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An Integrated Approach to Minimizing Shock and Vibration Damage

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Abstract

As the worldwide rig count continues to grow, it is vital that wells are completed successfully and within the authority for expenditure (AFE). Shock and vibration are leading causes of failure to rotary steerable systems and measurement-while-drilling tools, costing the authors' company millions of dollars in repair costs per year. Client costs included a reduction in rates of penetration (ROPs), wasted trips, damaged bottomhole assemblies (BHAs) and bits, and rig down-time.

Many companies provide tools to measure drillstring dynamics, which include lateral, axial, and transverse shocks and rotational-speed fluctuations in the drill string. However, these measurements alone do nothing to reduce shock and vibration, and tools are still damaged as a consequence.

This paper establishes the need for a more effective approach to mitigating damage from shock and vibration. The authors will show that effective mitigation requires a comprehensive process of planning, execution and evaluation.

The authors will describe the implementation of a shock and vibration standard and steps taken to sensitize client organizations about the new approach. Shock and vibration issues at the rig are flagged in real time and monitored remotely from an operations support center. A communications structure is put in place to ensure that key personnel are fully informed about the issues. These personnel include field service managers, shock and vibration experts, drilling engineers and product champions.

Implementation of the standard and the communications framework enables detection and mitigation of shocks at the rig while monitoring the job remotely. Service provider experts work in real time with the client and other service providers and optimize BHA design to prevent recurrence of the problem.

Implementation of the standard, coupled with training, is expected to save the service supplier several millions of dollars annually, increase mean time between failures and positively impact client operations.

Introduction

It will come as no surprise to anyone in the drilling industry that shock and vibration (S&V) can cause significant damage to downhole tools and the wellbore. What is surprising is the tendency to treat such damage as an inevitability, with attempts at prevention or mitigation being made primarily on an ad hoc, well-by-well basis. While there are no definitive, industrywide statistics on the percentage of well costs attributable to S&V, the authors' Company has long realized that as much as 75% of lost-time drilling incidents more than six hours in duration were associated with drilling mechanics.[1]

Far from being an inevitable cost of the drilling process, much of the damage caused by S&V is preventable, especially with recent developments of downhole sensors in logging-while-drilling (LWD) tools and the development of new techniques which convert raw data into meaningful information in real time. The expense of preventing S&V is analogous to the expense of fire prevention which, while not trivial, is significantly less than the cost of fire suppression and the replacement of fire-damaged property.

To address this problem, the Company has developed a comprehensive S&V prevention and mitigation process. As outlined in this paper, the approach relies on three fundamental elements: a recognition of the causes of S&V; a systematic approach to anticipating and preventing those causes; and effective mitigation of those incidents that cannot be prevented, through planning, real time monitoring, and timely action.

As a mandatory, systemwide approach, the S&V prevention and mitigation process has already begun to achieve significant benefits, with less damage to tools and less non-productive time spent assessing, repairing or replacing damaged equipment, resulting in lower overall well costs.

Cost of Shock and Vibration

Vibration-induced failures—washouts, twist-offs, downhole tool failures and uneven or excessive wear on tubulars—are severe and costly, amounting to millions of dollars in losses for the authors' Company annually. Sustained high levels of vibration increase the rate of drill string and top-drive fatigue. S&V can also have a significant impact on drilling performance, affecting distance drilled, ROP, and downtime for repairs and maintenance. High levels of torsional vibration and stick/slip reduce the efficiency of rotary steerable systems, making it harder to achieve the desired directional response. Well bore integrity can also be affected; lateral vibrations are a direct indication that the BHA collars are crashing into the wellbore, and even less dramatic vibrations can damage unstable formations.

Shock and Vibration Maze

Many different types of shock can be generated downhole, including stick/slip, torsional vibration, axial shock, lateral shock, bit whirl and BHA whirl.

The severity of shocks can be characterized in terms of their:

- magnitude, the deceleration which the tool undergoes as it impacts the borehole
- duration, the length of time over which the shock event takes place
- frequency, the number of times the tool experiences a shock greater than its threshold in a given period of time (typically given as counts per second).

In addition to shock measurements, the use of a reliable real time caliper, downhole weight on bit (DWOB), downhole torque (DTOR), and lithology data in addition to properly calibrated surface weight on bit (SWOB), surface torque (STOR), and rotary speed (SRPM) data is essential in completing the picture of downhole events.

Causes of Shock and Vibration

Once vibration is encountered, it is essential to identify the mechanism quickly in order to determine the specific steps required to mitigate it, and to do so quickly enough to mitigate it and prevent serious damage from occurring.

Vibrations often result from a complex interplay of factors. The following are some of the principal elements:

- Inclination is important; axial vibrations are more likely the more vertical the hole; paradoxically, in certain circumstances an increase in angle can also act to dampen vibrations.
- BHA designs with slick or pendulum assemblies may increase the likelihood of vibration.
- BHA components that increase shock include undergauge stabilization; straight-blade stabilizers, smaller DCs; aggressive, high-torque mud motors.
- Bit selection also plays a role; polycrystalline-diamond compact (PDC) bits generate higher vibrations, as do aggressive features like larger cutter size, lower number of cutters, fewer blades and low back-rake angles.
- Formations are an important variable; higher vibrations are likely in hard/abrasive formations with high coefficients of friction and restitution, e.g., conglomerates, boulders, cherts, interbedded/intercalated formations, sandstones and limestones.
- Higher friction factors will generate higher vibrations, especially stick/slip.
- Large ratio of hole size to BHA/tool diameter will generate more vibrations.
- Poor hole conditions can sometimes generate vibrations, including poor hole cleaning, washouts and ledges.

Standardized Path

Recognizing that shock is the number one cause of tool failure for the Company, a comprehensive Shock and Vibration Standard has been created and implemented to ensure that the methods by which shock is prevented and mitigated are well understood by both company and client personnel. Compliance with the standard is mandatory, unless there are specific issues which justify the granting of an exemption.

Roles and Responsibilities

The Shock and Vibration Guidelines is a companion document to the Standard. It defines the internal processes and tools required to ensure compliance. It also specifies the responsibilities of all Company personnel involved in the process, including:

- Operations Manager
- Field Services Manager
- Cell Managers
- Sales Engineer
- Repair and Maintenance Supervisor
- Service Quality Coach
- Shock and Vibration Champion.

The Company's Operation Support Center (OSC), a facility that offers real time commercial services for clients, plays a key role in the implementation of the S&V Standard. Depending on the particular services being supported, personnel with various levels of expertise are made available to the OSC, including senior measurement-while-drilling (MWD) and LWD engineers, service quality coaches, drilling engineers, geoscientists, geologists, and others.

The OSC's responsibilities include:

- Monitoring of active jobs to ensure the S&V Guidelines are being followed
- Real-time monitoring and initial response to shocks and vibrations, in conjunction with wellsite personnel
- Tracking successes and failures of S&V mitigation and compiling material for both internal and client review meetings.

The Company's Drilling Engineering Centers (DECs) are also an integral part of service delivery, providing customized drilling solutions and assisting in the planning, execution, and evaluation of a well. Its responsibilities include:

- Assisting in the bit selection and ensuring that alternative bits are available as a contingency
- Ensuring BHAs are designed with good drilling mechanics practices

- Conducting analysis of all BHAs, including hydraulics, torque and drag, and the natural vibrational tendency of the BHA
- Assisting in the bit selection and ensuring that alternative bits are available as a contingency
- Assisting in designing an alternative BHA and recommendations for the next run when high levels of shock and vibration are seen during real-time monitoring
- Working with the team to produce key performance indicators (KPIs) when shocks have been an issue on a job.

Communications

The Standard emphasizes the importance of establishing clear lines of communication among all key personnel and facilities, including responsibilities for notification and consultation when established thresholds of shock or vibration are exceeded or when evidence of damage is detected. These guidelines include parameters determining when notification of the client's organization is required.

In order to properly communicate S&V issues both internally and with the client it is important that all relevant information is reported and recorded, including:

- S&V status and summary on daily reports
- Drilling mechanics logs produced, reviewed and reported to the client
- Reporting of high S&V runs
- Reporting of successes of S&V mitigation
- Written failure reports
- Service quality reviews with clients.

The Standard also specifies standard data formats to be used to ensure consistency and completeness.

Training

Training is a very important part of the program, for Company, rig contractors and client personnel alike. The Standard specifies levels of training for Company personnel, and emphasizes the importance of providing an orientation and more detailed training for client personnel, to ensure that all team members understand their specific responsibilities. The Company recognizes that in order for the mitigation strategy to be successful, the clients must understand its benefits and be aware of the potential costs and consequences of S&V. Toward this end, the Company provides information and training at the rig site and in client offices.

Exemptions

If it is not possible to adhere to the statements in the Standard, an exemption is required from the Company operations manager and the DEC. Scenarios that would require an exemption may include:

- The same bit and/or BHA being run after severe shock and vibration issues on the previous run
- No satellite data link sent to a job in an area with known S&V issues
- Failure to include S&V limits in client contract
- Drilling at S&V levels that exceed tool specifications or contractual limits.

Audits

Finally, the Company will audit each location once a year to ensure compliance with the Standard.

Implementation: An Integrated Approach

In order to meet the goals established in the Standard, the Company has created an integrated approach consisting of three phases: planning, execution, and evaluation. The increase in drilling activities worldwide has created a lack of experienced field engineers, so the Company relies on experts in the OSC, using the most advanced analytical resources, to assist in all three phases of the process.

Phase 1 – Planning

The purpose of the planning phase is to provide a scientific prediction of the shocks which could be expected while drilling, and to recommend the most appropriate BHA design and drilling parameters to reduce the possibility of generating high shocks.

The advantages of detailed planning include elimination of unnecessary trips to change BHA, and creation of drilling parameters to mitigate shocks without major interruptions.

(1) The planning phase begins with a definition of the down hole components that play a role in the generation of the shocks. Offset data from nearby areas and performance evaluation provide important inputs at this stage of operations.

Bit optimization is one of the most critical factors in dealing with shocks. Proper communication with bit manufacturers is essential to ensure that bit performance and specifications are fully understood. Bit manufacturers have developed software to assist in the planning process.

Bit performance evaluation should include:

- The cutting structure (cutter size/density, cutting depth, back-rake and side-rake angles)
- Blade geometry
- Bit hydraulics (jet geometry, number of jets per blade)
- Rock strength (confined/unconfined)
- Geological nature of formation (laminations, interbedded formation, hard/soft rock interfaces)
- Optimum surface weight on bit
- Optimum rotary speed.

(2) The next step is to evaluate the BHA stabilization. Vibration analysis is performed on the proposed BHAs to evaluate and finalize the best stabilizer placement to avoid high shocks (**Fig. 1**). The DEC uses the Company's integrated drilling engineering design software to reliably identify and correlate shocks to various components in the BHA. Its powerful modeling capabilities are used to predict expected lateral shocks at the natural frequencies of the BHA with the stabilizers placed at different positions. This phase of planning may require a collaborative approach, involving the participation of bit and reamer manufacturers, to assemble all the inputs for a successful analysis. **Figs. 2 and 3** illustrate inputs and modeling involved in reamer selection by a bit and reamer provider.

Offset data from nearby wells can be used to update the models to achieve more accurate results for the well under study. **Fig. 4** illustrates the use of drilling and shock data from an offset well to determine the cause of several incidents of twist-off when drilling through a salt interval. By identifying the S&V-related causes of the problem, modeling several different BHAs to minimize them, and following a detailed mitigation plan, subsequent wells in the area were completed with no non-productive time (NPT) recorded due to failure of downhole components.

In addition to analyzing S&V, modeling is also used to assist in ROP optimization by evaluating a wide range of drilling parameters with each BHA configuration.

Based on these analyses, a set of drilling dynamics guidelines is established for different shock levels (**Fig. 5**).

(3) Proper communication with the field team is established prior to running in hole to determine the data points to be transmitted to the surface and the frequency of their transmission. The goal is to acquire sufficient data for effective shock and vibration analysis without sacrificing the quality of the rest of the LWD data.

(4) If hole-opening while drilling is planned, modeling takes account of the hole-opener configuration and its layout in the drill string. Based on area experience and modeling results, recommendations are made on the use of stabilizers below and above the reamer to maintain minimum lateral displacement when the hole is opened to the larger size. Reamer manufacturers have also developed software to assist in the planning process.

(5) Training is an integral part of the planning process. Engineers must understand the physical concepts behind shocks and methods of interpreting the measurements provided by the LWD tools. They must be trained to identify the types and sources of shocks and to provide the proper solution for them before significant damage is caused.

(6) It is also vital to properly educate clients and their field personnel—company men, toolpushers, drillers, assistant drillers—on techniques for detecting and mitigating shocks. This may include educational "road shows," pre-drill workshops designed to assist in establishing good lines of communication, provide specialized S&V detection and mitigation knowledge, and dramatize the importance of taking timely and appropriate action.

(7) Before the execution phase begins, it is also important via a pre-drill risk assessment to establish the limits for what should be considered high-level shocks needing attention and what are considered acceptable levels (**Fig. 6**). These limits are not rigid numbers to follow, but are guidelines based on engineering experience, the particular shock mode detected, and a determination of the principle cause or causes of that shock.

After having done all that is possible to model and minimize potential problems, it is essential to communicate to the drilling team the types of shock that are still likely to occur, where and when they can be expected, and specific actions required to mitigate them. This is summarized in graphic form in a large wall chart for use at the drilling site (**Figs. 7, 8**).

A communications chart details the notifications protocol required when the established shock-level thresholds are exceeded (**Fig. 9**).

Phase 2 – Execution

Successful execution of the plan relies on real-time monitoring and analysis, effective communication, and a timely and appropriate response.

Experts at the OSC remotely monitor and analyze real-time data from the drilling site. The data can be transmitted to the OSC via any of a number of high-speed data transfer technologies. From the OSC, experienced engineers using the most advanced resources available provide rapid analysis and recommendations to the field. This is similar to the use of telemetry to relay patient information from the scene of an accident to an emergency center, where experts can assess the symptoms and recommend life-saving responses in the critical first few minutes.

Another advantage of remote monitoring is that more than one engineer is available, providing a range of expertise that can be especially valuable in complex situations.

A software toolkit developed to remotely analyze real-time drilling data and present it in a graphical fashion provides a clear basis on which real time drilling optimization decisions can be made. It enables the user to make practical sense of the vast amounts of data modern LWD tools can produce, and permits the OSC to gather, analyze, and optimize drilling data as it arrives. The software's rig-state detection functionality accurately analyzes complex data streams and displays pertinent drilling performance information in clear graphic form. Drilling data can be assessed continuously and analyzed with torque-and-drag and/or hydraulics models.

The software can display synchronized time and depth data combined with a precise graphic representation of the BHA (**Fig. 10**). Users can monitor and review any event that occurs during the drilling process and can capture events for future reference. This capability allows the engineer to monitor performance against any user-defined function, correlate drilling parameters with drilling performance and identify ways to enhance performance, all in real time.

Figure 11 is a snapshot from a real-time depth-based plot correlating lateral shocks with the SWOB and rotational speed in revolutions per minute (SRPM). The graphic shows the immediate result in shock reduction when action was taken soon after the shocks began to elevate.

Figures 12, 13 and 14 plot shocks versus various drilling parameters, providing a real time correlation between causes and effects to guide decisions about when and how to take corrective action.

Figures 15, 16 and 17 are from real-time plots revealing that the reamer is causing higher lateral shocks and stick-slip when reaming through an inclusion of salt. The proper SWOB and SRPM were determined and subsequently applied every time a new inclusion was encountered.

Triaxial analysis is also performed using the same software to find the range of drilling parameters that correspond to the "sweet spot" (stable drilling range) for the BHA in hole.

The software can also perform triaxial analysis on the fly (**Figs. 18, 19**), enabling the operator to correlate SRPM and SWOB with stick/slip, lateral or torsional vibration and select the best range of parameters to operate within the sweet spot.

Advanced smart alarms programmed into the software signal both the OSC and rig personnel when a critical preset threshold is exceeded. This system uses different color codes for different levels of shock and sounds an audible alarm when attention is required.

In shock analysis and mitigation, the OSC normally establishes the roles of communication and the chain of command, in collaboration with client representatives, to ensure that all recommendations are received quickly enough to permit a timely and effective mitigating response.

Available shock measurements include information about the low frequency, high amplitude shock peak, which may not show when measuring the averaged data within the sampling period above the pre-designed thresholds. This is in many cases vital in the process of mitigation.

Downhole conditions and hole cleaning problems contribute to the excitation forces that create S&V, hence monitoring hole-cleaning efficiency, torque and drag also help avoid high stick/slip and torsional vibration, which can lead to mode coupling shocks and unnecessary complications. It is also necessary to monitor mud properties, especially mud lubricity, and monitor the different effects on stick-slip and torsional vibration.

Phase 3 – Evaluation

The evaluation phase begins the moment the BHA is pulled above the rotary table. All components are visually inspected for any sign of damage or indication of BHA whirls.

The bit is also inspected and graded, and pictures of different parts of the bit are taken to provide as much data as possible for the final evaluation and for archiving the lessons learned in a knowledge-base management system in the real time software toolkit (**Figs. 20, 21**).

The information gathered is sent directly to the OSC via high-speed data link for review and analysis by expert staff. Combined with recorded LWD data, it provides the basis for a quick evaluation and recommendation of any changes in the BHA before drilling the next section. Triaxial analysis may result in recommendations to change drilling parameters, and further analysis may suggest replacing or changing the type of bit before drilling ahead. **Fig. 22** shows the result of proper bit selection and S&V mitigation techniques.

In the final stage of the evaluation phase, complete data is assembled and a detailed analysis performed. The analysis includes:

- Documentation of field data and the relevant cross plots for correlation and events analysis
- Formation type and rock strength analysis and a comparison of results with pre-drill analysis
- Evaluation of bit performance in different formation types
- Evaluation of BHA optimization, with recommended modifications of BHA design
- Triaxial analysis and "sweet-spot" identification
- Calibration of the pre-drill models
- Modify bit database to include all changes in the bit to improve bit selection and optimization
- Incorporate lessons learned from analysis of recorded data, wire line caliper, resistivity and borehole images in the mitigation process

Quantifying the Benefits of the Approach

Two example cases illustrate the value of effective S&V mitigation process.

Case Study 1

The S&V mitigation process was used in the drilling of two deepwater wells in the Gulf of Mexico. Data from two offset wells was incorporated into the pre-drill analysis and planning phase to determine the causes and remedies for twist-offs and RSS tool failures encountered in the area. The problems occurred while drilling the top of salt and in the salt sections.

Table 1 compares results before and after applying the S&V mitigation process. Tool failures and resulting NPT were reduced to zero, and on-bottom ROP was significantly increased as a result of the mitigation process **(Figs. 23, 24, 25).**

Table 1: Comparison of Wells in Gulf of Mexico

	Offset Wells (No Mitigation)		**Subject Wells** (Mitigation Applied)	
	Well #1	**Well #2**	**Well #1**	**Well #2**
Failures Requiring Trip	5	3	0	0
Total Footage Drilled	21,000	19,650	19,800	23,000
NPT Due to Tool Failure	196	92	0	0
On-Bottom ROP (ft/hr)	46	48	77	65

Case Study 2

The authors' Company was contracted to provide MWD and RSS services on three rigs in the Rocky Mountain area of Colorado. The MWD provided drilling mechanics variables, including real-time stick/slip data, to detect and help mitigate high downhole vibrations.

High to severe stick/slip levels were experienced on two of the three rigs, seriously impacting the drilling process with damage to bits and downhole tools. Nine wells were drilled on four different pads initially, six before the study was started. Three wells we monitored during the study. With a total of 17 RSS runs, six RSS failures and four MWD failures were recorded, along with excessive bit wear and failures related to stick/slip.

The study involved extensive collaboration between personnel from the authors' company, rig personnel, equipment manufacturers and client engineering staff, and utilized real-time monitoring and analysis to determine the root causes of the high stick/slip and resulting tool failures. The team made recommendations and implemented guidelines to successfully mitigate the stick/slip-related RSS failures.

As illustrated in **Fig. 26**, the number of BHAs required to drill the intermediate hole section was reduced from two before the study to just one after the recommendations were implemented, saving approximately 14 hours per round trip, resulting in substantial cost savings for the client.

RSS tool failures were also reduced, from six before and during the study to just one failure after implementation of S&V mitigation (**Fig. 27**). The single failure after recommendations were implemented was due to high mud solids. The reduction in tool failures represented a significant cost savings for both the authors' company and the client.

Effective ROP was increased from 45 ft/h to 69 ft/h, directional control was improved with lower stick/slip levels, and average footage per day was increased from 1,081 to 1,316 ft.

Conclusions

The high cost of shock and vibration damage justifies the creation and implementation of a detailed, companywide S&V Mitigation Standard.

In the pre-drill, planning phase of the process, much can be done to predict the potential extent and likely causes of vibration. Advanced modeling software permits the selection of a BHA design that minimizes S&V problems. Planning also results in a detailed set of guidelines for drilling, specifying the potential problems that may occur and specific steps to take to mitigate them.

In the execution phase, real-time monitoring and analysis provide alerts when problems first appear, in time for effective action to be taken. Experts in the Company's OSC and DEC can monitor events remotely and use sophisticated analytical technologies to provide effective solutions on-the-fly.

In the post-trip, evaluation phase, information on BHA and bit condition is gathered, correlated with recorded LWD data and analyzed to determine any recommendations for changes in drilling parameters, BHA or bit, before drilling resumes.

Systematically applied, this S&V mitigation process offers significant advantages for service provider and client alike.

References

1. Burgess, T.M and Martin, C.A: "Wellsite Action on Drilling Mechanics Information Improves Economics," SPE/IADC 29431 paper presented at the 1995 SPE/IADC Drilling Conference, Amsterdam, 28 Feb – 2 March.

Figures

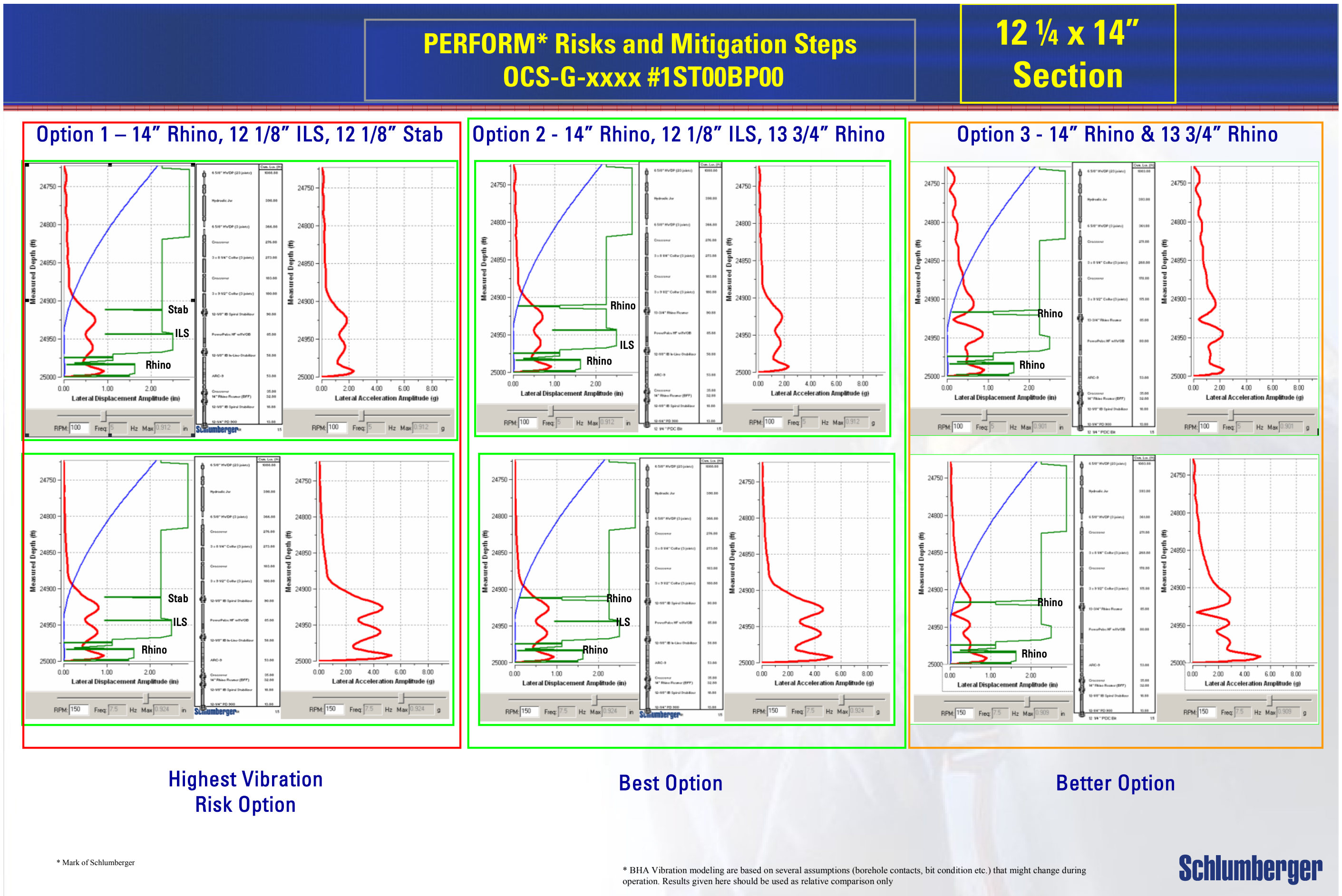
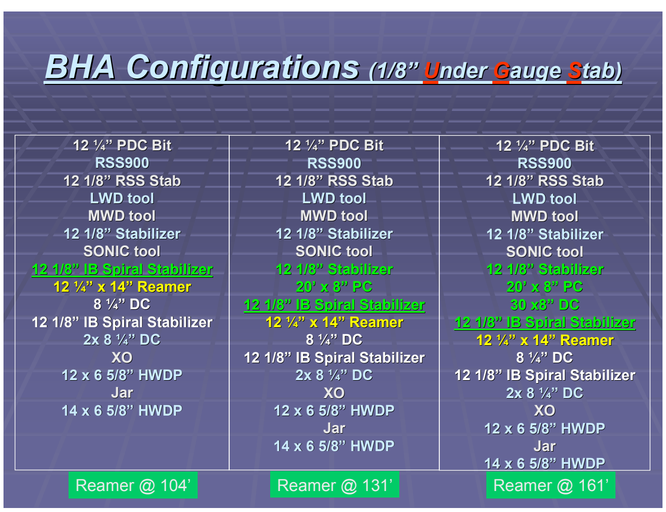
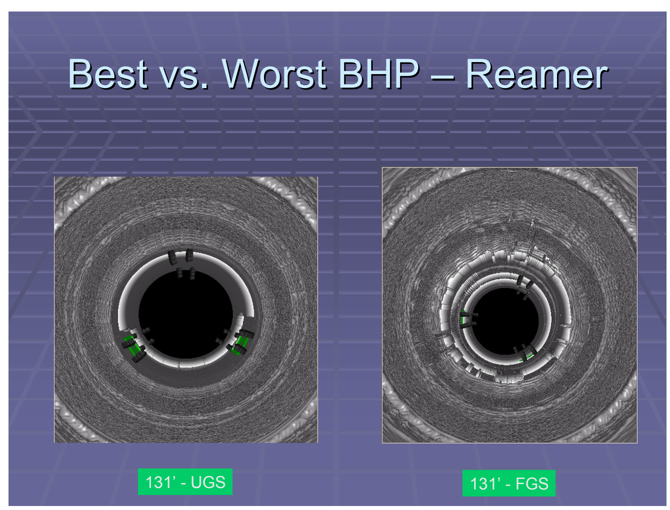


Fig. 1—Pre-drill analysis models the lateral displacement and the maximum lateral acceleration for different BHA configurations under different weight-on-bit and rotational speed scenarios.



Courtesy: Smith International

Fig. 2—Different scenarios of reamer and stabilizer replacement in the BHA, supplied by reamer vendor to aid in achieving the best bottomhole profile.



Courtesy:: Smith International

Fig. 3—The model suggested the use of the 1/8-in undergauge stabilizer below the reamer at 131 ft from the bit for the best bottomhole profile.

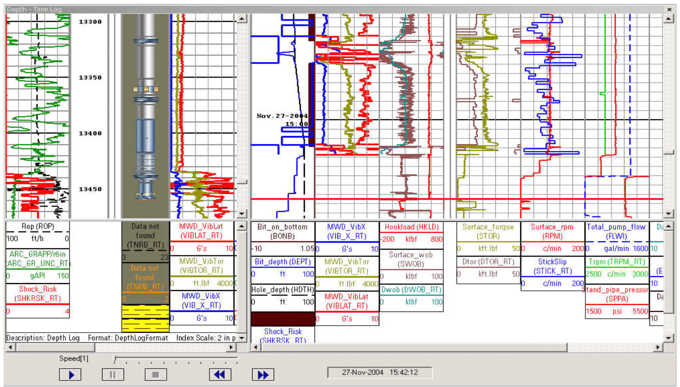


Fig. 4 —Time/Depth data plot from offset well showing twist-off event in the transition zone above the top of salt.

Schlumberger Drilling Dynamics Guidelines			
StickSlip Ratio (Stick_RT/RPM)			(Log scales: 0-200 rpm)
<50%	0 - 0.5	Low	No problem over time
50%<100%	0.5 - 1.0	Medium	>25 hours, medium risk of failure
100%<150%	1.0 - 1.5	High	>12 hours, high risk of failure
>150%	> 1.5	Severe	>1/2 hour, severe risk of failure

	Level	Shock Variable			
		Vib X	Vib Lat	Stick Slip	Vib Torq
1	Low	<0.5	<0.5	<50%	400
2	Medium	0.5 – 1.5	0.5 – 2.5	50% 100%	400 – 600
3	High	1.5 – 3.5	2.5 – 5.5	100 - 150	600 – 700
4	Severe	>3.5	>5.5	>150%	700

Fig. 5 —Drilling dynamics guidelines for different levels of shock.

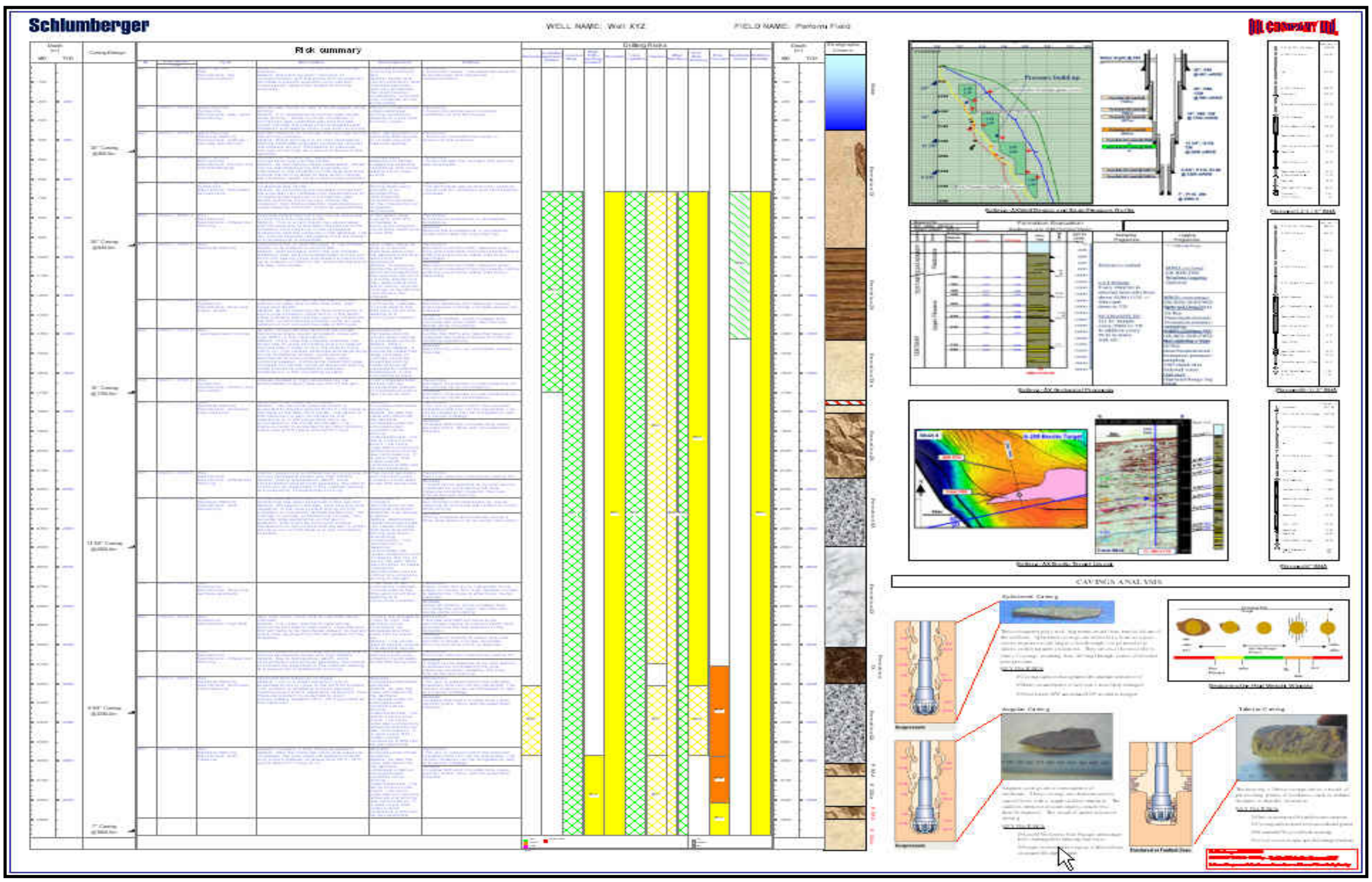


Fig. 6 —Graphical representation of the pre-drill risk assessment.

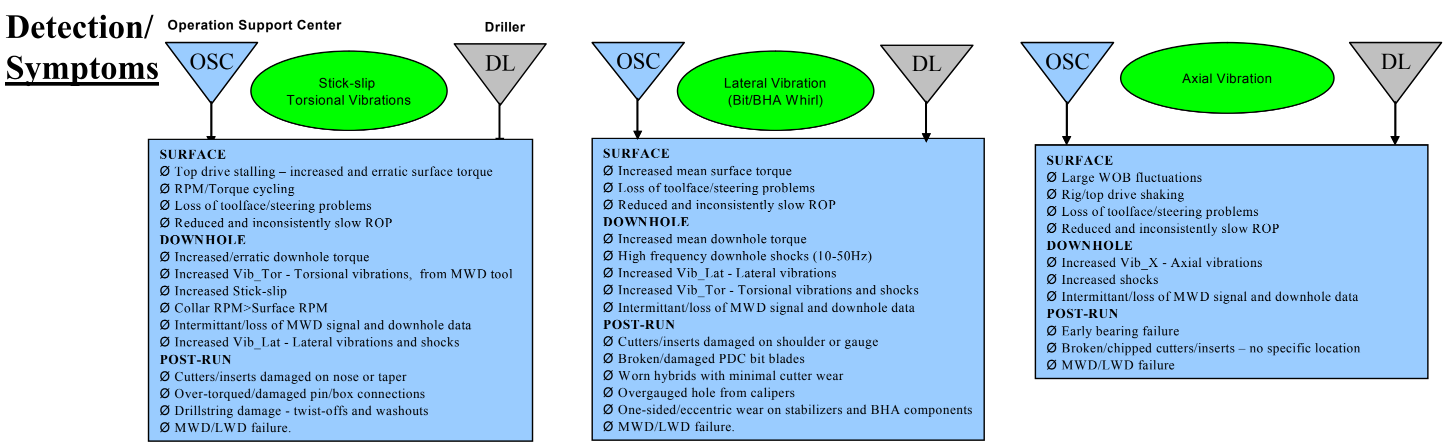


Fig. 7—Types and symptoms of expected shock – Part 1 of S&V Mitigation wall chart for display at the drilling site.

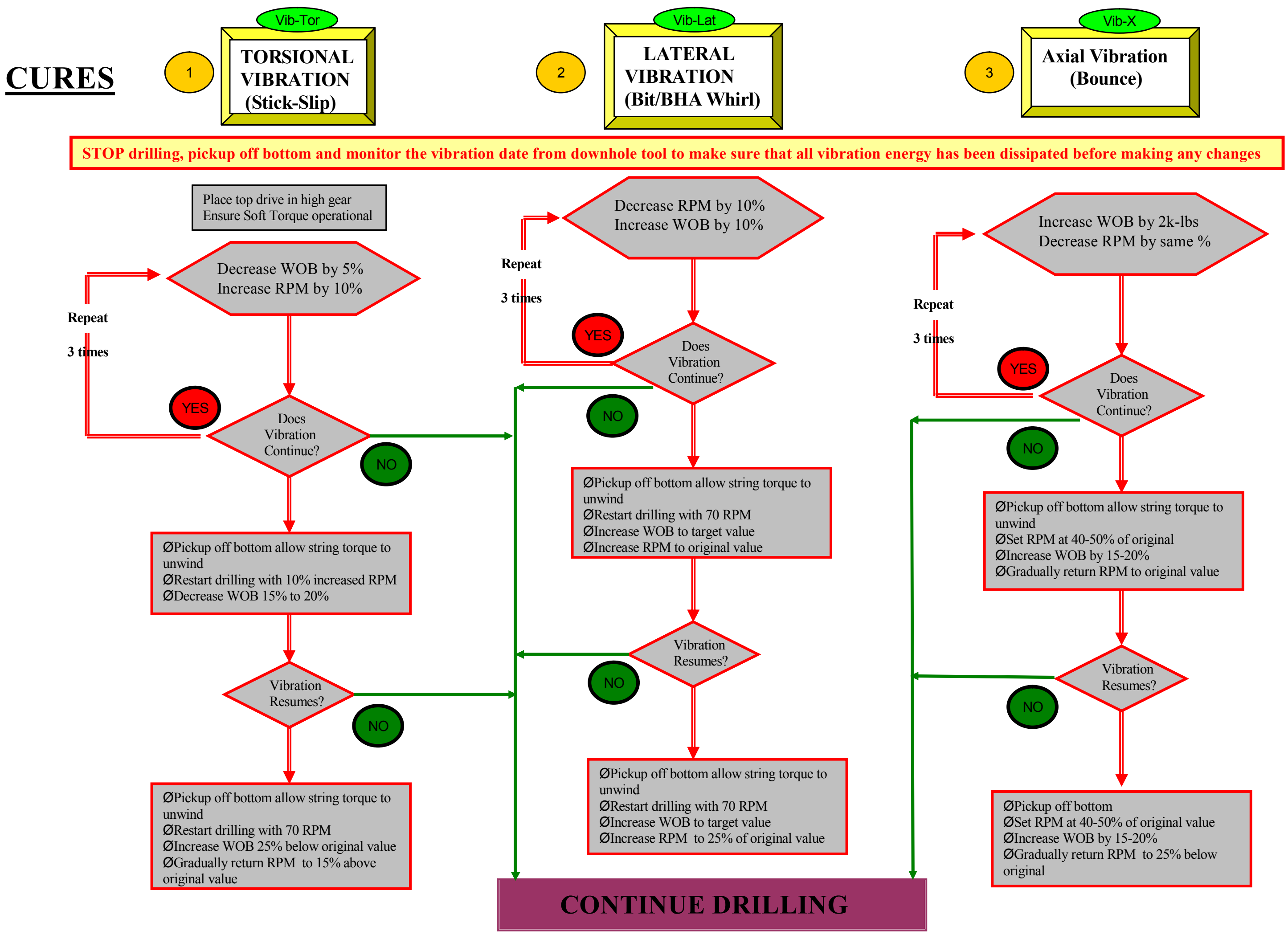


Fig. 8 —Specific mitigating actions to be taken when S&V is encountered – Part 2 of S&V Mitigation wall chart for display at the drilling site.

Shock and Vibration Mitigation Communication Chart

Shock Level	Period Shock Level Experienced For						
	After 5 minutes	After 15 Minutes	After 30 Minutes	After 1 Hour	After 6 Hours	After 12 Hours	After 24 Hours
Shock Level 1	Mitigate	Mitigate	Mitigate	Mitigate	Mitigate	Mitigate	Mitigate
		Inform Directional Driller	Report in Daily Paperwork	Report in Daily Paperwork	E-mail FSM	Phone FSM	TOOL OUT OF SPECIFICATIONS
			Record in the ERS	Record in the ERS	E-Mail Sales Engineer	E-mail & Phone Sales Engineer (During office hours)	Exemption required to continue drilling
Stick-Slip 50 to 100% of CRPM			Inform the Company Man	Inform the Company Man	Issue S&V notification letter to Company Man	Sales engineer call Client in Town ASAP	Inform the Company Man
OR			Inform OSC	Inform OSC		Discussed in the Morning Meeting	E-mail & Phone Sales Engineer (During office hours)
2cps <30 over 50 G			Inform Directional Driller	Inform Directional Driller			Sales eng call client in Town & issue notification letter.
MEDIUM Risk							FSM contacts DEC to work on alternative BHA
							Inform Directional Driller
Shock Level 2	Mitigate	Mitigate	Mitigate	Mitigate	Mitigate	Mitigate	Mitigate
	Inform Directional Driller	Report in Daily Paperwork	Report in Daily Paperwork	E-mail FSM	Phone FSM	TOOL OUT OF SPECIFICATIONS	
		Record in the ERS	Record in the ERS	E-Mail Sales Engineer	E-mail & Phone Sales Engineer (During office hours)	Exemption required to continue drilling	
Stick-Slip 100 to 150% of CRPM		Inform OSC	Inform the Company Man	Issue S&V notification letter to Company Man	Sales engineer call Client in Town ASAP	Inform the Company Man	
OR		Inform Directional Driller	Inform OSC		Discussed in the Morning Meeting	E-mail & Phone Sales Engineer (During office hours)	TOOL OUT OF SPECIFICATIONS
30cps <100 over 50 G			Inform Directional Driller			Sales eng call client in Town & issue notification letter.	
HIGH Risk						FSM contacts DEC to work on alternative BHA	
						Inform Directional Driller	
Shock Level 3	Mitigate	Mitigate	Mitigate	Mitigate	Mitigate	Mitigate	Mitigate
	Inform Directional Driller	Report in Daily Paperwork	TOOL OUT OF SPECIFICATIONS				
		Record in the ERS	Exemption required to continue drilling				
Stick-Slip 150+% of CRPM		Inform the Company Man	Inform the Company Man				
OR		Inform OSC	E-mail & Phone Sales Engineer (During office hours)				
100 over 50 G		Issue S&V notification letter to Company Man	Sales eng call client in Town & issue notification letter.	TOOL OUT OF SPECIFICATIONS	TOOL OUT OF SPECIFICATIONS	TOOL OUT OF SPECIFICATIONS	TOOL OUT OF SPECIFICATIONS
SEVERE Risk			FSM contacts DEC to work on alternative BHA				
			Discussed in the Morning Meeting				
			Inform Directional Driller				

Fig. 9—Matrix detailing notifications required for each level of shock detected.

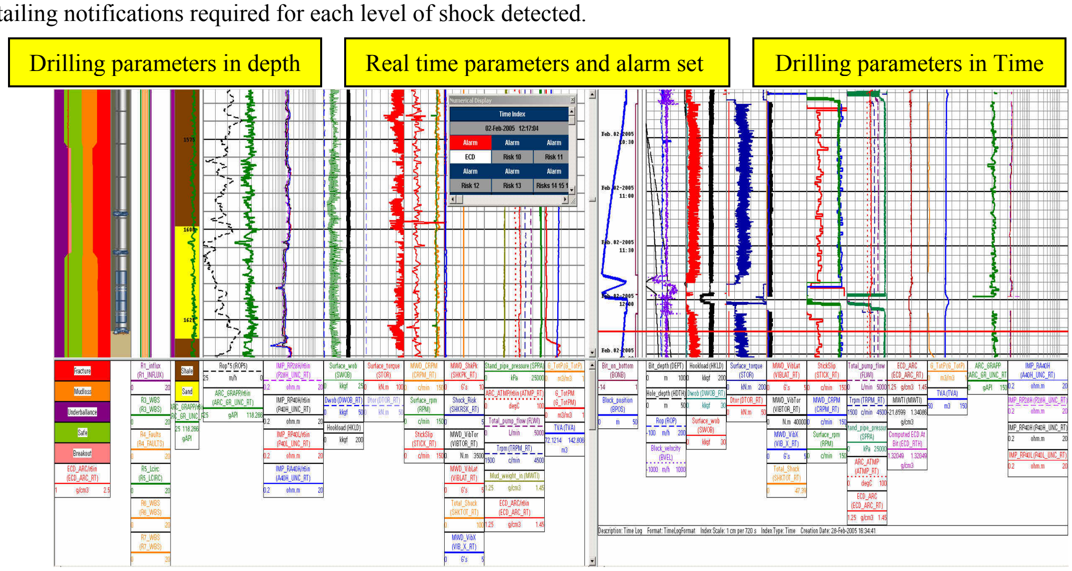


Fig. 10—Real-time display of integrated graphical display of drilling, geology and petrophysical data.

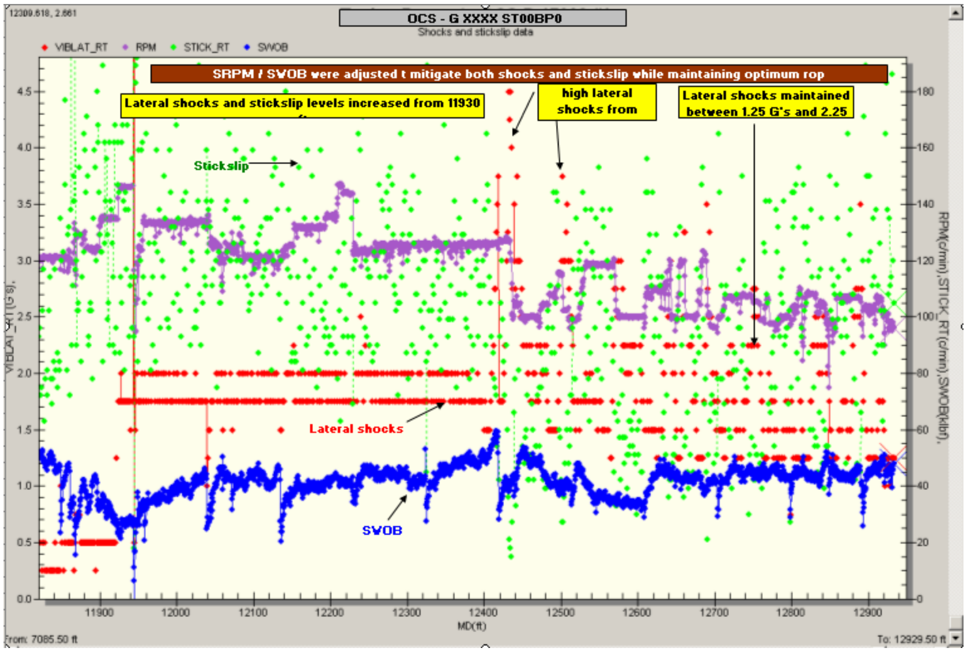


Fig. 11—Graphical display correlates lateral shock with SWOB and SRPM.

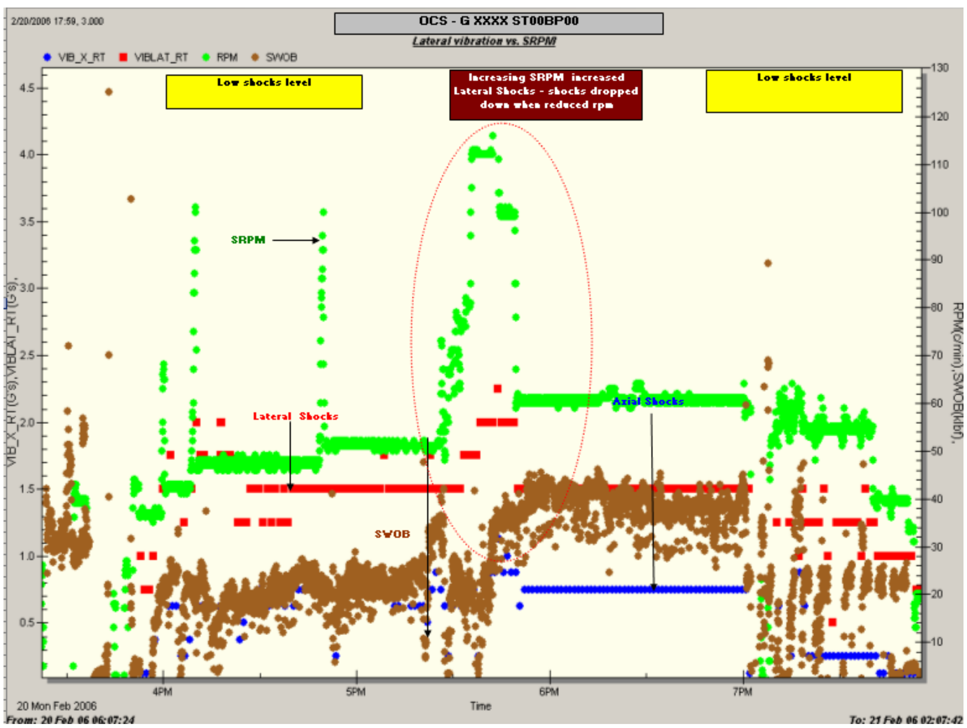


Fig. 12—Shock versus drilling parameters: Plot correlates between on-bottom and off-bottom drilling parameters.

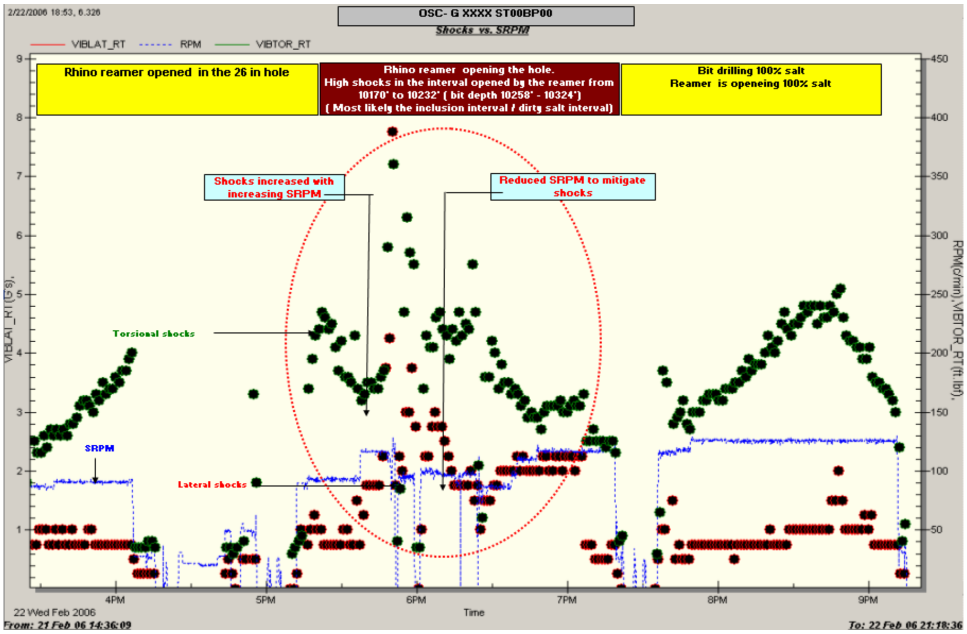


Fig. 13—Plot showing real-time correlation of drilling parameters with torsional vibrations.

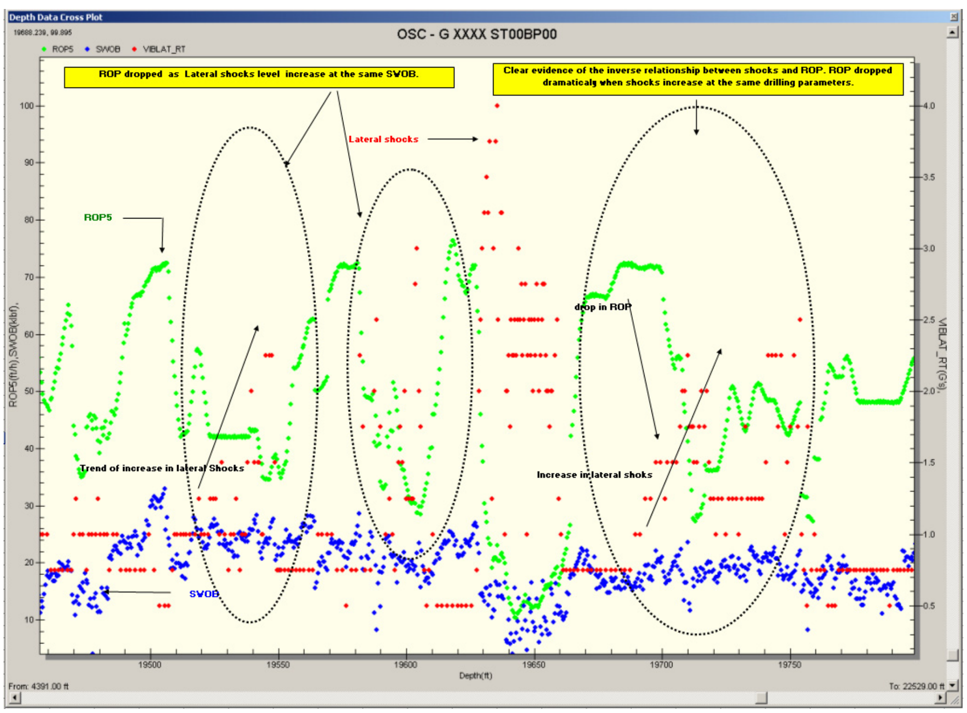


Fig. 14—Real-time plot shows good correlation between increase in shock level and drop in ROP.

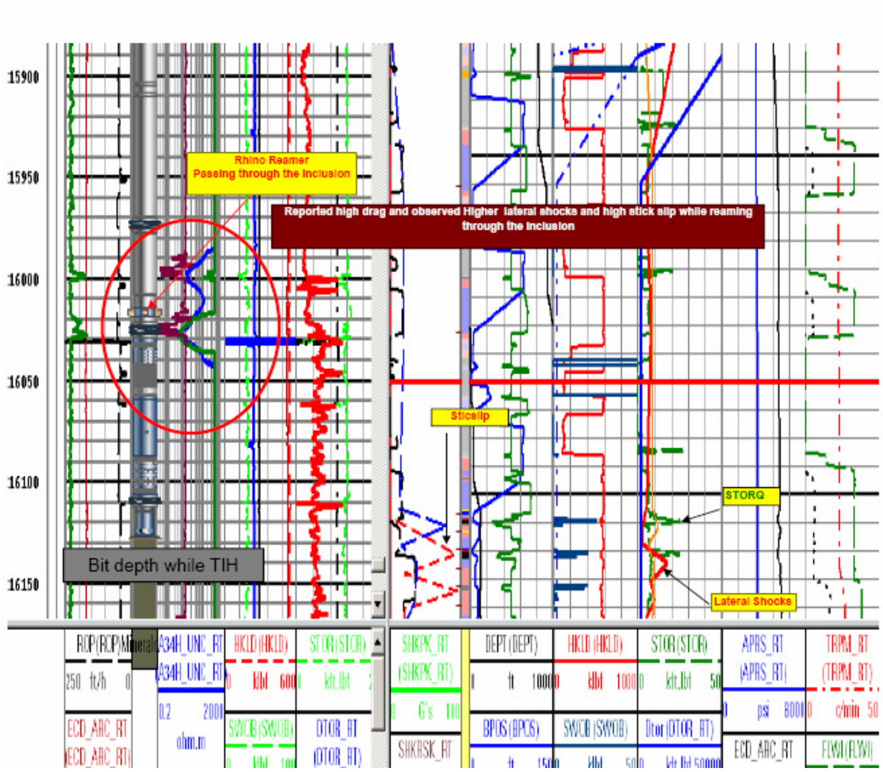


Fig. 15—Real-time plot reveals higher lateral shocks and stick-slip when reaming through an inclusion of salt. The proper SWOB and SRPM were determined, then applied every time a new inclusion was encountered.

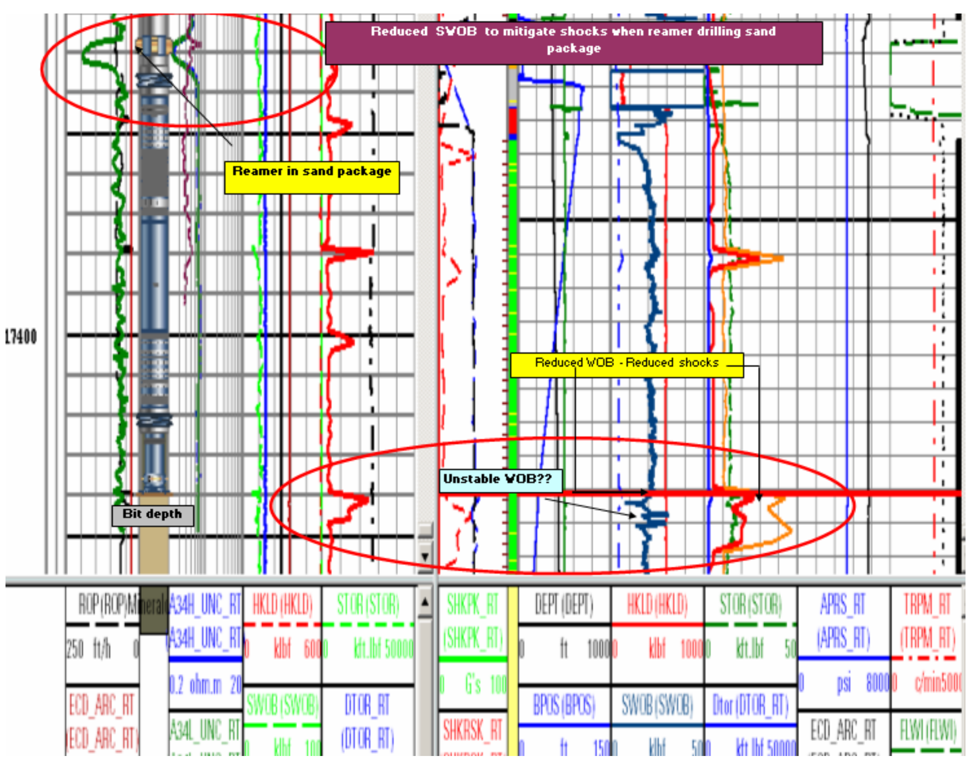


Fig. 16—Real-time display shows high shocks while reamer drills sand package; on-the-fly correlation permits determination of the proper range to be applied prior to reaming through subsequent sand packages.

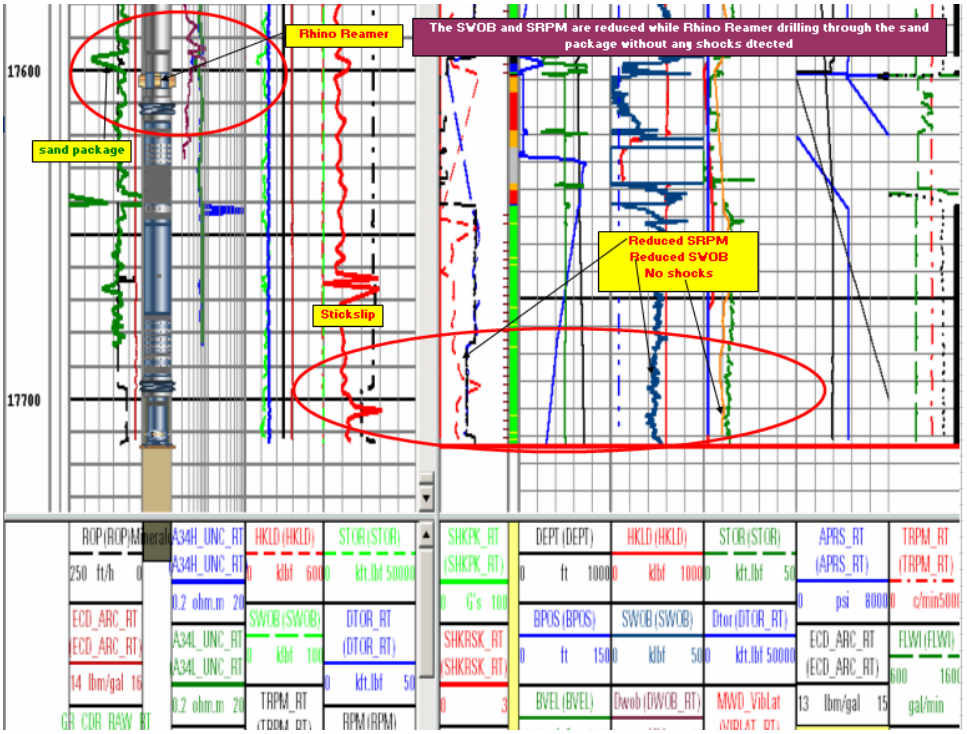


Fig. 17—The graphic shows a successful run with reduced shocks when the reamer penetrated subsequent sand packages after the new drilling parameters were applied.

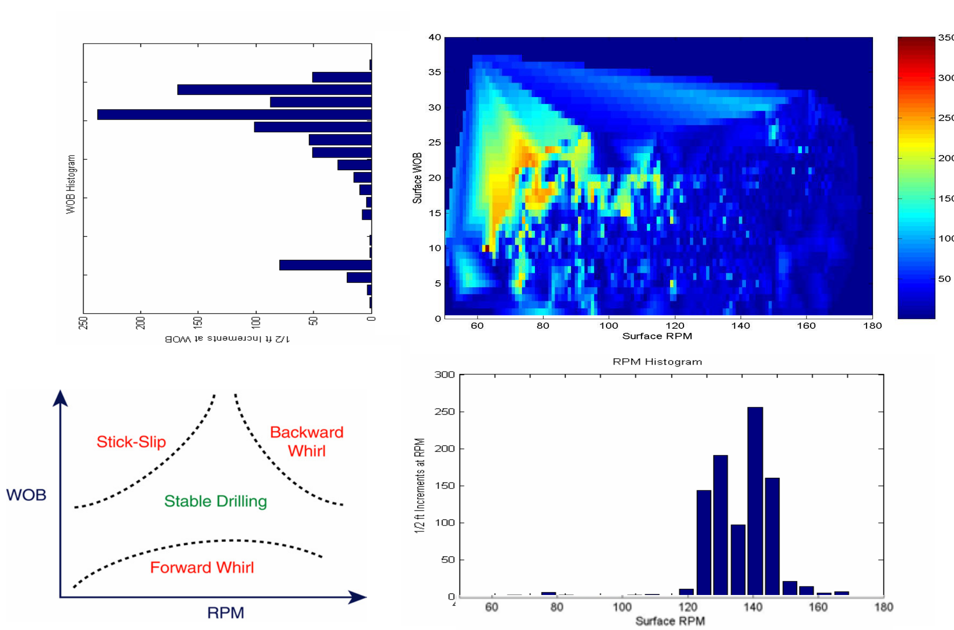


Fig. 18—The real time monitoring software has the capability to perform triaxial analysis on the fly. This analysis enables real-time correlation of rotational speed and weight on bit with stick-slip, lateral or torsional vibration and select the best range of parameters to operate within the "sweet spot" (stable drilling range).

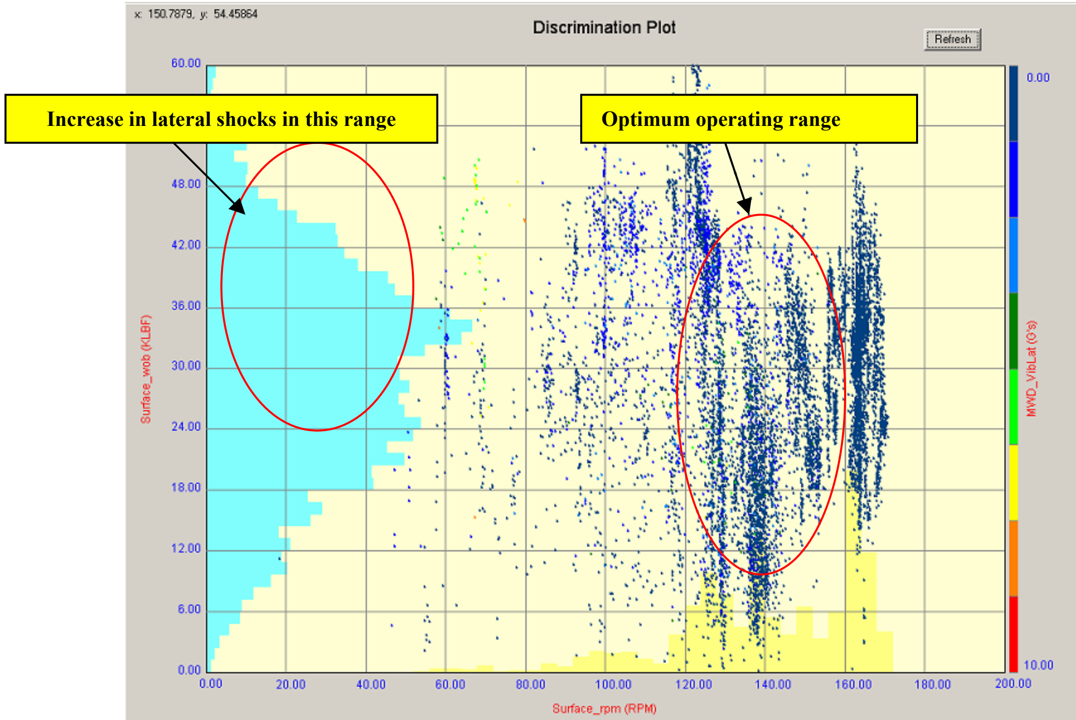


Fig. 19—Triaxial analysis is performed while drilling to determine the best range of drilling parameters to optimize shock mitigation. In this example, with SWOB higher than 30 klbs-F and SRPM below 80 revolutions per minute (RPM), the lateral shocks increase. Analysis suggests the best range of drilling parameters under the same conditions is 30-35 klbs-F for the SWOB and 150-160 RPM for the rotational speed.

Fig. 20—Close-up of bit damage occurring with no S&V mitigation.

Fig. 21—Failure due to improper bit selection and lack of mitigation process in place.

Fig. 22—This bit was recommended after the pre-drill analysis. The bit drilled the section without incurring any damage and was graded as new.

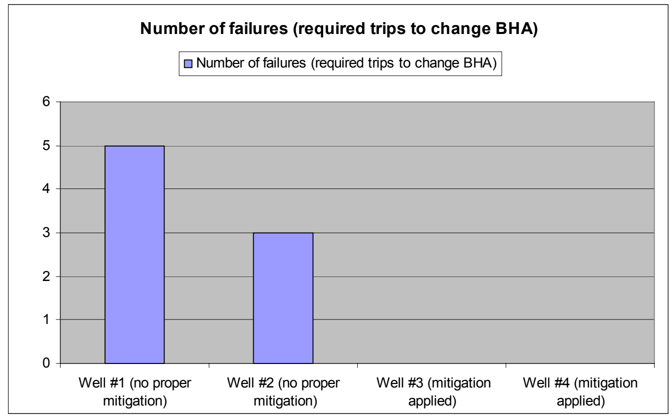


Fig. 23 —Number of failures (required trips to change BHA).

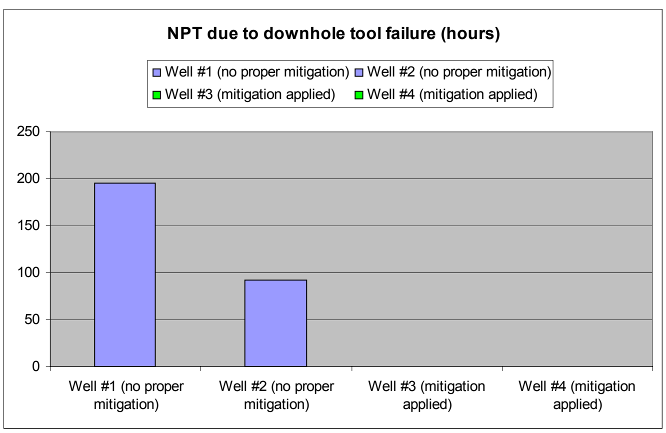


Fig. 24 —NPT due to downhole tool failure (hours).

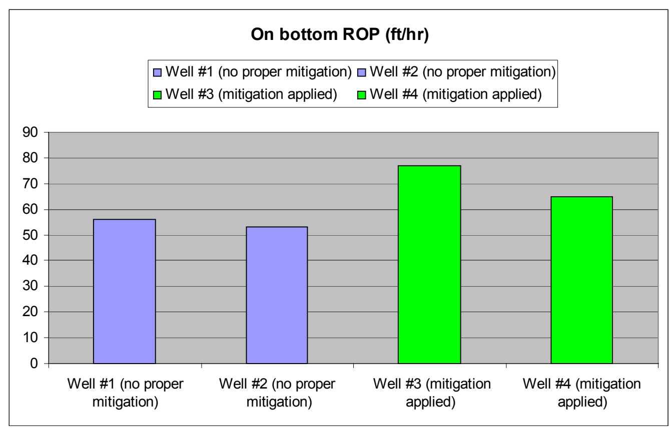


Fig. 25—On bottom ROP (ft/hr).

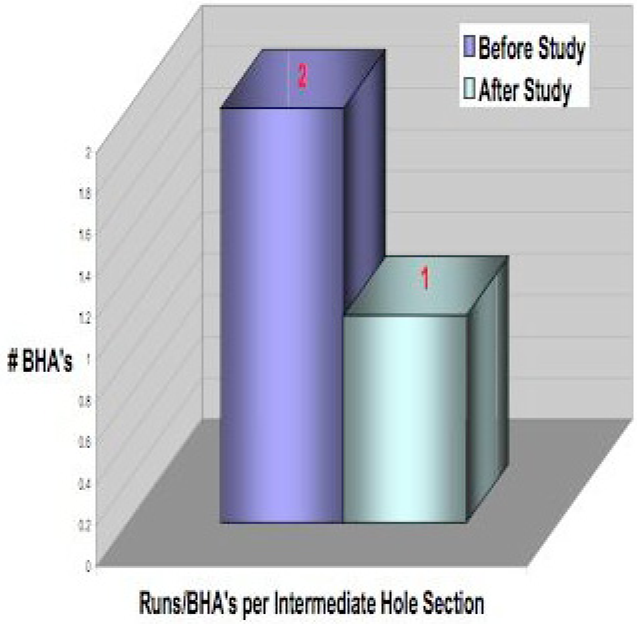


Fig. 26—Number of BHA runs per intermediate hole.

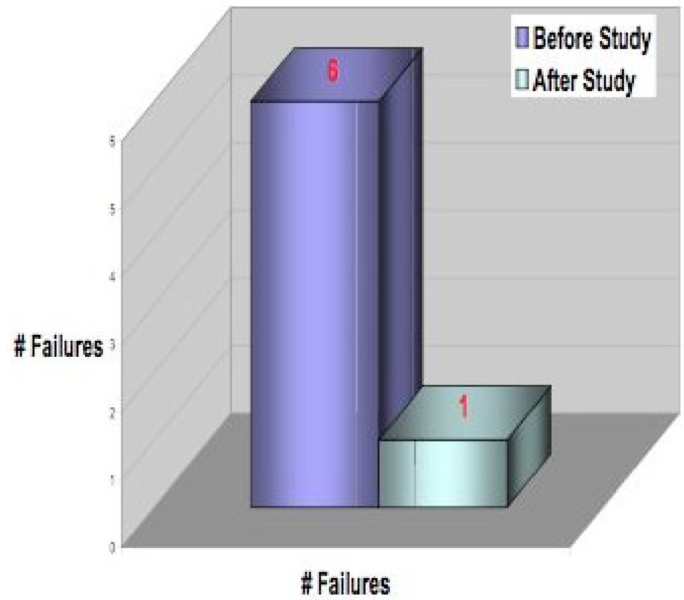


Fig. 27—Number of downhole tool failures.