EVOLUTION OF PRODUCTION LOGGING TECHNOLOGIES AND CAPABILITIES: “THE QUEST TO KNOW THE UNKNOWN” A BROWN FIELD CASE STUDY-MUMBAI HIGH, WESTERN OFFSHORE, INDIA


*Oil and Natural Gas Corporation Limited,
Schlumberger

ABSTRACT

Production logging traditionally has been used to describe the flow characteristic of a well. It is essential to identify zonal phase contributions and water entry points for water shutoff jobs. Over the years with the advancement of the technology, for the techno economic success, deviated and horizontal wells have been drilled. Application of highly deviated and horizontal wells for field development for primary recovery is now a worldwide practice.

Diagnosing production problems in a multiphase environment was not an easy task, and complex flow regimes in highly deviated and horizontal wells have made this task even more complicated. At the same time, with advancement in completion system design, it has become imperative to evaluate the effectiveness of the new completion design. Unfortunately traditional production logging techniques have not been successful in these conditions.

One of the key issues in diagnosing production problems is detecting and distinguishing hydrocarbons in high water cut wells with water phase flowing as continuous medium at the low side and dispersed hydrocarbon phase at the high side of wellbore. Technologies like the digital entry fluid imaging tool and gas holdup optical sensor tool have proven to provide accurate results. For horizontal and highly deviated wells where recirculation, crossflow, and phase segregation further complicate the flow behavior, complete imaging of the wellbore is needed to characterize the wells.

Brownfield wells surveillance has always been a key concern for the oil companies around the world to enhance and optimize oil production. Further, in the brownfield scenario, the complications aggravate and may require real-time decision making and intensive data analysis. Some of the typical brownfield issues are scale buildup due to immense water injection for pressure support, which is required for efficient oil displacement, complex fluid flow regime, recirculation due to insufficient lift, and casing damage resulting in unwanted formation water entry.

The study provides the most prolific summary and guide for case studies, success stories and lessons learned from the Mumbai High field in the last decade; evolution of the production logging tool from the most standard unit to multipoint digital entry fluid imaging, gas holdup optical sensor tools to identify and distinguish between the three fluid phases. The paradigm shift towards the key technologies like flow scan imager to evaluate the complex borehole fluid, flow regimes is also presented in this paper. Key observations after rigorous analysis has resulted in successful multi well operations.
INTRODUCTION

The Mumbai High Field is about 160 km North West off the Mumbai City and is the biggest oilfield in western offshore India (Ref to figure 1), with an aerial extent of 1200 sq km.

The Mumbai High Field is a multi-layered limestone reservoir with large variations in fluid flow properties both vertically and laterally, produces about 250k bopd (~40% of India's oil production). In terms of reservoir heterogeneity, The Mumbai high field is considered to be one of the most complex fields worldwide. The field started producing in 1976 and a Pressure maintenance scheme using water injection was started in 1984, since there was unexpected and sharp pressure drop with initial production.

The field is currently in decline phase with problems like increase in water cut and high GOR which are affecting the oil production the average field produces about 250,000 bbls of oil per day. Mumbai High field is separated by a Graben area into Mumbai high north and Mumbai high south.

Mumbai high north is basically the western flank of the anticline trending SE-NW direction dipping gently towards North West. Mumbai high south is western flank of the anticline structural dipping towards the west and south. Several oil and gas zones have been identified in this field, LIII being the most prolific with 90% hydrocarbon accumulations. The reservoir is essentially composed of limestone layers separated by the thin shale sections. The shale section divides the L-III reservoir into no of zones which are termed as A1, A2, B, C, D and E. Several thin shale sections further sub-divide A2 into seven sub layers. Both the fields are supported by partial water drive from western side extending from north to south. In order to maintain peripheral water injection was started. However the benefit accrued on by the peripheral water injection was insignificant. Therefore two rows of water injection were installed in central part of the field.

PRODUCTION LOGGING-THE BEGINNING

Production logging began in 1930’s with the introduction of temperature measurements in oil and gas wells, inducted with the sense to locate fluid entry using the resistance sensor.

In the 1940’s the spinner for flow rate and pressure measurements were also added to temperature surveys to obtain more detailed information of the well bore, type of fluid can be identified using the pressure derivative.

Future developments were more meaningful with the feasibility of monitoring real time production logging. This was of an obvious help as it provided more flexibility and command over the production logging operations.

In the late 1960’s the next phase of development was instrumental gain in acquiring the information particularly in multiphase environment. Density and capacitance meters were introduced to solve complex multiphase flow behavior.

Initially the original purpose of using temperature sensor was to locate the hydrocarbon bearing zones from non productive interval. However due to the differences in the thermal properties of hydrocarbon and water were small to affect the overall thermal conductivity of reservoir section. This meant that original purpose of using temperature was a futile exercise, although temperature logging was later recognized as means to evaluate production well characteristics by analyzing anomalous temperature behavior. Temperature logs are still used for these applications, like gas entries, casing leak detection and fluid movement behind casing, the most common applications are qualitative identification of injection and producing zones. Despite the advancement of technology temperature logging effectively remains the core of production logging. Production logging tool was inclined to basic temperature interpretation, pressure and spinner response, with the presence of single phase fluid in the wellbore the derived qualitative results were satisfactory; and complications related to the interpretation were minimal. However with passage of time the reservoir behavior kept deteriorating and losses, channeling, casing damage casing etc became common issues. These are also usual behavior in Mumbai high field.
Quality of results was satisfactory in the initial phase of a production logging in a green field environment, with single phase flow; however some observations were still ambiguous. Minor water inside the borehole in a low water cut well, is beyond the resolution of density sensor. Similarly capacitance sensors are unreliable in high water cut wells, hence providing a limited operational window for logging operations.

Evolution of Production logging tool is in coherence with the introduction of deviated, horizontal wells in oilfield. These deviated and horizontal wells can have complex flow regimes that render interpretation from conventional production logging sensor. Traditional PL measurements use flowmeter (spinners) for velocity, gradiomanometer for density, capacitance for holdup, manometers for pressure and thermometers for temperature. Of all these measurement density, spinner and capacitance and temperature become less reliable because of the limitation of applicability in horizontal wells. It is therefore inevitable for researchers and engineers to develop a more robust production logging technique. Thus successfully evaluate the performance of horizontal wells.

**Digital Entry Fluid Imager Tool:** The FloView* bubble count and holdup measurements are based on four low frequency (LF) probes. These probes discriminate between electrically conductive and electrically non-conductive fluid. Since, water is the electrically conductive medium in producing oil, gas wells the probes discriminate between water and hydrocarbons. Each probe measures the number of bubbles of the dispersed phase. That is the number of oil bubbles in the water continuous phase and number of water bubbles in the oil continuous phase. The FloView outputs the bubble count for each probe and an average bubble count is computed from the individual outputs of the four probes. The probes cannot currently distinguish between gas and oil. Further the probes can identify individual bubbles of the dispersed phase i.e. oil bubbles in a water continuous phase and water bubbles in an oil continuous phase. Each probe can then output the number of bubbles as a function of time giving the output of bubble count per probe.

Water holdup for each probe is computed as a function of time the probe spends in water. The average holdup is computed from the output of the four individual probes (Refer to figure 1). The direct reading of DEFT log can provide an image of fluid distribution in wellbore.

The FloView holdup measurement requires no master or wellsite calibration. Since the FloView clearly identifies any bubbles of oil in water and due to the superior resolution of the holdup measurement, the FloView can clearly identify the first point of oil entry. This is extremely useful in high water cut producers where traditional holdup tools such as gradiomanometer cannot provide answers. Both the bubble count and water holdup aid in identifying the type of fluid being produced by each perforated interval. The Floview* probes have vivid applications to identify the minor hydrocarbon entry inside the borehole irrespective of the water cut.

![Figure 1 Calculation of Water Holdup](image-url)
**Gas Holdup Optical Sensor Tool:**

One of the breakthrough technologies in the production logging is development of Gas holdup optical sensor tool. This sensor is based on the fiber optical technology, is a versatile tool with the capabilities of locating the first entry of liquid in a gas well or first entry of gas in a liquid well.

**Using fiber optic technology**

The GHOST tool uses the optical properties (refractive index) of fluids to differentiate gas from liquid in downhole conditions (Refer to figure 2). Within the tool body, light is emitted from an LED source, travels along an optical fiber protected from the downhole environment and arrives at a needle-size probe manufactured from sapphire (Refer to figure 14). When the light reaches the tip of the probe, some of it is transmitted through the wellbore fluids, while the remaining light is reflected and travels back through the optical fiber. The reflected light travels through the Y coupler to a receiving photodiode and is converted into an electrical signal. The amount of reflection depends on the refractive index of the medium (gas or liquid) and the shape of the probe. The probe is designed so that the amount of reflected light is much greater when the probe is in gas than when it is in liquid. In air or gas almost 100% of the light is reflected. In liquid less than 40% of the light is reflected. Because the refractive properties of gas and liquid are so different, making it easy to distinguish between gas and liquid in the bore hole (for holdup calculations Refer to figure 3). Some of the key field applications of gas holdup optical sensor tool are detecting <1% of gas in liquid or liquid in gas, identification of water entry points in gas wells, verify bubble point pressure.

![Figure 2 Reflected light Vs the Refractive Index of various possible borehole fluids](image1)

![Figure 3 Calculation of gas holdup](image2)

**Reservoir saturation tool (RST®) - Bridging gaps between the known and the unknown.**

**RST*-Water flow Log:** Due to the limitation of available production logging sensors in horizontal well it was inevitable to integrate and make use of available tools. Look for more robust physical measurement; this is important for confidence in measurement, which would decide the fate of a sick well. A burst of fast neutrons from the Reservoir Saturation Tool activates the oxygen atoms into small region surrounding the neutron source in the tool. Oxygen is present in water and not in oil, thus these activated oxygen atoms in a process like fluorescence, radiate in the form of gamma rays. The phenomena remains after a short time after the neutron burst (till the t_{1/2} of the activated oxygen) (Refer to fig: 4, 5).

If the water is moving in the pipe these activated oxygen when pass the detectors in the tool. The time between the neutrons burst till it reaches the detectors shall be the time of flight for water flow in casing/conduit. The tool uses a
variable neutron burst width from 0.1 to 3 seconds with delay from 3.5 to 20 sec to measure water flow rates in the range from 6 ft/min to 500 ft/min. Additional GR detector may be incorporated to measure high water flow rate wells.

The RST tool can also be inverted to measure the downward water flow rate. One of the most versatile property of RST* tool is to measure and see beyond the pipe and water flow, thus unfolding a big limitation of Production logging tool sensors.

RST*-Three Phase Holdup Log: Accurate determination of phase holdup is a daunting task in a horizontal environment especially due to the fluid segregation in borehole. Due to the limitation of available tool physics, complete estimation of borehole holdup is limited only within the pipe. Holdup estimates in such an environments “behind the pipe” can be made using the pulsed neutron tool. The RST* minitron generates high energy pulsed neutrons, which collides with the formation elements leaving them in high energy excited states (Refer to fig 15). These elements subsequently produce characteristic decay spectrum. A basic C/O ratio is calculated from the carbon and oxygen spectrum which eventually results in volume of oil in formation. The majority of carbon and oxygen excitation is localized, i.e. within a range of 10-12 inches radially from the tool. The RST* tool has 2 detectors to determine the relative carbon and oxygen elemental yields. The combined inputs of NCOR*, FCOR* and NICR are used to determine the three phase (oil, water and gas) holdup in the wellbore (Refer to fig 16). Production logging suite can be combined with the RST* to better evaluate the complex flow profile.
FLAGSHIP* TECHNOLOGY

Huge number of high angle wells has been drilled in the western offshore region of India. The upsurge of deviated and horizontal wells creates boreholes with complex multiphase flow entirely different from the vertical wells. Based on the deviation, type of fluid flow, velocity and holdup of different phases, logging with traditional Production logging suite can be extremely unreliable. Thus resulting data from standard production logging in these horizontal wells may not be resourceful; hence it is necessary to measure both the velocity and holdup of each flowing phase in order to derive flow profiles. In horizontal wells flows are stratified and a small change in well deviation can produce major changes in these quantities independently of any fluid entry (Refer figure 6, 18). Stratified flow, down flow, water sumps, oil and gas traps, and three-phase flow are all concerns in horizontal wells. The Flagship* Production Service Platform* technology was the first of its kind in which the horizontal well production profiling was performed with some high certainty.

Figure 6: Experimental analysis of water-oil Stratified flows in 5.5 in. Casing with 50% Water Cut, the flow view image shows the huge change in holdup with minor changes in deviation.
CASE STUDY: Well: XYZ Flagship* Logging

The Horizontal well XYZ was completed with perforated tubing in 6” drain hole, the well is completed with CTU friendly completion (3.5” tubing from top to bottom of the drainhole) in Mumbai high field (Refer to figure 10). The Objective was to pinpoint the reason for huge water cut in the well, quite unlikely then the client expectations, Diagnose the problem and propose an effective solution. Due to the high deviation of the well it was decided to run the production logging on Maxtrac* conveyance.

The job was performed in 3 runs to meet the objective.

Run1-Maxtrac*+ PLT

Run2-Maxtrac*+PLT+RST-WFL*

Run3-Maxtrac*+RST-WFL* (Inverted)

RESULTS

1. Very small quantity of flow (less than 100 bbl/d) is detected from drain hole.
2. The top perforated tubing section was found to be the major contributor (X173-X201m, between the two packers) through the leaky 7” liner hanger top (Refer to fig 7).
3. Inverted WFL between 7” liner hanger top and the perforated section indicates a down flow which confirms the leak in 7” hanger top.
WAY AHEAD FOR HORIZONTAL WELLS-

Flow Scan Imager

The Vertical well fluid flow scenario the flow is relatively simple and the conventional Production logging gives reasonable results. However with increase in deviation the challenges aggravate. Standard production logging resulted in ambiguous interpretation, thus making it inevitable to invent a robust technical solution for horizontal wells. The biggest concern was zonal quantification in near horizontal wells since only one spinner was used for flow rate estimation resulting in ambiguous flow rates. Some of the complex and key fluid flow regimes identified are mentioned below (Refer to fig 8).

![Fluid flow regimes in horizontal wells.](Image)

Fluid flow inside the borehole may depend of various factors, including pipe diameter, flow rate, fluid type and fluid characteristics and most important deviation. The flow scan imager is the first of its kind production logging using computational fluid dynamics simulations. A conventional production logging suite with a fullbore spinner responds to both the phase velocity and momentum in central part of the borehole. As in the horizontal wells the fluid is stratified thus affecting large portion of gas occupies the top portion of wellbore.

**COMPARISON OF FLAGSHIP* WITH FLOSCAN IMAGER***

FloScan* imager has proved its versatility with availability of multiple sensors including 5 mini spinners, 6 water hold up (DEFT*) probes, 6 gas hold up (GHOST*) probes and shorter tool string thus making it an excellent tool for a horizontal wells in a brown field environment (Refer to figure 20). The tool can be logged with the help of Modular skid units (MAST). Flagship on the other hand consists of a PSP*+GHOST+DEFT*+RST* combined suite rig deployment on the other hand is a must for flagship operation (Refer to fig 9).
Effective FSI* planning on the other had drastically reduces the Rig/Mast time for Production logging operations by reducing the multiple pass requirements as in case of Flagship* operations. The floscan Imager* helps is real time identification of complex flow, most accurate flow profile including crossflow and recirculation. This helps in rapid decision making for any workover jobs if any.

CASE STUDY: FLOSCAN IMAGER*

Well: ABC FSI* logging: ABC is a horizontal well completed with 3.5” (ID= 2.992”) tubing sections (pre-perforated and blank) in 6” drainhole. The well is completed with CTU friendly completion (3.5” tubing from top to bottom of the drainhole) in the Mumbai High South field (Refer to figure 23). As per the completion strategy, the well was completed as two compartments using blank tubing sections with swell packers at the middle of drain hole in the LIII-A1layer. This basic objective of the production log was run to compute a multiphase flow profile and to identify and quantify total downhole flow rate(Refer to fig 24,25).

The job was performed in 2 runs to meet the objective.

Run1-Maxtrac*+ FSI*
Run2-Maxtrac*RST-TPHL*

RESULTS

1. Both the compartments are contributing almost equally towards the total production of well.
2. RST*Pro Water flow log station was recorded against the blind section (between the two swell packers) measured a water velocity (Vw) of around 25m/min; this further confirmed the significant water coming from bottom section (Refer to fig 26).
CONCLUSIONS

Production logging perhaps is as old as the Oil Industry; its importance lies in the fact that it is the crux of most of the workover jobs. Stimulation, reperforation Squeeze etc are performed based on the production logging analysis.

The prominence of horizontal wells over the past in Mumbai high field over 2 decades has increased the demands of more robust wellbore intervention encouraged research centers to come out with new logging techniques thus helping in the evolution of production logging.

1. Introduction of Digital entry flow view tool (DEFT*) and Gas holdup optical sensor tool (GHOST*) which is combinable with production logging suite. These key technologies help improve the interpretation and reduce uncertainties especially in deviated wellbore conditions.
2. The Introduction of Flagship* was first of its kind logging services to reduce the uncertainties associated with interpretation of horizontal wells.
3. Most Drastic innovation in cased hole logging services evolved from the introduction of FloScan Imager*(FSI*).

Nomenclature

GHOST* - Gas Holdup Optical Sensor Tool
DEFT* - Digital Entry Flow Imaging Tool
LED - Light Emitting Diode
PSP* - Production Service Platform
FloView-DEFT* Probe
RST - Reservoir Saturation Tool
RST*TPHL - Three Phase Holdup Log
WFL* - Water Flow Log
NCOR* - Near Carbon Oxygen Ratio
FCOR* - Far Carbon Oxygen Ratio
NICR* - Near Inelastic capture count rate
Flagship* - Advanced Production Logging suite mainly for horizontal well applications
FSI* - FloScan Imager Tool
MaxTrac* - Conveyance technology
Emeraude: Kappa Software production for Production log analysis.

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REFERENCES


ABOUT THE AUTHOR

Mr. Yogesh Chandra is Deputy General Manager ONGC (Wells). He has an experience of over 25 years in well logging operation. He is currently based in Mumbai for Mumbai High operations.

Mr. Arun Pandey is Domain champion-India operations mainly looking after the wireline operations of production logging, perforation and well integrity. He has an over 30 years experience in oilfield operations with schlumberger.

Mr. Ajit Kumar is Senior Borehole Production engineer, has Bachelor in petroleum engineering from Indian School of Mines. He has over 6 years experience in Oil industry and has an expertise in Production logging, perforation design and well integrity.

Mr. Konark Ogra is Borehole Production engineer with Schlumberger, has Bachelor in petroleum engineering from MIT, pune (University of Pune). He has over 3 years of experience in Oil industry as a log analyst for Data and consulting services, primarily specialising in Production logging and well integrity operations.

Mr. Ravi Sinha is Borehole Production engineer, has Bachelor of Technology (B.Tech) degree from Indian School of Mines. He has 4 years experience in Oil industry and has an expertise in Production logging and well integrity operations support.

Mr. Vibhor Verma is Borehole Production engineer, has Bachelor of Technology (B.Tech), Petroleum degree from Indian School of Mines. He has 3 years experience in Oil industry and has an expertise in Production logging and well integrity.
Figure 11 Western India fields, with present status of Oil, Gas discovery

Figure 12 DEFT* and GHOST* probes

Figure 11 Complete picture of FloView and GHOST provide a complete phase solution. In this example gradio can’t distinguish between oil and gas

Figure 14 Working physics behind the GHOST* Probe-Refractive Index
Figure 15 RST\(^*\) TPHL measures the fraction of Oil, Water and Gas in borehole.

Figure 16 Workflow to determine the Holdups from RST\(^*\)-Three Phase Holdup Log \(^*\).

Figure 17 The flow regimes changes Vs the deviation and applicability of FlagShip\(^*\) Operations.

Figure 12 Some of the various challenges while logging horizontal wells are undulation, trapped fluid. Stagnant water usually accumulated on the low side of the casing, and gas at the high side.
Figure 19 FloScan Imager has been designed in order to scan the wellbore and provide most precise and sensitive borehole holdups and flow velocities.

Figure 20 FloScan Imager Tool components

Figure 21 Stratification of fluid in horizontal wellbore condition

Figure 22 Individual spinners respond to fluid flow relative to their position inside wellbore as compared to flagship where only single spinner is available.

Figure 23 Well Sketch -ABC
Figure 24 Processed results from Emeraude Software

Figure 25 Comparison of FSI* Holdups and RST-TPHL Holdups

**FSI* Production Logging:** Resolving the complex flow regimes - A common problem in the Mumbai high wells

**Well:** ABC

Figure 26 Complete flow profile analysis in horizontal wellbore environment with the help of multisensor FSI* tool