operating system effectiveness
7. The tool shall be designed for operation in 4 ½” or larger inner diameter (ID) completions.

The main features of the Jet Tool are the ability to create a hole in the casing and to subsequently jet a lateral into the formation through the casing exit hole. To achieve this a Drilling Machine and a Jet Drum has been developed. The Drilling Machine contains a drill bit driven by a combination of an electrical motor and a hydraulic piston, creating a 1 ½” diameter hole in the casing. The Jet Drum holds a 3/8 in, 50 m long jet hose, which is coiled around a cylindrical drum. The drum has an electric motor enabling the drum to feed the hose out while creating the lateral, and to spool the hose back in.

The Drilling Machine and the Jet Drum are the main components of the BHA. In addition it contains the following components (see fig 1):

- Tubing End Connector
- Controller Unit/Power Pack
- Anchor
- Orienter/Indexer
- Steering-tool
- Stroke Cylinder.

The BHA is run on a CT with an internal electric line for power supply and communication to/from the surface, and a ½ in. outer diameter (OD) capillary line for jet fluid supply.

The Controller Unit is the brain of the tool and it activates the various tool functions according to the signals from the tool operator at surface. The controller includes an internal hydraulic power-unit and a solenoid valve operated distribution system.

A hydraulically operated anchor has been developed and incorporated in the BHA. Its function is to attach the BHA to the casing wall in order to maintain it in exactly the same position from the point that the casing hole is being drilled until the lateral has been jetted.

One of the main objectives with the treatment is to enhance the production pressure distribution and to determine the depth and direction of the lateral. The hydraulically operated orienter in the BHA, enables the tool to create laterals in various directions perpendicular to the mother well. The Orienter rotates the lower part of the Jet Tool (below the anchor) and positions the tool face in the requested direction. Verification of direction comes from a steering tool located below the orienter.

A Stroke Cylinder is placed above the Drilling Machine and Jet Drum. Its function is to position the Nozzle Head exit in front of the casing hole created by the Drilling Machine. The Stroke Cylinder is hydraulically driven.

Tool Operation:

1. Lower the BHA down to the reservoir target depth
2. Attach the tool to the casing wall by means of the anchor
3. Drill a hole in the casing/production liner with the drilling machine
4. Stroke out the telescopic joint to position the nozzle head exit in front of the hole in the casing
5. Jet a lateral into the formation by pumping the jetting fluid through the internal capillary tube, into the high-pressure hose, and finally through the jet nozzle
6. Retract the telescopic joint
7. Reposition the tool, either by vertical repositioning, or by rotating the tool face by means of the orienter
8. Repeat the procedure, and pull out.

The Jetting Tool Prototype has been developed over an 18 months period. The Drilling Machine and the Jet Drum have been manufactured and tested in accordance to the functional requirements. The Drilling Machine proved to drill through a 5-½ in., 17 lb/ft, Cr 13 casing in 9 minutes. The Jet Drum has been function tested by running the jet hose in and out from the jet-drum with the hose pressurized up to 220 bar.

Study of the Penetration Mechanism set in force by the Jet Nozzle effect

Penetrating hydrocarbon formations with water-jet energy is by no means a new invention. The jet power effect has been employed for various down hole applications. Veenhuizen (1) and Kolle (2) describe the effect of applying jet energy in combination with conventional drill bit technology in order to enhance the rate of penetration in hard formations. Dickinson (3), Maurer (4) and Pols (5) describe jet penetration technologies where laterals are created purely by use of clean water jet energy. The jet penetrating efficiency in different rocks along with various nozzle configurations and operating jet parameters have been frequently discussed topics. This data has been incorporated in this study during the development process. The paper focuses on the observations related to the specific nozzle head as illustrated in fig 2 and how the jet power generated through this nozzle head acts on the formation. Both the various penetrating mechanisms and the nozzle heads self-generating net forward pull force are discussed.

Penetration Effect. Four main penetration mechanisms were identified:

- Surface Erosion
- Hydraulic Fracturing
- Poroelastic tensile failure
- Cavitation.

Surface erosion. Surface erosion is the process where rock fragments are removed from the surface of the rock due to the shear and compression forces exerted on the rock surface due to the jetting flow. It is reasonable to assume that this process takes place, but the effectiveness is yet to be defined. There is in principle no difference between this process and the process taking place in conventional drilling, thus the energy required should be more or less equal. The impressive penetration rates reported from tests indicate therefore that more effective processes also take place.

Hydraulic fracturing. As the build-up of pressure at the stagnation point diffuses into the formation, the formation may fail in tension if this pressure is higher than the stresses set up by the far-field formation stresses. Figure 3 shows a sketch of this mechanism. This pressure diffusion will take place as long as the permeability is not negligible. However, the characteristic size of the volume with elevated pore pressure will be the same as the characteristic size of the area hit by the water jet. As the water jets are fine, such hydraulic fractures will not extend far into the formation, and the extra compression stress exerted by the jet on the free surface of the formation may inhibit this process. It is assumed that this process may considerably enhance the surface erosion process, if the nozzle head is optimally configured.

Poroelastic tensile failure. A rapid fluid pressure decrease at the rock surface will induce effective tensile stresses in the formation equal to the decrease. If this induced tension is higher than the sum of the smallest effective stress in the formation and the tensile strength, the rock will fail in tension. This induced tension occurs as the compressibility of the rock grains and pore fluid is not equal, and any deviation from equilibrium between the rock grains and pore fluid has to be restored by fluid flowing through the pore space. This flow takes time due to the finite permeability of the rock, and gives rise to this transient poroelastic effect. However, for high permeability sandstones (1 Darcy) the time scale is around 1 µs, which may be unrealistically fast. However, the time scales inversely with the permeability and for chalk (1 mDarcy) or shale (1 mDarcy) this effect may be important**.**

Cavitation. When the water accelerates to pass through corners of the nozzle, the pressure may drop below the vapor pressure. This may cause vapor bubbles to form. As the flow moves into a larger area, the pressure recovers to a certain degree. This increases the pressure above the vapor pressure, causing the vapor bubbles to collapse or implode. The shock waves may be extremely high and cause additional erosion and tension effect.

Pull Effect. The net pull effect that works the nozzle forward can be derived from three main mechanisms:
- The under pressure force
- The jetting force
- The ejector force.

Under pressure force. To explain the nozzle head forward feeding force, a model for nozzle suction has been proposed. This model is based on the observation that any flow emerging from a nozzle and impinging on a solid wall will be deflected and create a static pressure lower than the surrounding pressure in a circular section at the nozzle perimeter. Figure 4 explains this mechanism. An important feature is that the radial velocity v_r is inversely proportional to the gap, decreasing the gap will increase the velocity, consequently the static pressure, p_{stat}, will decrease.

In the present case, the static pressure can come down to the level of surface atmospheric pressure, creating a pressure difference between the nozzle front area and the surrounding fluid almost equal to the structure hydrostatic pressure.

The following formulas are used for estimating the real “under pressure” pulling effect.

Continuity equation:

$$Q_i = 2\pi rh \cdot u(r) \qquad (1)$$

where

Q_i = *flowrate through each nozzle*

h = *gap between nozzle and bottom of hole*

$u(r)$ = *velocity in radial direction*

Bernoulli equation:

$$\rho \frac{u(r)^2}{2} + P(r) = P_0 \qquad (2)$$

where

ρ = *density of water*

$P(r)$ = *pressure a distance r from the nozzle exit*

P_0 = *surrounding pressure*

From equation (1) and (2) we obtain:

$$P(r) = P_0 - \frac{1}{2}\rho(\frac{Q_i}{2\pi h})\frac{1}{r^2} \qquad (3)$$

Force equation:

$$S_{pressure} = \int_{r0}^{R} (P(r) - P_0) 2\pi r dr \qquad (4)$$

From equation (3) and (4) we obtain:

$$S_{pressure} = -\frac{1}{2}\rho(\frac{Q_i^2}{2\pi h^2})\ln(\frac{R}{r_0}) \qquad (5)$$

This equation expresses the under pressure pulling force. Note that variation of the parameters r_0 and R will not change the result drastically, because $\ln(R/r_0)$ is a slow function of the argument R/r_0. To obtain a large pulling force due to under pressure at the front of the nozzle require a very small gap h between the nozzle and bottom of the hole.

Jetting Force. Using a nozzle head to provide a pulling force is utilized in commercial applications like cleaning up sewer pipes. A typical nozzle configuration has outlets in radial direction for cleaning up and backwards nozzles to provide a pulling force. The nozzle head referred to in this study has both forwards and backwards pointing nozzles. The nozzle configuration should have a net pulling force, enabling the nozzle to return to the bottom of the hole after being pulled out off hole during a clean-up operation.

Alone the nozzles do not create an impulse that is sufficient to provide a net pulling force of the magnitude required in this application. A minimal force is created directly by the mass flux from the backward pointing nozzles. But as soon as the jets from these nozzles act in annular chamber they will have an ejector effect that will suck away water from the front end of the nozzle head. This assist in keeping the low local pressure at the front of the nozzle head, thus supporting the under pressure mechanism.

Calculation of the jetting force S in the pulling direction:

$$S_{jetting} = \rho u_0^2 A_0 - \sum_{i=1}^{6} \rho u_i^2 \cos\varphi_i A_i \qquad (6)$$

where

$$A_0 = \frac{\pi}{4} D_0^2 = \qquad \textit{inside hose area}$$

$$A_i = \frac{\pi}{4} d_i^2 = \qquad \textit{nozzle area}$$

$$u_0 = \frac{Q}{A_0} = \quad \textit{inside hose velocity}$$

$$u_i = \frac{Q}{6A_i} = \qquad \textit{nozzle velocity}$$

Test Description. The study has tested a concept for penetration through the formation using the jetting nozzle as illustrated in fig. 2 as both pulling mechanism and penetrating mechanism.

The tests have verified the:

- Under pressure force in front of the nozzle
- Ejector effect
- Direction of the jetting force
- The penetration effect.

Jetting force test. The objective of the test was to verify the direction of the jetting force (see test configuration; figure 5). The nozzle was connected at the end of a 10-mm outer diameter hose, which at the other end was connected to a pump. The hose and nozzle was hold in the middle of the test cell, the pump was started and the pulling force was measured. The jetting force proved to give a negative contribution to the net pulling force.

Ejector force test. The objective of the test was to verify the existence of the ejector force (see test configuration fig 6). The hose and nozzle was hold in the middle of a plexiglas pipe, the pump was started and a featherweight measured the pulling force. The ejector force gave a clearly contribution to the net pulling force.

Under- pressure force test. The objective of the test was to verify the under-pressure force (see test configuration fig 7). A rock sample with a pre-drilled hole was connected to the end of the plexiglas pipe. The nozzle was lowered down to the rock sample at the bottom of the pipe, the pump was started and a featherweight measured the pulling force. The under pressure force gave a clearly contribution to the net pulling force.

Back pressure during the tests was 1 atmosphere only. Increased back pressure will increase the under-pressure force, thus increasing the net pulling force. The test results are presented in table 1.

Penetration. Figure 8 shows the test configuration for the penetration test. The objective of this test was to get reference data on the penetration speed, bottom hole geometry and cuttings at both atmospheric and 4 bar back-pressure. The tests were performed in both Bentheimer and red sandstone rock samples (see test results in table 2). The holes created during the tests are illustrated in fig 9 and 10.

Well productivity improvement.

The main purpose of drilling “short” horizontal well laterals perpendicular to the mother-well is to reduce the pressure drop close to the well bore and thereby improve the effective drainage radius and flow profile around the well. The technology provides full lateral and vertical “treatment“ control, which in some situations may be difficult to achieve in traditional acid and proppant stimulations.

Lateral jet drilling technology has a big potential for increased productivity from reservoirs that:

A) are thin and irregular - The laterals could effectively intersect isolated productive zones which might otherwise be missed.

B) are homogeneous but intersected by interceded low productivity zones - The jet technology provides means for vertical treatment control as it is not dependent on any diverter agents nor any form of zonal isolation of the zone to be treated.

C) are close to a gas cap or water table. – The laterals will provide reduced pressure drop and hence reduced potential for water and gas coning. In addition the technology provides means for controlling the treatment and not penetrate (frac) into the gas or water zones.

D) have high vertical to horizontal permeability ratio. – Horizontal laterals will produce more economically.

Other factors influencing the potential for productivity increase is the level of skin damage in the mother well, the magnitude of reservoir permeability and also reservoir fluid properties.

Jet lateral productivity simulations. In order to investigate some of the above parameters, a 31 by 31 areal and 15 layer simulation model was built. The model extended 1103 metres squared and 43-metre thickness. The model reservoir properties and grid are shown in table 3 and figure 11. The 7" mother well is completed throughout the reservoir and provisions are made to complete four 2" laterals at 3 different levels (heights) in the reservoir. Each 50-meter long lateral is offset 90 degrees to each other constituting a total of 12 laterals.

Sensitivities. All sensitivities are compared to the same base-case and the productivity increase is calculated as the ratio between the sensitivity PI and the base-case PI. Results from the base-case are given in table 4. In each sensitivity only the one parameter investigated is changed at a time in order to isolate the effect of changing that particular parameter.

The following 4 reservoir parameters have been investigated.

1) Reservoir permeability
2) Effect of skin damage in the mother well
3) The ratio between the vertical and horizontal permeability in the reservoir
4) Oil Viscosity.

Results and conclusions. The results from the simulations are shown in figures 12-15.

1) The benefit from drilling horisontal laterals increases with decreasing reservoir permeability.
2) Connecting to the reservoir formation beyond the damaged skin zones has big impact on total productivity of the well.
3) Benefit from drilling horizontal laterals is most profound in reservoirs with high Kv/Kh ratios.
4) Productivity increase is dependent on fluid viscosity. Best change in productivity is seen in high viscosity reservoirs.

A last series of runs were then made applying average values from the sensitivities above (Table 4). The results show that drilling 1 lateral improves the productivity by a factor of 2, whereas drilling 1 lateral at 3 levels in the reservoir section gives an increased productivity by a factor of 3.5. Drilling 2 laterals in 3 levels (6 laterals total) increased the productivity by a factor of 4.6.

Conclusion

The coiled tubing conveyed jetting tool offers a new method for well production and injection enhancement. Compared to conventional technology in the market today, this technique represents a safe and cost effective alternative as several laterals will be drilled in one CT run.

This CT operation will be performed in wells without a need for pulling tubing or handling big volumes of chemicals at high pressures. Full vertical and lateral control of the "treatment" in the mother well is achieved.

All critical tool components have been function tested in accordance to field requirements. Promising laboratory tests and reservoir simulations are carried out which supports the viability of the technology.

Further research and testing of the jet nozzle penetration mechanism are required in order to identify the optimal nozzle configurations. A program for such testing is currently ongoing.

Acknowledgements

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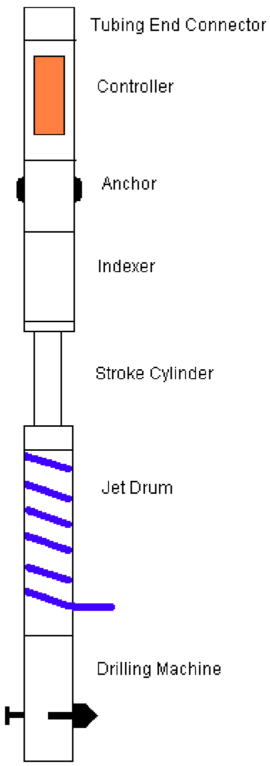

Fig. 1 - Schematic of Jet Tool

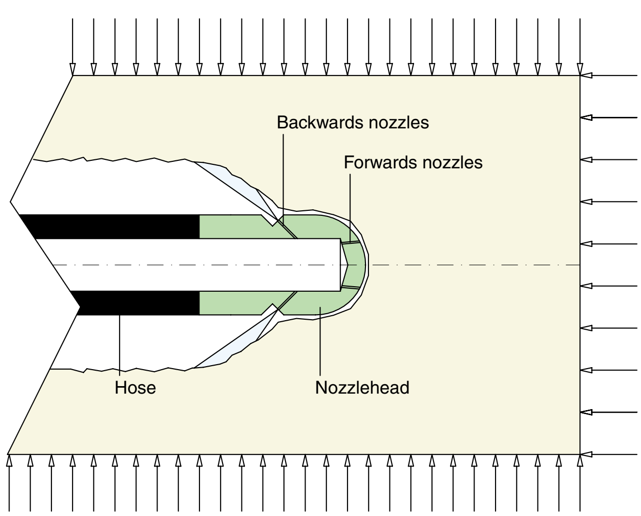

Fig. 2 - Sketch of the nozzle

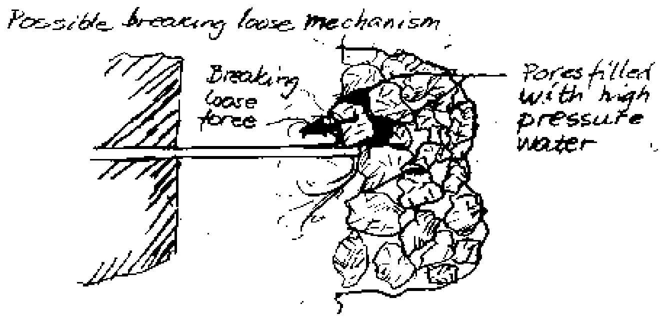

Fig. 3 - Build-up of pressure at the stagnation point

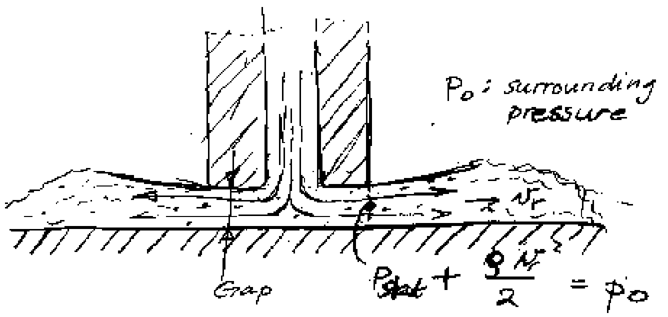

Fig. 4 - Sketch of the nozzle suction principle

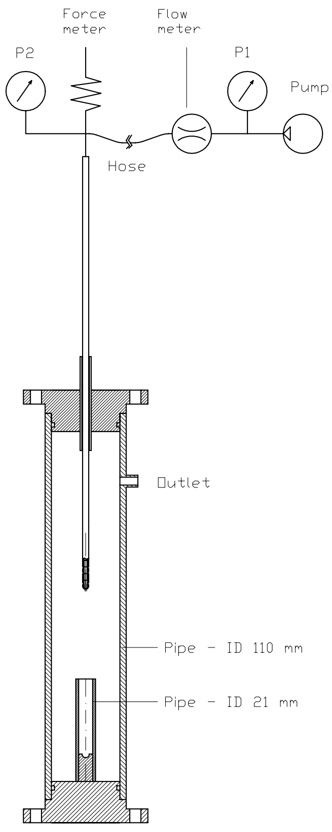

Fig. 5 - Configuration for testing the direction of the jetting force

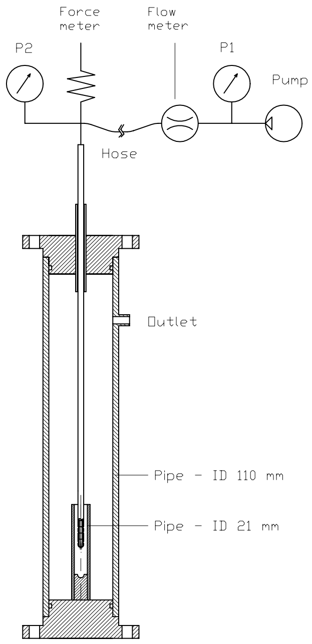

Fig. 6 - Configuration for testing the ejector force

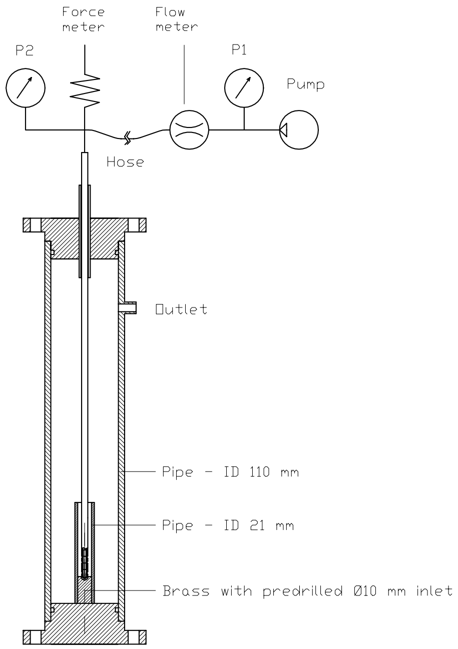

Fig. 7 - Configuration for testing the under-pressure-force

Force Component	Pressure drop through nozzle:	Flow rate:	Pulling force:
Jetting force	211 bar	6.7 l/min	-250 g
Ejector force	211 bar	6.7 l/min	61 g
Under- pressure force	211 bar	6.7 l/min	220 g
Total force			31 g

Table 1: Test results - Pull force

Rock Sample	Pressure drop through nozzle:	Flow rate:	Result
Bentheimer	210 bar	12.6 l/min	See fig 10
Red sandstone	130 bar	10 l/min	See fig 9

Table 2: Test results – Penetration

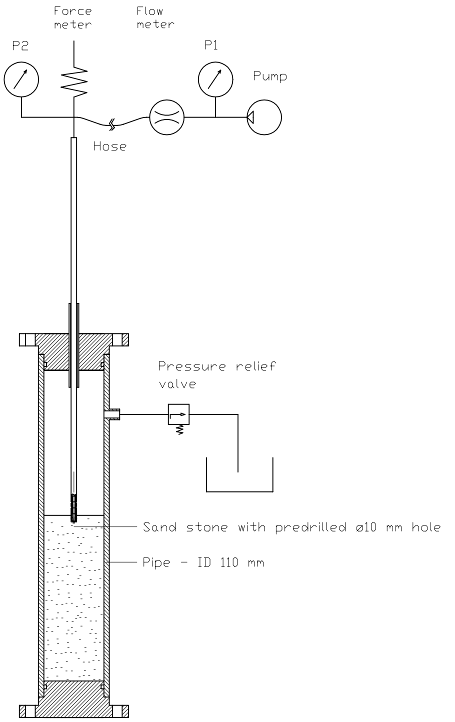

Fig. 8 - Configuration for testing the penetration

Fig. 9 - Hole in Red Sandstone

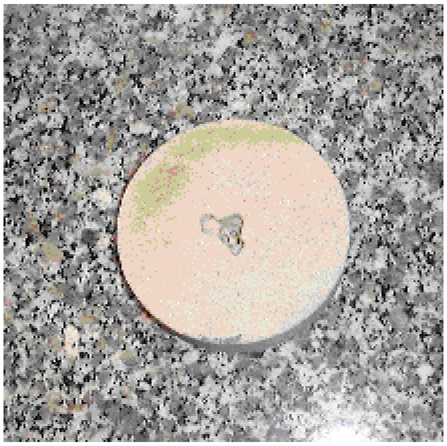

Fig. 10 - Hole in Bentheimer

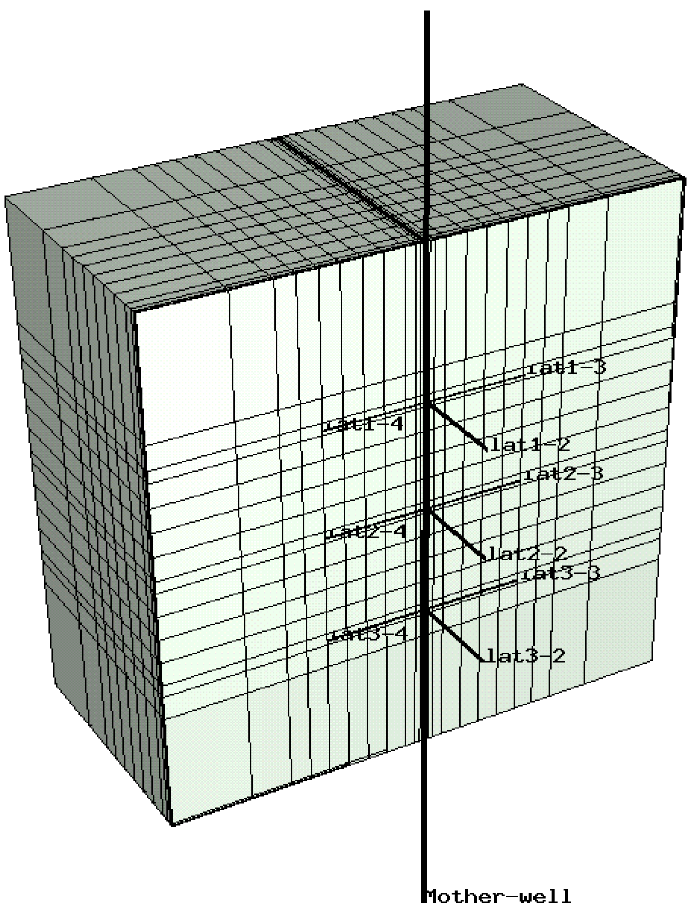

Fig. 11 - Simulating Grid

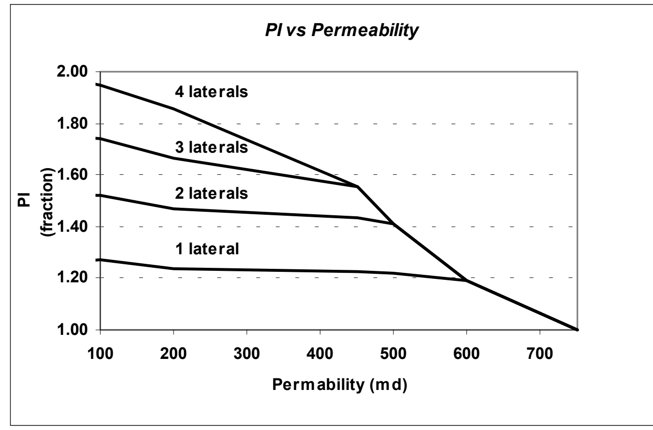

Fig 12 - PI vs. Permeability

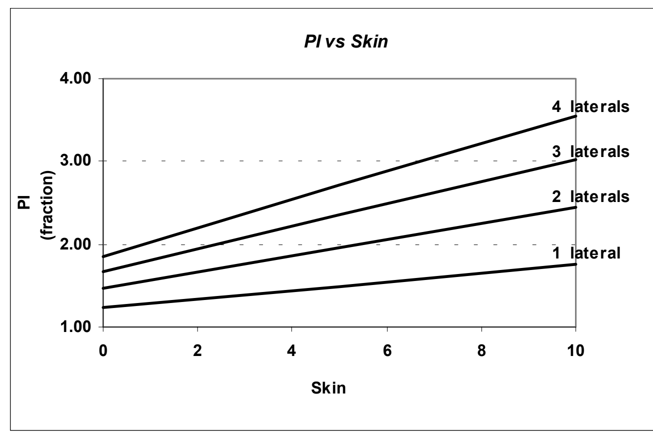

Fig 13 - PI vs. Skin

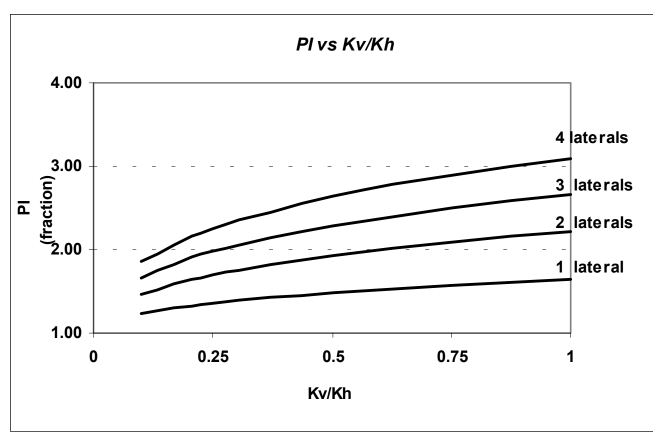

Fig 14 - PI vs. Kv/Kh

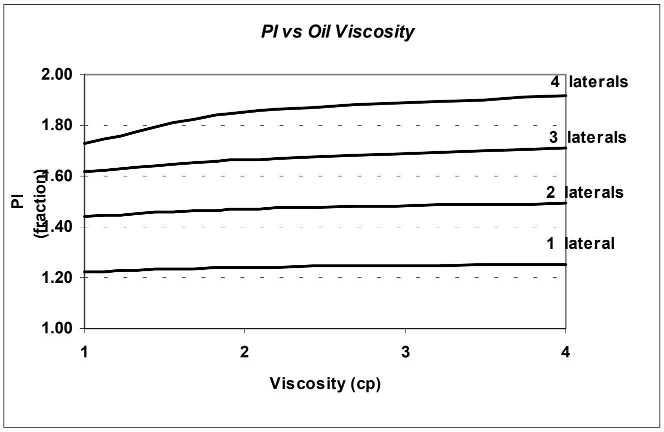

Fig 15 - PI vs. Oil Viscosity

Parameters	Data:
Fluid	Oil/Wat
Porosity	0.2
Permeability	200 md
kv/kh	0.1
Res. Pressure	200 bar
Swir	0.25
Sor	0.3
Oil Viscosity	2 cp
Oil Density	0.72 g/cc
Oil FVF	1.4
Wbhp	150 bar
Prod rate limit	4000m^3/d

Table 3 - Res. model base case data

Case	PI Increase (Ratio)	Perm	Press	WFBHP	Kv/Kh	Skin	Viscosity
Base Case		200	200	150	0.5	5	2
1 Lateral	**2.0**						
3 Laterals	**3.5**						
2 Lateral, 3 Levels	**4.6**						

Table 4 - Productivity Simulations