AADE-03-NTCE-54

Achieving the Technical Limit: An Engineering Targeted Approach

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Abstract

This paper describes an iterative approach to achieve the drilling technical limit, or optimum performance by reviewing and applying sound engineering practices to operations. The goal of the technical limit is to eliminate removable lost time by employing engineering principles and optimum horsepower in all events to determine what is possible. Time determinations are relegated to an objective-forward technical approach. The objective statement of "what should be possible" replaces the subjective question of "what is possible".

Teams plan in a workshop environment to develop technical limit well construction plans. The following steps are crucial to achieving the technical limit:

1. Analyzing historical information from global, regional and area resources.
2. Developing engineered solutions within a team workshop environment.
3. Creating rig operations and execution best practices documents as checklists and reminders.
4. Ensuring that best practices, skills, and appropriate training are applied to rig operations.
5. Apply learning criteria.

Introduction

There is a "Two-Fold Path" toward realizing Technical Limit. Both folds are interrelated and function symbiotically—they cannot function independently of each other. The first fold of the path is sound engineering principles. It is here that objective and scientifically proven laws define and determine what is physically possible to achieve. A keen understanding of these engineering principles is critical because it defines what is technically possible and can therefore set engineering planning and implementation in motion.

Before striving to reach a technical limit, teams must be aware that the following criteria must be met:

- Global operations have achieved the reality of a one-bit-for-one-hole section, which can routinely be achieved, given today's available technology.
- Teams apply minimum mud weights to ensure wellbore stability and maximize horsepower.
- Teams can achieve flat-time, world-class benchmarks.
- Teams use economically justifiable rig and other associated equipment modifications in order to achieve the application of maximum horsepower for the new well.

The Second Fold—comprised of motivational, team and training issues —dovetails into the first fold of the path to technical limit. This is the complement of sound engineering principles, and it serves as the practical "follow-through" for achieving Technical Limit. While they are a necessary prerequisite, sound engineering principles (in and of themselves) are simply academic, moot and ultimately fruitless if we fail to:

- Motivate teams to employ the engineering principles.
- Empower individuals to address the engineering principles within a team environment.
- Apply learning principles.
- Motivate and train rig execution teams.

Learning principles require that we capture and transmit knowledge of the engineering principles, with something just as simple as a checklist for issues such as health, safety and environmental issues, events such as "tripping" and guidelines such as stuck pipe avoidance. By transmitting this knowledge to other team members we enhance the possibility for the technical limit, as they learn from other team's successes and mistakes.

This paper walks through an example of the methods used in order to achieve a technical limit by first reviewing and applying fundamental engineering principles, then, by serving as a compliment to the team's knowledge, applying learning principles.

Technical Limit – Rigorously Applying Sound Engineering Principles to Operations

The technical limit approach discussed herein differs from conventional technical limit approaches. In this approach, Productive Time events are developed by first recognizing that the full and proper application of horsepower is necessary to optimize force in all dynamic events.

Where Bond, et al[2], likened the achievement of technical limit to that of an athlete setting a world record, the methodology herein holds that it is possible for engineers to achieve the technical limit through diligent preparation and planning. But, they must get back to basics: reviewing and applying engineering practices, governed by laws of physics. Best-in-class performance is awarded to those who have the patience and will to succeed.

Teams generally ask the following questions: "*How are we currently performing*?" "*What is our Best Performance*? and "*How do we achieve better performance*?". Simple answers to these questions are available in the pure technical context of the application of maximum horsepower necessary and allowable for a given drilling operation. The goal of the technical limit is to eliminate removable lost time by employing engineering principles and optimum horsepower in all events to determine what is possible. Time determinations are relegated to an objective-forward technical approach. The objective statement of "what should be possible" replaces the subjective question of "what is possible".

Therefore, achieving the technical limit, as a targeted, or iterative, approach begins with the application of fundamental engineering principles during the planning phase of drilling operations to provide simplicity and objectivity to the implementation phases of well. In this regard, all wells drilled anywhere are the same. *That is, the force required to remove rocks of a given compressive strength can be determined and remains a reliable constant of physical nature.*

This paper considers the following elements critical to the technical limit:

- The force necessary to remove rock of a given compressive strength.
- Bit requirements from interpolation of correlative compressive strength information, as opposed to often unreliable bit record comparisons.
- Mud weight applications by extrapolating minimum weight trends from offset data to ensure wellbore stability.
- Forces created by tectonically imposed stress vectors in addition to pore pressure determinations leading to optimized margin management and casing seat selection.
- Optimized cleaning rates by determining optimum Carrying Capacity Indices.
- Exposure to chemical elements (shale and salt reactivity to drilling fluids.)

Further, in order to drive the technical limit, we must review the equipment used in the drilling operations, such as:

- Available and backup horsepower
- Drill strings that minimize friction losses
- Hydraulic horsepower
- Cleaning capacity requirements and optimum circulating rates.

(Note: Flat times are influenced from offset reality and global benchmarks, and interpolated to be the best possible performance by eliminating Lost Time, and applying Invisible Lost Time (non-productive time related to conditions and activities within control of well activities) coincidental with the event itself, such as BHA (Bottom Hole Assembly) makeup to ensure one-bit, one-section performance.)

An Iterative Approach to Technical Limit

In addition to the normal and customary motivational team issues, there are three essential targets, or iterations, involved in this approach:

- Target 1 – Global Rate of Penetration (ROP). Planning to determine optimum dynamic criteria and changes necessary to achieve the maximum technical components of dynamic operations.
- Target 2 – Extending information from Target 1 and the application of learning principles, plus the organized development of Flat Time synergies.
- Target 3 – Extending information from Targets 1 and 2 plus the application of new technologies.

In this Technical Limit process, planning is undertaken by first aligning multidisciplinary goals and objectives. Teams summarize and analyze key drilling information from area, regional, and global sources. A Basis of Design document inclusive of all work scopes is developed as a key document to the well delivery process, tracking well plans are developed. In addition, rig operations and performance execution documents are developed as checklists and operational guidelines to enhance rig site management functions and operations. These documents, along with primary planning documents, are linked to operations tracking details for “real time” reference at the wellsite.

Drilling improvements are driven by Best Practices and lessons criteria captured for reset and incorporated into work scopes and processes to thereby improve future operations.

Application of Technical Limit – JNOC Workshop

The purpose of the workshop conducted with JNOC was to develop criteria in regards to planning and implementation for future operations, or “Target 1,” as referred to above.

The key well used for historical analysis was a prior well drilled off of the Northwest coast of the island of Hokkaido. The well was a 5,050 meters deep and experienced High Pressure, High Temperature (HPHT) characteristics, complicated by the presence of tectonic stress. The JNOC team developed a task chart for the conduct of the workshop to determine Technical Limit. A summary of the stages (milestones) of development follows:

- Reviewed and defined multi-disciplinary goals and objectives and the scope of the well.
- Summarized offset well history by commonly accepted time categories.
- Analyzed offset well history and problems encountered and develop solutions and mitigation’s based on technical issues.
- Determined “Flat time” benchmarks for the new well.
- Created a drilling operations tech limit plan for the new well.
- Developed a Technical Limit Authorization for Expenditure (AFE), commensurate with optimum time determines and benchmarks.
- Developed Drill Time Schedule.
- Developed Work Scopes and master Basis of Design documents for:
    - Casing Program
    - Fluids Program
    - Directional Program
    - Bit Program
- Developed Interval Drilling Plans reflecting procedures, solutions and problem mitigation for each hole section, or drill the well on paper.
- Finalized the drilling program.
- Developed rig operations and performance execution documents as checklists and guidelines for the well site operation.

During the planning phase of the workshop, Target 1 applied the following Technical Limit goals:

- One bit–for–each hole section.
- Minimum “weighting” trends to ensure well bore stability.
- Optimum casing seat selection driven by relationships of imposed tectonic stresses and pore pressure predictions, which can often be quite different, especially in HPHT operations.
- Best-in-class flat times were determined from global benchmark data, the premise being that the “best-of-the-best” can be achieved in any given drilling operations.

Applied engineering is irrefutably the same for any well drilled. This approach differed from some technical limit schemes in that all dynamic determinations are entirely objective and based on fundamental engineering principles of force and mass. The “one-bit, one-section” selection was made from comprehensive rock strength analysis. The determination of how much horsepower it takes to fail and remove rock dominates the planning and implementation criteria.

Discussion of the Targeted Technical Limit Approach

Planning. This approach challenges engineers to practice engineering. Target 1 is objective; therefore, removable time is not a factor. From a technical standpoint, this removes the classic, subjective question of *“What can be accomplished?”* and replaces it with the development of an objective scenario as to “*What should be accomplished?”* Future iterations could consider removable time, but mainly in the context of flat time accomplishments to improve benchmark performance and the application of lessons learned. Engineering dynamics will change according to changes in correlative rock strengths and ancillary horsepower requirements.

The following statements summarize this approach:

- Approaching the technical limit is based on sound fundamental engineering principles.
- Approaching the technical limit is not a subjective “guess” as to what is possible; rather an objective determination as to what should be possible from an engineering perspective.
- Approaching the technical limit is possible and therefore can routinely be achieved based on current technology.
- Applying new technologies and learning’s heightens the move towards technical limit.

Lost time that is identified in the historical well was primarily a result of the improper application of "weighting" techniques, and the mechanical inability to achieve maximum performance. The failure to recognize the stress component as a result of tectonic force vectors contributed to many lost time incidents in the historical well.

For the JNOC Example the analysis considered the following:

Compressive Rock Strength. Interpolation of compressive strength geomechanics indicated that confined stresses were abnormally high. The origins of these stresses were excessive mud weights in the example historical wells that contributed to fluid loss events, which resulted in the acceleration of bit wear and low rates of penetration.

Bit Selection. Bit selections were relegated to fixed cutter bits for the new well plans and were based on correlative compressive strength for given hole sections. The maximum compressive strength for a given section determined the aggressiveness of the bit design. The confined components of compressive strength—the result of inordinately high mud weights—were eliminated, allowing for more aggressive bit selection. Optimum circulating rates for each hole section were determined from the JNOC drilling manual based on fluid properties and circulating indices. Once circulating rates were determined, then the horsepower necessary to deliver the optimum rates and manufacturers' maximum weight on bit was determined. The drill string was designed to deliver at least 50% HHP (Hydraulic Horsepower) at the bit. Fig. 1 indicates flow rates for optimum hole cleaning.

Penetration rates were interpolated by reviewing the optimum performance measures of similar bit types in other global operations with comparable Lithology and rock strengths. The bit comparisons were not subjected to conventional bit records, but rather to bits that were known to achieve maximum performance under optimum dynamic conditions.

Wellbore Stability. The wellbore stability model considered offset trends, and adjusted them to minimum mud weights that are necessary to ensure wellbore integrity. "Weighting" up was considered only as hole conditions necessitated, such as evidenced by inordinate torque/drag events, concave cuttings, or changes tectonic stresses or pore pressure gradient trends. In any event, the practice of proper well control techniques is essential to ensure that weighting events are not conducted unless conditions require. This requires vigilance at the wellsite, along with proper training in well control techniques. It was also noted that, in the historical well, "weighting" up often occurred at casing seats, irrespective of where the actual increasing pore pressure trend occurred. This resulted in several fluid loss events and unnecessary wasted time for wiper trips. In addition, it was concluded that background gas alone was not an indicator of increasing pore pressure.

Therefore the wellbore stability model has at a minimum the following criteria:

- Elimination of "weighting" requirements as a result of the presence background gas alone.
- Maintaining circulating rates that minimize Equivalent Circulating Density (ECD) effects.
- Increasing mud weight that requires the consideration of several factors before initiating weighting operations:
- Recognizing that inordinate increases in torque and drag, or torque spikes, with the recognition that concave-shaped, or splintered cuttings over the shaker could be a result of tectonic stresses as opposed to increasing pore pressure.
- Verification of increases in flow line volume and subsequent shut-in pressures are required prior to increasing mud weight and should always be undertaken as required by proper well control techniques.

Fig. 2 indicates the difference between the JNOC historical example well and the application of mud weight trends, versus the planned well.

Tectonic stress played an important role in misinterpreting pore pressure trends. In the presence of normal gradients, tectonic stress can mask actual pore pressure requirement. The problem is that increased mud weights are often required to ensure wellbore stability in the presence of tectonic stress. The failure to recognize tectonic vectors has the following minimum negative impacts on drilling operations:

- Required weight increases can create unacceptable fluid loss events in the presence of normal pressure and porosity.
- Pore penetration stress increases as mud weight increases, creating unnecessary wetting of shales and ultimate stress relief conditions (sloughing).
- Reduced ROP due to inordinate confined stress as a result of unnecessarily high mud weights.
- Elliptical hole shapes destroying bits and rates of penetration performance.
- Complicates directional issues.

The solution to the tectonic stress problem requires recognition in the planning phase of operations. Casing seats were simply driven deeper to match, as close as possible, the actual pore pressure with the stress imposed by tectonically induced vectors. Recognizing this problem, and accommodating it in the casing program to ensure wellbore stability and integrity, has been a key factor in improving drilling performance and wellbore stability.

Recognition of tectonic stress from historical data, if available, can be made by:

- An elliptical hole caliper (requires X-Y caliper).
- Pinched bits.
- Unexpected BHA "walk".
- Inordinate fluid losses in the presence of normal gradient trends.
- Geophysical interpretations.

Casing seat revisions were also recommended in the JNOC example and are depicted in Fig.3.

Directional Program. The directional program requires bit designs which comply with formation compressive strength requirements. It also requires optimum hydraulics to ensure motor performance in the highest possible envelope.

Gauge protection, BHA and weight distribution requirements are then designed around rock strength parameters. Build-and-hold, along with normal directional criteria and special hole cleaning requirements, meet formation compression strength requirements. The drill string and horsepower available must accommodate all required normal drilling criteria, plus the added criteria of motor pressure drop and stall safety factors.

Alignment of the directional well path with the principal tectonic stress vector is critical to optimum drilling performance and wellbore stability.

Flat Time, Benchmarks, and Drill Time.

Flat time represents a significant portion of expended well time. Benchmarks from other operations become important in terms of the realization that "best-in-class" flat time performance is often achieved can be challenged and improved. However, the starting point should not be a subjective "guess," but rather an objective approach to determine time for flat time events.

The new wells used global benchmarks for operations such as logging, coring, tripping, casing insertion and cementing, along with other flat time events.

Once benchmarks were determined for flat time projections, an overall drill time calculator for determining global ROP and costs was developed by hole sections. Table 2 shows the drill time and cost calculator. Figure 4 represents Drill Time for a Technical Limit well.

Other "best practices" would include training to reduce unscheduled events and performance engineering to track daily operations in work process templates with process improvement suggestions for reset and future operations.

Implementation. Implementation of the planning efforts and actual well operations requires first modifying rig and ancillary equipment to achieve the technical goals that were determined in the planning phases of an operation. Implementation should be front-end loaded by early planning efforts and should precede motivational and training issues.

Development of Rig Checklists and Execution Documents

The JNOC team developed over forty-seven (47) checklists representing well construction events. Much as a pilot refers to checklist prior to take-off, these checklists were developed as reminders of issues that must be remembered and executed to ensure safe and efficient operations. The details of the checklists and guidelines will not be dealt with in this paper. An example of the Technical Limit guidelines and checks is provided for review in the following as presented in Table 1. The goal was to employ a systemic "drill" down approach for events such as Blow Out Preventer (BOP) testing, tripping, directional BHA design, running casing, cementing, etc. These documents were linked to learning templates for reference in the proper drill down sequence. In addition, the checklists incorporated avoidance issues, such as stuck pipe, well control and other events that routinely create non-productive time and safety events. The checklists were designed for wellsite reference, to be managed by the well site supervisor to improve team participation in the well construction effort. The checklists also included safety issues to enhance routine "tool box" meetings.

Conclusions

Use of a systematic process for planning and execution relegates achieving the technical limit to a rather routine accomplishment. The determination of how much horsepower it takes to fail and remove rock dominates the planning and implementation criteria. Ultimately, teams must work to first, review and apply sound engineering principles, realizing that all dynamic drilling operations are governed by sound engineering principles and practices, and then, employ Best Practices and learning principles to successfully execute the drilling operation.

In developing this model, the subjective approach of determining “Removable” time is eliminated, and replaced by an engineered, objective approach that considers the following:

Technical Limit = Practical Limit:

One Bit - One Section - Minimum Mud Weight, Maximum Hydraulics
If:

- *The well is thoroughly planned*
- *Fundamental engineering principles are applied in all dynamic operations.*
- *Best Practices are applied.*
- *Crews are properly trained.*
- *Proper equipment to optimize horsepower is available and used.*

Acknowledgements

The authors wish to express thanks to the Japan National Oil Company: Tetsuro Tochikawa, Eitaro Doi, Motoi Wakatsuki, and Masaki Ishikawa for their participation, support and information they supplied to develop this project and paper.

Nomenclature

BHA = bottomhole assembly
BOP =blowout preventer
ECD = equivalent circulation density
EMW = equivalent mud weight
RKB =rig floor Kelly bushing elevation
ROP = drilling rate of penetration
RPM = revolutions per minute
TD=total depth
TVD=true vertical depth
WOB = weight on bit
AFE = Authorization for Expenditure

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3. Kadaster, A.G., Townsend, C.W., Albaugh, E.K.,” Drilling Time Analysis: A Total Quality Management Tool for Drilling in the 1990’s”. SPE 24559, presented at the 67th Annual Technical Conference and Exhibition for the Society of Petroleum Engineers. Washington DC, October 1992.

Tables and Figures

Figure 1 – Determination of Optimum Circulating Rates for the JNOC Study Well, the MITI Chikappu Exploratory Test Well

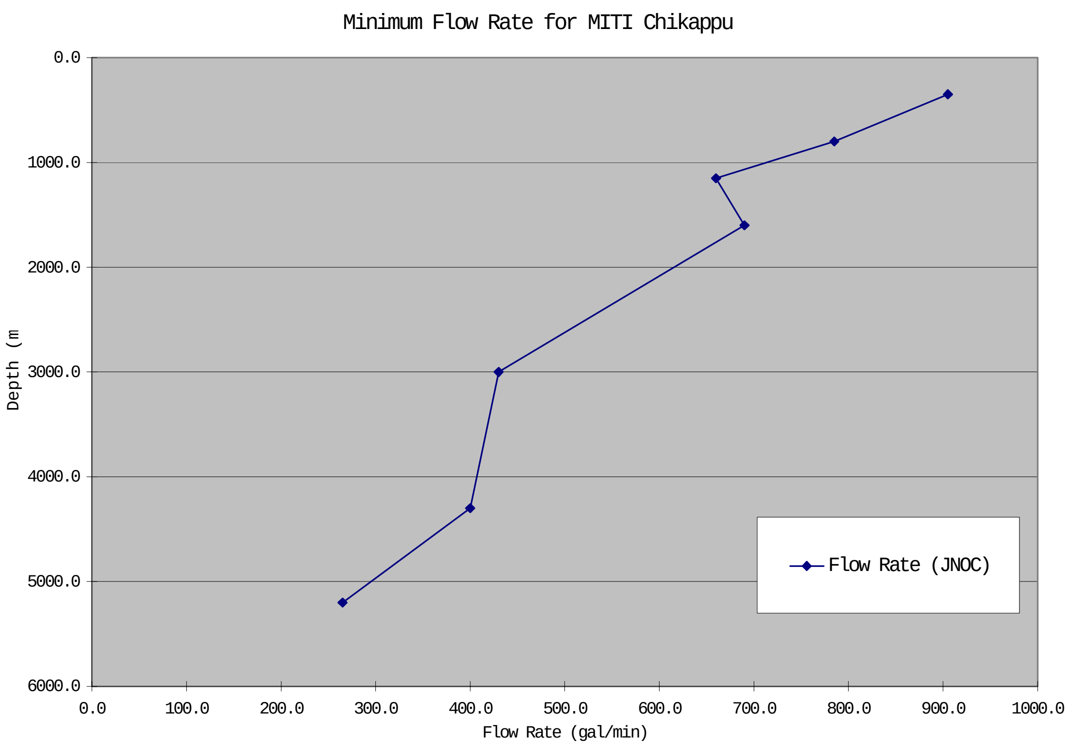

Figure 2 – Comparison of historical actual weighting with planned minimums based on recognized events

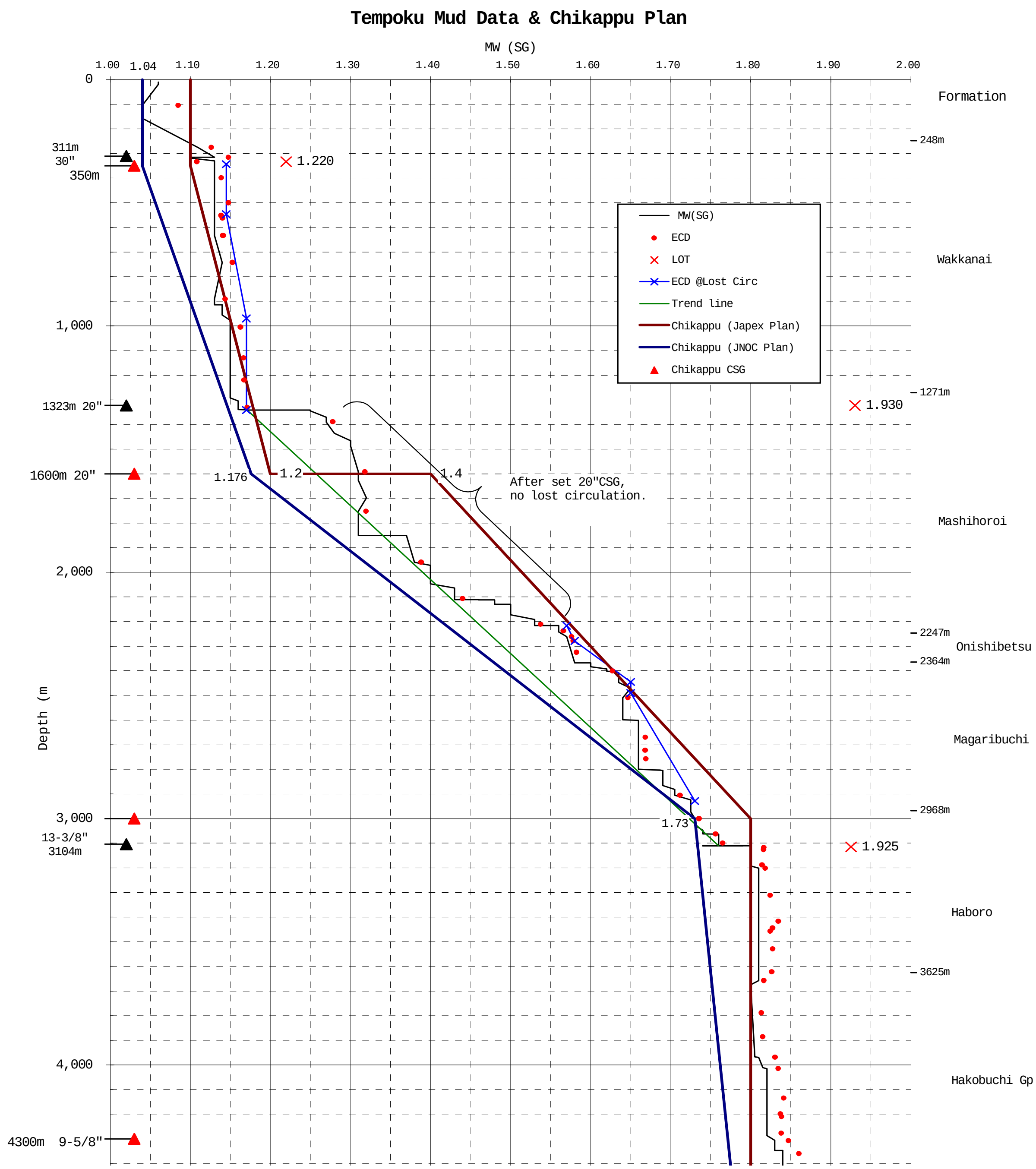

Figure 3- Considered changes in casing program as a result of tectonic stresses

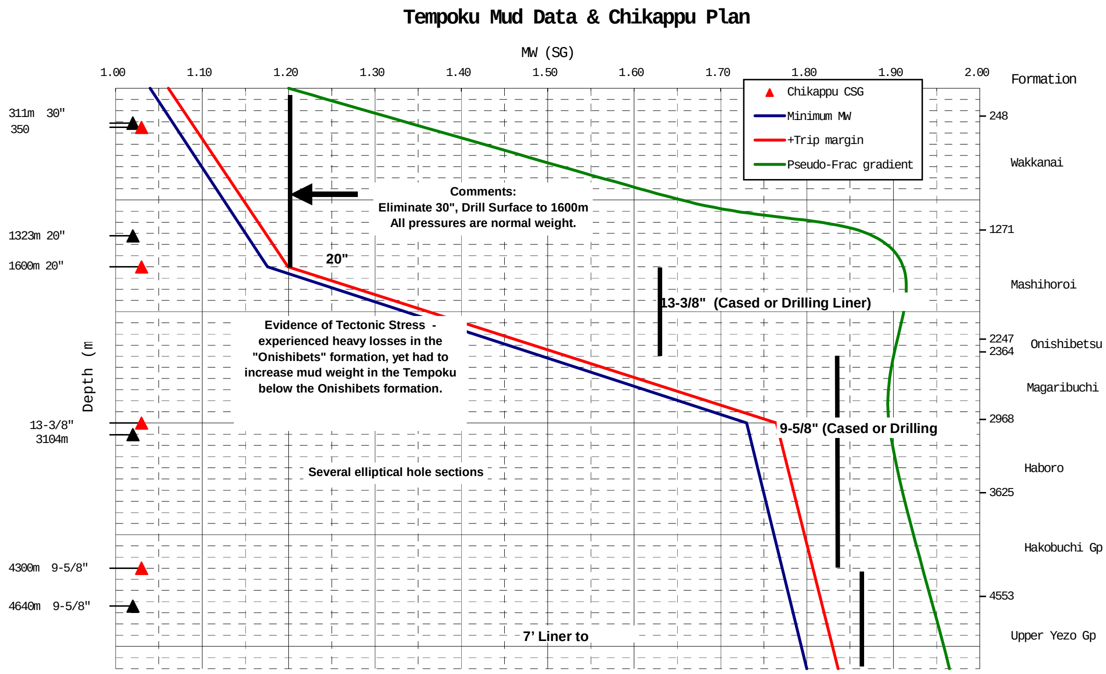

Table 1 – Example Information from a Rig Operations and Performance Execution Document.

General Technical Limit Guidelines for Increasing Mud Weight

Low Mud Weight Indicators	**High Mud Weight Indicators**
Unexpected High ROP	Unexpected Low ROP
Cavings – Particularly “Concave”, splintered	Abnormal Bit Wear
Flow Rate Increase	Will "overwet" shales, lessen chemical inhibitive effectiveness
SIDDP+ – Well Control	Creates unnecessary fluid losses, risk of fracturing softer formations.
Drilling Break gas failing to “fallout” after circulating	Increase opportunities for “Ballooning”, possibly creating unsafe drilling conditions.
Torque/Drag Increase	Inordinate fluid loss events

Guidelines for “Drilling to Conditions” or Technical Limit Drilling

- Drill with minimum mud weight.
- Background gas (or even an increase in background gas) alone IS NOT a sufficient reason to increase mud weight. In fact, in fractured formations, if the mud weight is too high, it can create a “ballooning” effect, and actually create an unsafe well condition.
- Monitor Torque/Drag envelope, particularly observing torque spikes.
- Drill out casing shoes with prior section weight, then increase mud weight only as hole conditions dictate.
- Continuously monitor “shakers” for concave cuttings, sloughing, gumbo.
- If possible, know the direction of principal stress vectors. Drilling in the direction of the principal stress vector improves ROP, and borehole stability.

Reasons to Increase Mud Weight

- Increased flow line rate, pit levels – Take SIDPP, follow proper well control procedures - KNOW exactly HOW MUCH to weight up by observing SIDPP, if any.
- Concave Cavings, torque spikes.

Formation pressure = Tectonic Stress Component + Pore Pressure

In the presence of Tectonic Stress – Any (or a combination) of the following four events will occur:

- Concave and/or splintered cuttings.
- High Torque/Drag.
- Excessive reaming/backreaming.
- Out of gauge bits.

The Problem

Increasing mud weight can cause non-protected (no casing) uphole losses where tectonic stresses ARE NOT present, and pore pressure is normal.

The Solution

Recognizing tectonic conditions early, hopefully in the planning phase – this can be accomplished from:

- Wellbore stability modeling, geophysical data.
- Analysis of offset information – particularly correlative “X-Y” caliper information. The evidence will be an eccentric hole.
- Out of Gauge Bits are positive indicators of tectonic stresses.
- Effective control of tectonic stress, particularly in the presence of normal pore pressure, is usually only mitigated by setting casing.

Table 2 – Time Breakdown for Technical Limit Well – Days

MITI Chikappu Exploratory Test Well
Tempoku Area
Technical Limit - One bit, One Section

Phase	Phase I	Phase II	Phase III	Phase IV	Phase V	Phase VI	Phase VII	Phase III	Phase IX		
Activity	Drill 17-1/2"	Ream to 26"	Set 20"	Drill 17-1/2"	Set 13-3/8"	Drill 12-1/4"	Set 9-5/8"	Drill 8-1/2"	Set 7" Liner	TOTAL	
Projected Depth - MD	1600	1600	1600	3000	3000	4300	4300	5200	5200		
Calculated Phase Time	5.33	2.44	6.99	6.32	6.21	11.35	12.03	20.86	19.08	90.62	
Hole section drilled - Meters	1600	0	0	1400	0	1300	0	900	0		%
MIRU/RD									3.00	3.00	3.3%
Section ROP (1)	1.67			1.94		2.71		7.50		13.82	15.3%
Hole Opening		1.50								1.50	1.7%
Section BHA				1.28		2.28		1.75		5.31	5.9%
Extra Build Time	1.00									1.00	1.1%
Conditioning	0.3	0.1	0.1	0.3	0.1	0.6	0.3	0.8	0.3	2.75	3.0%
Trips	1.23	0.62	0.62	2.50	1.25	2.05	2.05	4.19	2.80	17.30	19.1%
Logging	0.88		2.79			3.16		5.77	1.00	13.59	15.0%
Run Csg./Cmt	0.00	0.00	1.50	0.00	2.08	0.00	2.67	0.00	2.08	8.33	9.2%
Drill out			0.75		0.75		0.75			2.25	2.5%
WOC									0.50	0.50	0.6%
Surveys	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.90	1.0%
BOPE NU& testing	0.00	0.00	0.83	0.00	1.67	0.00	1.67	0.00	1.04	5.21	5.7%
DST's									2.00	2.00	2.2%
Coring							4.09		5.58	9.66	10.7%
Trouble Time										0.00	0.0%
Rig Service	0.21	0.09	0.27	0.24	0.24	0.44	0.46	0.80	0.73	3.49	3.8%
TOTAL PHASE	5.33	2.44	6.99	6.32	6.21	11.35	12.03	20.86	19.08	90.62	100.0%
CUMULATIVE	5.33	7.77	14.75	21.07	27.29	38.64	50.67	71.53	90.62		
ROP Meters/DAY DRLG ONLY	960			720		480		120			
ROP Meters/Hr. DRLG ONLY	30.00	0.00	0.00	30.00	0.00	20.00	0.00	5.00	0.00		
OAL Meters/day drlg	300	0	0	222	0	114	0	43	0		
ROP - Feet/Day	3149	0	0	2362	0	1574	0	394	0		
ROP - Feet/Hr.	131	0	0	98	0	66	0	16	0		
Benchmarks:											
Trip Time (M/Hr):	216.0	216.0	216.0	200.0	200.0	350.0	350.0	310.0	310.0		
Trip Time FT/Hr):	708.5	708.5	708.5	656.0	656.0	1148.0	1148.0	1016.8	1016.8		
No.Trips/section	2.0	1.0	1.0	2.0	1.0	2.0	2.0	3.0	2.0		
Trip Time - Days:	1.2	0.6	0.6	2.5	1.3	2.0	2.0	4.2	2.8		
Coring Trips						3.0		3.0			
Coring Trip Time						4.1	0.0	5.6			
Logging Time - Hrs.:	0.9		0.0	2.8	0.0	3.2	0.0	5.8	0.0		
BOP/NU/Test			0.8		1.7		1.7		1.0		
C&C	0.3	0.1	0.1	0.3	0.1	0.6	0.3	0.8	0.3		
Run/Cmt. Csg.			1.5	0.0	2.1	0.0	2.7	0.0	2.1		

Figure 4 – Represents Drill Time Projections for the Technical Limit Well