Drilling Technology for Deep and HPHT Containing Sour Gas well in the ChuanDongBei Field of China

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Abstract: ChuanDongBei Field of Sichuan Basin is a HPHT deep gas reservoir with multiple pressure systems, with maximum formation temperature up to 156 ℃ and pressure gradient of 1.86 at the depth of 6500m. Part of the well section contains more than 5% CO_2 and near to 10% H_2S, so drilling operation is extremely challenged. Firstly, this paper introduces drilling challenges such as lost circulation, severe caving-in, pipe sticking in upper section, sour gas corrosion problems, low penetration rate in the middle and deep section.

Secondly, a lot of available key drilling technologies are innovated and provided, including casing program optimization, air and nitrogen drilling to improve ROP, combination drilling with anti-HT motor and fit for purpose PDC bits, anti-HT mud along with losses prevention technologies such as MPD, anti-gas channeling and big temperature difference cementing slurry in the long interval, BOP and H_2S sour gas monitoring system with emergency plan and some management advices for deep HTHP containing sour gas wells.

Finally, some unexpectable application results regarding these techniques to solve a series of drilling difficulties have been mentioned according to 40 wells cases. Take well LG01-XY as an example, which was improved average ROP to 6.4m/h, extended the footage to 1713m in one specialized bit with air hammer, reduced drilling period to 145days, reached “zero pollution, zero harm, zero accident” achievement during H_2S interval, got premium cementing result and well bore qualify. So it could be used as a technical reference while drilling in deep HTHP containing sour gas wells in similar geologically complicated gas fields.

Keywords: Drilling technology for deep and HPHT containing sour gas well, chuandongbei field of china, challenges and solutions, case study.

1. INTRODUCTION

ChuanDongBei Field is located in Northeast of Sichuan Basin, which refers to some complex oil and gas field in NanChong, Da Zhou, Guang An, Guang Yuan and Ba Zhong etc., such as PuGuang, Tie Shanpo, Du Kouhe, Luo Jiazhai and Long Gang as shown in Figure **1**.

The main features of ChuanDongBei field are high tempreture (maximum156℃), high pressure(maximum 100MPa), ultr-deep(average depth 6542m) and rich sour gas(CO_2: 3.29-8.63%, H_2S: 1.67-9.09%). There are total about 30 strata layers and sub zones, which show the complex and uncertain pressure system in this area, referred to Table **1**. Take Long gang gas field as an example. When the first exploration well LG001 was spuded in April, 2006, where after the second and the third exploration well LG002 were drilled in Nov.2006 and well LG003in Dec.2006 respectivly. The conventional five-layer casing program was not safe to deal with the geological risks and muti-pressure formation and strong uncertainty of pressure in the exploration and development of ChuanDongBei area, so a six-layer unconventional well profiles was proposed and implemented successfully in multiple wells from LG61 to LG68 in 2008 accordingly as a new innovation casing program for deep wells, referred to Figure **2**. With regard to ROP, a general exploration and development history of offset fields showed us that it was taken 1407days to reach the TD of 6063m in well WK01 by average ROP 0.95m/h in the 1990s and the well DS01 with TD of 6288m was dilled within 510 days by average ROP 1.77m/h in 2005. Air and nitrogen and foam drilling along with anti-HT motor and PDC bit became an innovative technology to improve ROP dramatically by 150-500% in ChuanDongBei field. In reference to a big challenge resulting from sour gas, BOP and H_2S sour gas monitoring system associated with emergency plans are presented together with losses prevention and cementing technologies for booming the further exploration and development in ChuanDongBei area.

2. CHALLENGES

The difficulties for drilling in ChuanDongBei Area addressed below:

2.1. HTHP and Sour Gas

The offset drilled wells indicate that rich concentration H_2S and CO_2 in FeiXianGuan and ChangXin Zone with the range value 1.67-9.09% H_2S,

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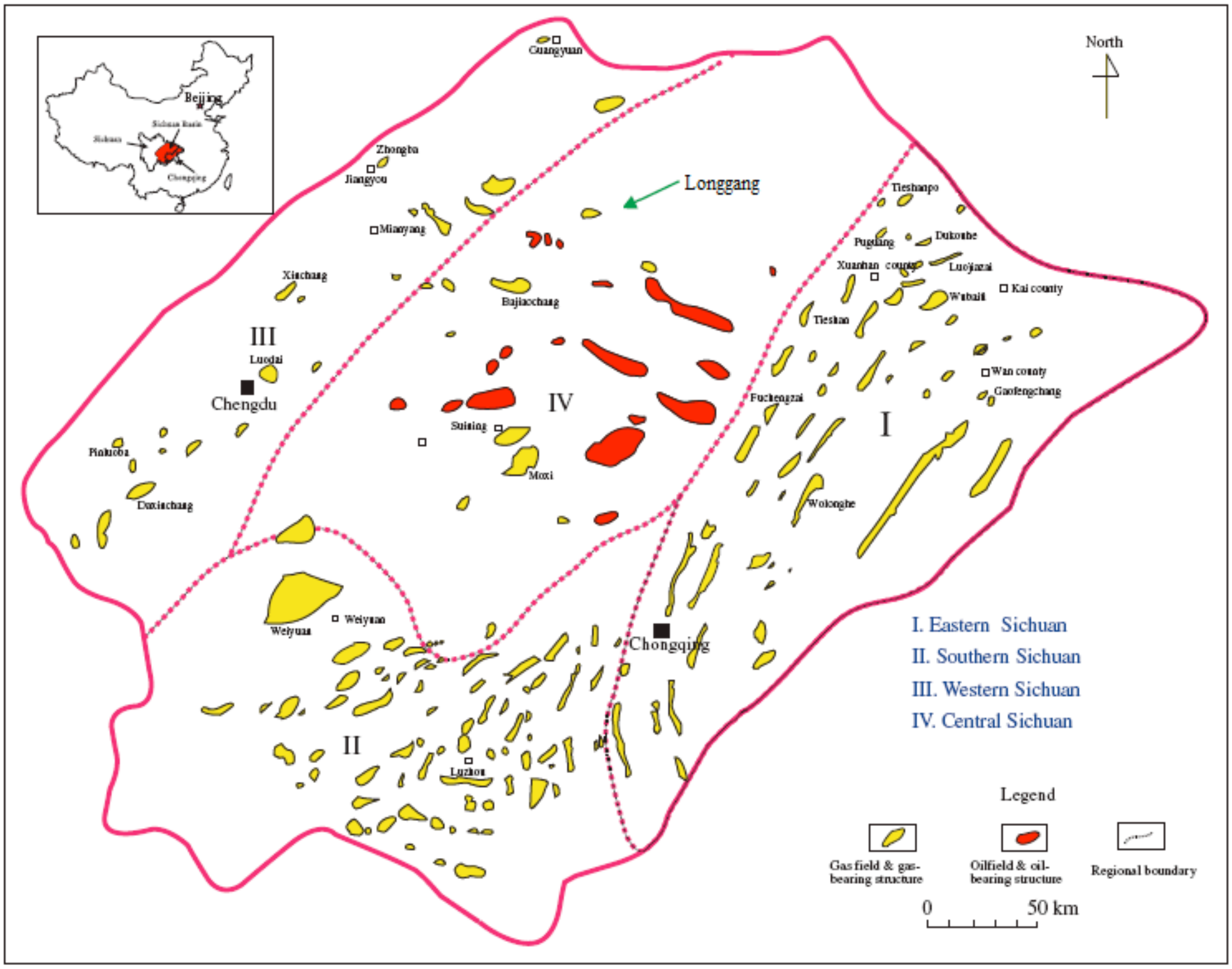

Figure 1: Location map of chuandongbei area **(**picture courtesy of marine and petroleum geology).

Table 1: Stratified Formation of LG001-3

Stratified Formation	Bottom Depth (m)	Thickness (m)	Stratified Formation	Bottom Depth (m)	Thickness (m)	Stratified Formation	Bottom Depth (m)	Thickness (m)
PengLaiZhen	573.00	573.00	ZhenZhuChong	3517.00	190.00	LeiKouPo1	4802.00	437.00
XuLing	1209.00	636.00	XuJiaHe6	3560.00	43.00	JiaLinJiang5	4842.00	40.00
ShaXiMiao1	2450.00	1241.00	XuJiaHe5	3710.00	150.00	JiaLinJiang4	5180.00	338.00
ShaXiMiao2	2956.00	506.00	XuJiaHe4	3796.00	86.00	JiaLinJiang3	5365.00	185.00
LiangGaoShan1	3083.00	127.00	XuJiaHe3	3874.00	78.00	JiaLinJiang2	5595.00	230.00
LiangGaoShan2	3126.00	43.00	XuJiaHe2	4052.00	178.00	JiaLinJiang1	5905	310.00
Transition layer	3148.00	22.00	XuJiaHe1	4076.00	24.00	FeiXianGuan4	5929	24.00
Da'AnZhai	3229.00	81.00	LeiKouPo4	4170.00	94.00	FeiXianGuan 3-1	6343	414.00
Ma'AnShan	3291.00	62.00	LeiKouPo3	4268.00	98.00	ChangXin	6643.89	300.89
DongYueMiao	3327.00	36.00	LeiKouPo2	4365.00	97.00			

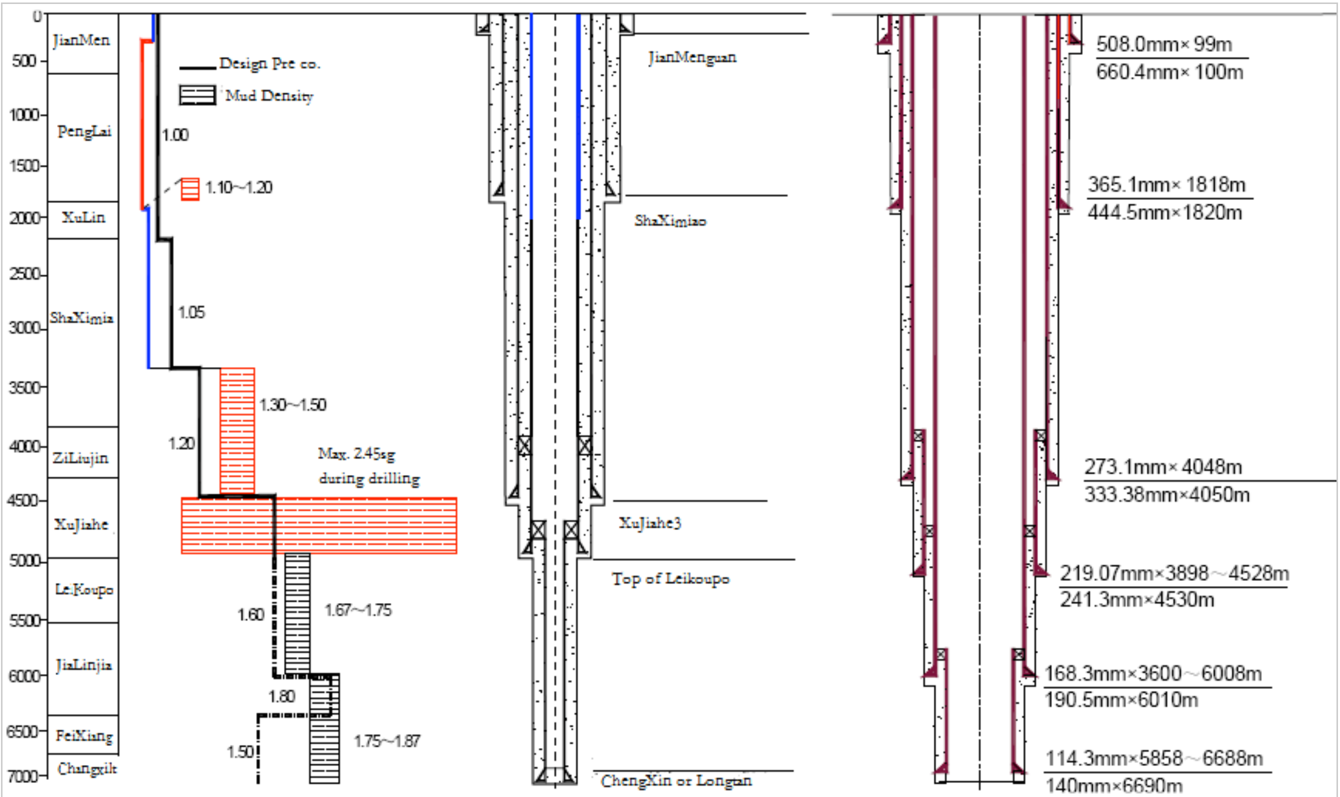

Figure 2: 5th Interval in w ell LG6 and 6th interval casing program in Well LG61.

Table 2: Gas Component Distribution in ChuanDongBei Area

Well Name	Relative Density	Natural Gas Component(%)			H_2S	CO_2	Critical Pressure	Critical Tempreture
		Methane	Ethane	Nitrogen	(g/m3)	(g/m3)	(MPa)	(K)
LG027	0.615	92.4	0.06	0.37	46.2	77.33	4.85	200.7
LG026	0.614	91.79	0.08	0.64	24	92.56	4.8	198.6
LG006	0.6841	85.23	0.04	0.4	44.2	219.81	5.04	208.6
LG028	0.5859	96.15	0.07	0.58	63	127.19	4.69	194.4
LG001-23	0.6432	88.01	0.06	0.93	81.12	94.98	4.97	205.9
LG001-28	0.6316	89.07	0.08	1.37	73.71	75.94	4.91	203.5
LG001-26	0.63	89.35	0.04	0.75	82.03	75.39	4.96	205.2

average 4.51% H_2S; 3.29-8.63% CO_2, average 5.2% in ChangXin Zone and 1.27-4.30% H_2S, average 2.56% H_2S; 2.46-5.10% CO_2, average 3.39% in FeiXianGuan Zone as shown in Table **2**.

Moreover, the bottom pressures of drilled wells have been reached to over 110MPa and tempreture increased in excess of 150℃ in Well LG017, which bring out big challenges for drilling fluids and cementing operation.

2.2. Multi-Pressure and Multi-Payzone

As are indicated from well LG004, LG061 etc that at least four payzone exist from FeiXianGuan and ChangXin Zone to XuJiaHe2 and ZiLiuJing Zone [1], where high pressure salt water occurs in JiaLinJiang2 with 1.8-2.1sg formation pressure and 2.45sg high pressure happened in XuJiaHe2 associated with normal upper interval such as PengLaiZhen and Xulin Zone as shown in Figure **2**.

Table 3: Formation Water Statistics of ChuanDongBei Area

		Iron Concentration(mg/L)						Total Salinity
Item	Relative Density(D420)	$K^{++}Na^{+}$	Ca^{2+}	Mg^{2+}	Ba^{2+}	Cl^{-}	HCO^{3-}	(g/L)
Range	1.02-1.16	46309-83305	12731-21752	1547-2818	39-2373	103294-160826	52-276	18.66-263.24
Average	1.12	52756	16125	2224	1386	129023	149	157.1

Table 4: Conventional 5th Interval Casing program of LG001-3

Casing Program	Bit Size (mm)	Well Depth (m)	Casing Size (mm)	Casing Depth (m)
Surface casing1	660.4	53	508.0	52.76
Surface casing2	444.5	601.40	339.7	600.36
Intermediate casing	311.2	3554.00	244.5	3552.50
Liner1	215.9	5623.00	177.8	3389.94～5621.43
Liner2	149.2	6643.89	127.0	5460.22～6450.01

2.3. Wellbore Instability

It is characteristics of mudstone, unconsolidated sandstone and shale in Jurassic Period from JianMenGuan to the top of XuJiaHe, while interbeded coal bed of XuJiaHe are easy to cave-in and instability.

2.4. Poor Drillibility in Hard Abrasiveness

The rock drillibility classification of ZiLiuJing and XuJiaHe [1] are in excess of seven with hard abrasiveness. So one of typical example from LG004 is that a total of 18 bits used in 3775-4193m along with average footage 23.3m and 0.66m/h ROP.

2.5. Active Formation Water

The water type is $CaCl_2$, pH 5.43-7.74, Cl^- in the range of 10,3294-16,0826mg/L, density 1.02-1.116 on the basis of 25 water sample statistics referred to Table **3**.

2.6. High HSE Risks in Densely Populated Area and Hilly Terrain

There are over 600 residents around 500m away from wellhead in some wells of ChuanDongBei field, which is hilly terrain along with rivers and damsite as Sichuan is a large argriculture province with over 80million population in 45,000Km^2 area. So it is highly sensitive in terms of safety and environmental risks when drilling in these kinds of area.

3. CASING PROGRAM OPTIMIZATION

A key variable element for drilling design in HTHP and sour gas fields is the open-hole length of high pressure section, which would lead to differential sticking, unexpected drilling time and downhole complexity.

It was a conventional casing program of 5 intervals in ChuanDongBei area as shown in Table **4** until abnormal high formation pressure of XuJiaHe2 (maximum 2.3s.g) occurs along with CO_2 gas zone to some extents. In those types of wells, 177.8mm casing was set for isolating the ultra-high pressure, so 149.2mm bit could be used for the final open hole section which is over 2000m. It was so difficult to drill the remained complex formation and too slow ROP to finish the planned well duration for 149.2mm small hole. Additionally, the production capacity had been reached more than one million cubic meters per day for most wells in ChuanDongBei area with 128MPa target pressure and 144℃, so 114.3mm production tubing was provided and required. The only solution was to put 177.8mm casing deeper on the top of ChangXin referred to Table **4** with huge well control risk and severe losses due to a long open section.

The conventional casing program is Ø508mm × Ø339.7mm × Ø244.5mm × Ø177.8mm × Ø 127mm, while the unconventional casing program is Ø508mm × Ø365.1mm × Ø273.1mm × Ø219.1mm (without coupling) × Ø 168.28mm(without coupling) × Ø114.3mm (without coupling or open hole). The specific of this unconventional program is Ø508mm for unconsolidated surface interval, Ø365.1mm set to the top of ShaXiMiao for the next possible aerated drilling, Ø273.1mm ensuring the safe aerated drilling over 2,000m until top of XuJiaHe3, Ø219.1mm isolating the

Table 5: Unconventional Casing Program in Western ChuanDongBei Area

Casing Program / mm × Depth / m						
Well No.	**First interval**	**Second interval**	**Third Interval**	**Forth Interval**	**Fifth Interval**	**Sixth Interval**
LG61	Ø508mm×102	Ø365.1mm×1814	Ø273.1mm×4065	Ø219.1mm×4505	168.3mm×6392	Ø114.3mm× 6618
LG62	Ø508mm×154	Ø365.1mm×1803	Ø273.1mm×3833	Ø219.1mm×4629	168.3mm×6353	Open hole
LG63	Ø508mm×216	Ø365.1mm×2105	Ø273.1mm×4476	Ø219.1mm×5293	168.3mm×6990	Open hole
LG68	Ø508mm×164	Ø365.1mm×1988	Ø273.1mm×4346	Ø219.1mm×5248	168.3mm×7004	Ø114.3mm× 7205
Remark	Surface CSG	Inter CSG to top of ShaXimiao	Inter CSG to top of XuJiahe	Without Coupling Liner to Lei04	Without coupling liner toFei01, then tie-back 177.8mm CSG+193.68mmCSG(0-2000m)	Without coupling liner or open hole for pay zone

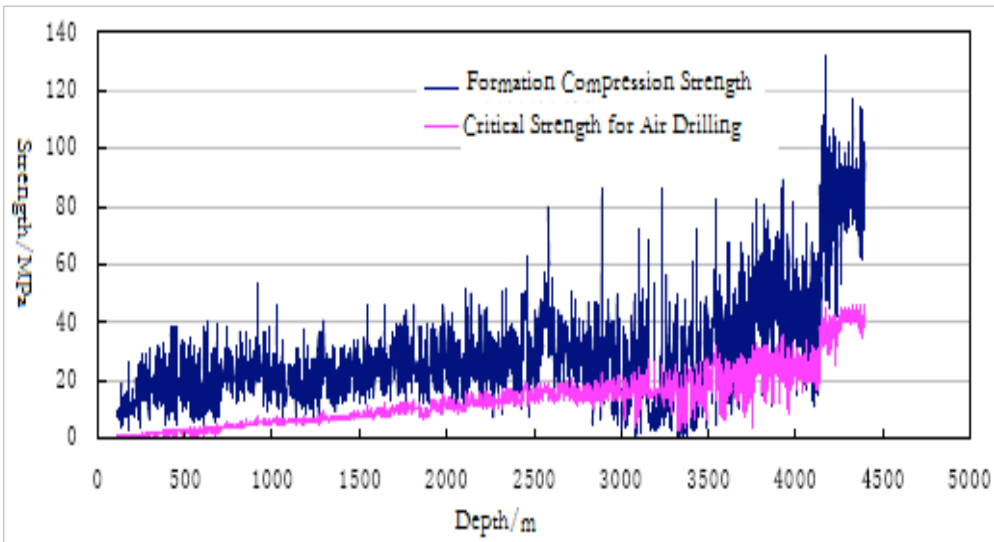

Figure 3: Wellbore stability appraisals for air drilling.

XuJiaHe1-3 abnormal high formation pressure, Ø 168.28mm liner for JiaLinJiang associated with possible rich sour gas and the final 6th interval with two options of running 114.3mm liner or open hole, which is depended on final pressure of LongTanZu. Besides, Ø168.3mm liner would be tie-back to the top with Ø 177.8mm plus 193.68mm combined casing string if abnormal pressure encontered as shown in Table **5**.

There are several features for unconventional casing program as shown in Figure **3**. At first, it can isolate four different pressure intervals between Ø508mm and Ø114.3mm, which leaves more space for preventing unplanned downhole. Secondly, three categories of flush casing without couplings reduce bit size in the upper section and beneficial to improve the drilling operation efficiency in a proper hole size. Finally, the liner hanging design provides a method for sovling the question of axial stress and casing grade limitation resulting from anti-sulfur requirement according to NACE standards. To conclude, it is an excellent experience to use “liner then tie back” for HTHP and sour gas wells as world famous gas field such as Khuff in Saudi [2].

It is a big challenge to perform work over job for rich sour gas wells and might have large impact on gas production once we kill the well and change the downhole tubing strings. So anti-corrosion casing and tubing should be optimized and used in these kinds of wells, where 80-110S (-SS or TS) casing and TPCQ and VAM-TOP gas [8] sealing connection are applied to ChuanDongBei area. It is highly recommended to use anti-corrosion casing below the permanent production packer meanwhile the subsurface safety valve also is necessary to be applied in the tubing string.

4. AIR DRILLING TO IMPROVE ROP

When it comes to air drilling, it is widely used to prevent formation damage in depleted and mature reservoirs and improve penetration rates in abrasive and hard rock formation. On the other hand, some disadvantages such as explosion when methan influx, mud logging challenges, cave-in or slough during water zone, well control risks at ultra-high pressure payzone, air compressor and booster limitation due to well pad space or cost concerns have negative impacts on its application [4]. So air and gas drilling feasibility study become a crucial step for decision to use it on special area except for economic and risk analysis.

The feasibility study includes the formation fluid analysis, which is regared water flow as the top priority on the condition there are some excisting oil and gas data on basis of geology program. Then wellbore stability is necessary to take into consideration.

According to adjacent drilling histories including wireline logging data, formation oil and gas show, mud logging curve et., most of intervals can apply air and nitrogen drilling due to few fluid and relative wellbore stability as referred to Figure **3**.

Furthermore, there are several factors that should be mentioned for air and nitrogen feasibility study.

1. Severe losses occurred in 53m with 1.02g/cm^3 bentonite mud such as well LG001-3, LG09, so the surface casing set to isolate then start air drilling in second interval(53-600m).

2. Although there were multi-pressures from ShaXimiao, LianGaoshan and DaAnzhai, the possible high pressure with water or gas happened in ZiLiujin [1] due to the lithology with shale, mudstone and sandstone. So the under balanced drilling will be replaced to mud drilling for safety factors. In another word, air drilling has been widely used in 311.2mm hole to the ShaXimiao about 3000m from 600m. The longer air drilling applied, the higher ROP achieved in this interval.

3. Because of its drawbacks, air and nitrogen drilling was not used in the formation, where the ultr-high pressure was likely to be encountered in XuJiahe, Changxin and Feixianguan, and where the rock was not self-supporting and might cave or squeeze to hole in ZiLiujin [1]. So, nitrogen drilling might be designed in Xujiahe with 215.9mm hole as at most 500m interval for improve penetration.

On top of that, there are some innovation technologies for gas drilling in ChuanDongBei area as below.

1. Air drilling got the maximum efficiency in shallow but big hole such as 444.5mm section. If the water influx was less than 0.5m^3/min, then some chemical powders were added into air for continuely drilling. Otherwise, transferring to mist or foam drilling when 0.5-7m^3/min water influx occurred. The ROP improved dramaticly from 7.83m/h, 8.4m/h to 9.77m/h as footage increased from 133.42m, 645.7m to 966m in well LG02, LG08 and LG10, when air hammar plus water-proof technologies became mature.

2. A series of approach were applied to shorten the time for air drilling transferring to mud drilling, where asphalt base mud along with reserve wetting agent was used to strengthen plugging capacity, condition mud cake and prevent cave-in. The time from stopping air drilling to start drilling in mud was 9d in well LG01, while average time was reduced to 2.8d and minimum 0.5d was obtained in well LG39, LG26 and LG13.

3. Dry well cementing technology was used to decrease well duration. The large hole size would bring out low cementing displacement efficiency and wait longer time for replacing mud then perform slurry cementing. Lab test and slurry recipe optimization on dry well cementing technology. The successful application indicated that at least 3d time was saved from average 8.3d per well to 5.3d per well for cementing in 339.7mm casing in ChuanDongBei field.

4. Some emerging downhole tools were developed for air drilling such as air hammar, featured stabilizer and air motor. As we know, air hammar was a useful tool for improving penetration rates while specialized stabilizer was developed for anti-deviation. Conventional stabilizer was design for mud flow rather than air move upward; by the time it caused big problems when few water influx into air drilling section. So innovative stabilizer was an emerging tool to prevent well deviation in less than 2°. Air motor also was designed and expecially used in directional drilling with air and nitrogen such as in well LG001-5, LG001-7.

The air and nitrogen drilling has been applied to almost all wells in ChuanDongBei field for more than 40 wells, accounting for 56% total footage and average ROP in excess of 10m/h increased by three times of mud drilling. Besides, seven new records for air/nitrogen/foam drilling have been achieved as the best ones in China as below:

- Dalily footage reached 575.13m in well LG10;
- One trip with air hammar BHA drilled 1744.9m in well LG10;
- Total footage for gas drilling was 3495.4m in well LG08;
- The longest nitrogen drilling was 820.56m in well LG02;
- Maximum ROP of air drilling reached 36.6m/h in well LG17;
- Maximum ROP of nitrogen drilling achieved 13.74m/h in LG01-XY;
- The dry cementing was used in the first time in well LG11.

5. ANTI-HT MOTOR PLUS FIT FOR PURPOSE PDC

Generally speaking, it is a big challenge for anti-HT motor in severe downhole environment when the tempreture is in excess of 120℃, because it is a contradiction system for a long life of the mud motor and high temperature resistance on basis of average 70h downhole operation time in ChuanDongBei field. Elastomer elements are the key points for anti-HT capability, so three categorizations of rubber have been chosen for the best performance in HTHP wells, HRN(Nitrile rubber), HSN(Hydrogenated nitrile rubber), THE(Modified special rubber) respectively as max. Anti-HT over 120℃, 150℃ to 177℃, accompanied with price ratio 1: 2.5: 10 based on HRN.

Several new anti-HT motor records were created in LonGang Field, which were Well LG002 as shown in Figure **4**, penetrated to 6,155m at 120°C bottom tempreture using total 155h, 577m footage; Well LG011, penetrated to 5,222m at 123℃ utilizing 183h, 522m footage and Well LG010, penetrated to 5,950m at 125℃ reaching 275h, 706.23m footage.

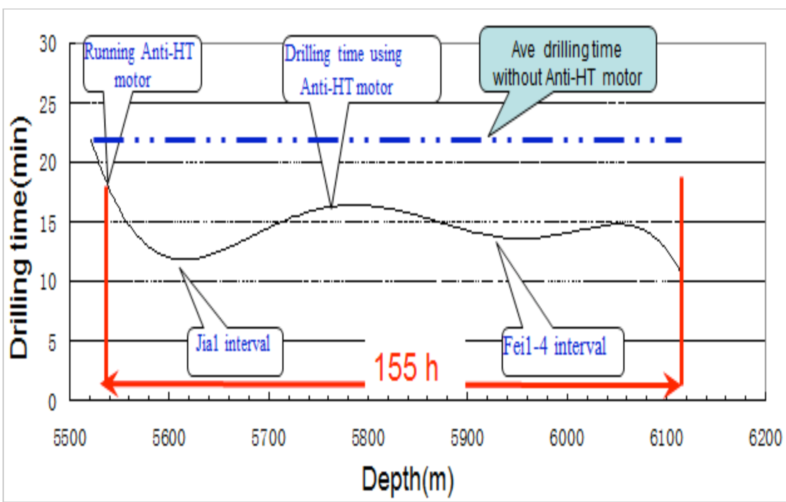

Figure 4: Drilling time log of anti-HT motor in Well LG002 (courtesy of beijing petroleum machinery).

Table 6: Results of Kd and PDC Optimization

Stratified Formation	Kd	Available PDC	Stratified Formation	Kd	Available PDC
ShaXiMiao	3.4-4.68	5 blades, 16-19mm	JiaLinJiang	5.4-6.7	Asymmetric blade
LiangGaoShan	2.69-5.86	5-6 blades, 16mm	FeiXianGuan	4.6-7.4	8 blades, 13mm
ZiLiuJing [1]	2.69-5.85	5-6 blades, 13-16mm	ChangXin	4.8-7.4	Helix blade
XuJiaHe	4.2-7.1	7-8blades, 13-16mm	LongTan	5-7.6	Fetured PDC
LeiKouPo	5.6-8.1	Negative rake in cutter design	XiXia	7-8.27	Equipped with back reaming bit tooth

Some intervals are very abrasive and high drillability, especially starting from LeiKouPo zone at the depth 5000m, where drill ability classification is even reached to 8.17 as shown in Table **6** along with chert nodule in ChangXin and Long Tan. Low ROP and short bit run times are typical for drilling in these formations, when roller bits and conventional PDC are not capable of getting expected footage. So, the challenges were sovled by to the newly designed fit for purpose PDC bit on the basis of complex geology condition and the past drilling performance as addressed with:

1. A latest cutter for maximum durability;
2. Back bake angles of cutting design to slow down wear propagation;
3. A matrix body for maximum erosion resistance.

It is noted that bit is not only depended on rock properties, but also rely on the downhole mud motor. The PDC bit should be optimized with available motor for the maximum ROP. The final cutting-edge PDC optimization and application were achieved better drilling performance that average ROP was 2.86m/h, improved by 50.5% compared with 1.9m/h historically when new PDC was used for 72.3% single well in the most of conventional HTHP mud.

6. ANTI-HT MUD ALONG WITH LOSSES PREVENTION TECHNOLOGIES

In terms of mud in ChuanDongBei field, polymer mud is used to surface interval and conditioned to transfer mud after air drilling, referred to Table **7**. However, the big challenges come from HTHP in target zone and severe losses in fracture carbonate formation. Anti-HT mud recipe has been conditioned based on deep interval recipe in Table **7** according to actual downhole tempreture.

On the other hand, severe losses are a big problem for drilling smoothly because there are some sour gases in the leakage zone. If a proper mud density to overbalance the contained gas formation pressure, ECD will be higher than loss pressure confficient as shown in Table **8**. While the safe drilling is the top priority in line with petroleum standards such as SY5087, which is 0.07-0.15g/cm^3 additional pressure density or 3-5MPa additional downhole pressure for drilling in the oil and gas zone. Basically, it is highly recommended to use the upper limit 0.15g/cm^3 for sour gas zone. However, it is impossible to apply extra 0.07-0.15g/cm^3 to mud density resulting from severe losses referred to Table **8**. So the only way to ensure safe drilling is a little additional downhole pressure to meet the standard requirement by the means of Managed Pressure Drilling (MPD).

Table 7: Drilling Fluid System and Format in ChuanDongBei Area

Interval	Drilling Fuild Recipe
Surface interval	(0.1-0.3%)PHP+0.2% CaO+(0.1-0.3%)KPAM+(5-8%)KCL+(2-3%)SEB(emulsify asphalt)+0.2% NaOH + 3% MSJ(polymer)
Transfering mud after air drilling	(50-60%)bentonite+(0.2-0.3%)KPAM+0.5% FA367+0.1% XY27+3% KHM+(1-2%)NRH(emulsify asphalt)+ 0.5% KOH+1-1.5% MSJ(polymer)+(0.5-0.8% CaO)+1% CMC-LVT(carboxymethyl cellulose)
Deep interval	(0.05-0.08%)PAM+2-3% SHR(resinol)+1-1.5% MSJ(polymer)+0.5% NaOH+(0.5-0.8% CaO)+ 4% SMP+4% SMC+(4-6%)lubric+(1-1.5%)H_2S scavenger+dilution+reservoir protection agent

Table 8: Severe Loss Statistic and Analysis in Well LG33

Well Depth(m)	Formation Pressure Coefficient	Mud Density(g/cm^3)	Annular Pressure Loss(MPa)	ECD(g/cm^3)	Loss Pressure Coefficient	Pressure Difference	Losses Statistic(m^3)
4595	2.06	2.13	3.96	2.21	2.2	0.01	43.4
4611	2.1	2.18	3.71	2.25	2.24	0.01	16.3
4639	2.13	2.21	2.25	2.24	2.22	0.02	170.5
4650	2.1	2.18	2.23	2.23	2.22	0.01	26.1

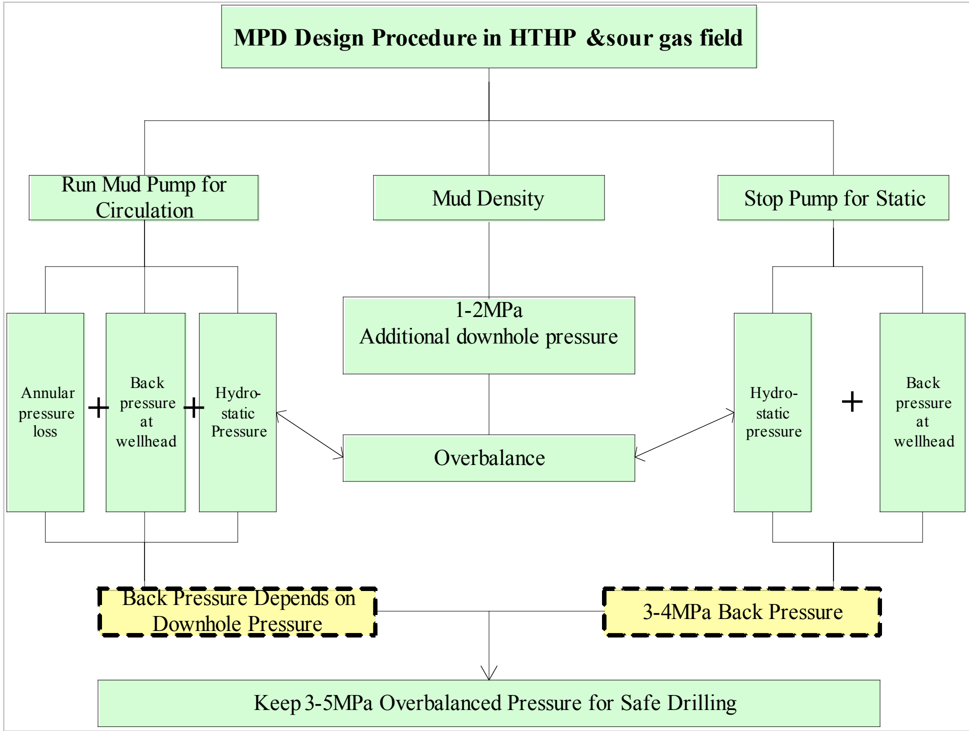

Figure 5: MPD design procedure flowchart.

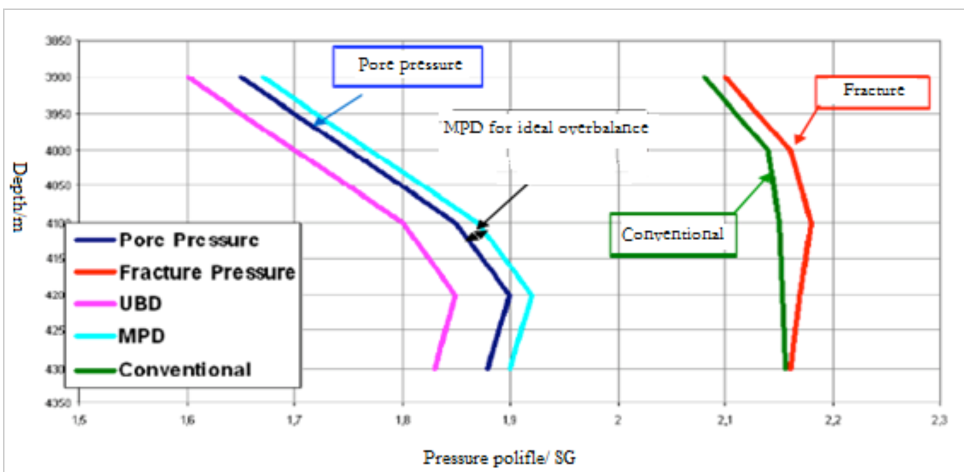

Figure 6: Pressure profile for MPD.

MPD is a useful method to control the downhole pressure in the middle of formation pressure and loss pressure to prevent severe losses and gas influx [7]. Elaborated MPD design procedure has been made as shown in Figure **5**, which reaches a goal of 3-5MPa overbalanced pressure. The applications indicate that 20-100psi extra downhole pressures have been achieved for drilling in leakage zone referred to Figure **6**. In addition, 10-140psi surface pressures are increased for 1.97-2.0g/cm^3 mud density during drilling in 4550-4700m, while 350-500psi surface pressures are necessary during making connections. On the whole, 2.08-2.2g/cm^3 equivalent circulation density has been kept to reach a near-balanced drilling, so there isn't any loss in Well LG35.

7. CEMENTING

Cementing challenges in ChuanDongBei field come from the severe losses due to narrow annular of small casing such as 127mm and 177.8mm, 50-70℃ large temperature differences resulting from 2000-3000m long isolated interval of deep well, gas channeling induced by HTHP and rich H_2S condition. In order to solve these kinds of problems, there are several cementing slurry systems that were developed including leakage proof system, anti-HT featuring large temperature difference system and corrosion resistant and antigas migration system.

Although density of cement slurry should be kept relatively low to avoid lost circulation problem during displacement of mud, it is not in effect sometime, especially for unconsolidated formation with fracture. Besides, it is recommended to add some lost circulation materials(LCM), like coarse or flake, even swelling fiber materials for mixing with the cement slurry.

In HTHP wells, the slurry becomes sensitive to high temperature as below:

1. Thickening time of the slurry is highly reduced;

2. Rheology of the slurry is decreased from plastic viscosity to yield viscosity.

It is critical that bottom hole circulation temperature for pumpig slurry and bottomhole static temperature for sheath set after stoping circulation are different impact on cementing quality. So, accurate prediction of bottomhole temperature should include circulation temperature and formation static temperature. Apart from provide fluid loss control additive, high resistant retarder is an important agent.

The cementing technology should not only sovle the challenge during placement of the cement slurry in the wellbore, but also provide a good cement sheath during the life of the well. Therefore, anti-corrosion slurry system has been developed for near to 10% H_2S extreme case [6]. Several factors are taken into condideration.

1. Rich contained silica materials are critical such as mico silica powder, coal ash with the exception of common silca flour;

2. Inner structures including porosity and permeability of cement sheath have directly impact on sour gas corrosion speed. Some emulsion agent, graphite and sulfide resistant material are highly recommended.

3. Ensure cement flours are totally disperse into water with enough batch mixing equipment and make sure the minimize of free water.

In general, the cement slurry recipe should consider class G with 1-2% expanded perlite, 1% anti-HT retarder, 0.4% fluid loss control agent along with 35-40% micro silica flour. Then, some special materials such as LCM are optional for different slurry systems in HTHP and sour gas ChuanDongBei field.

On top of that, dry well cementing technology has been widely used in ChuanDongBei area to save drilling cycle and cost, increase the slurry displacement efficiency after air drilling especially in the top hole. According to the size and depth of the hole during the dry well cementing, some slurry experimental evaluation methods of dry well cementing have been established accordingly, the cement slurry suited for dry well cementing was optimized and its performance was also evaluated for dozens of times. After that, a series of dry well cementing technologies including 2inch OD coiled tubing as an inner tube in the large casing have been applied successfully in the ChuanDongBei deep wells [5]. The max weight of casing was high up to 3600KN, the depth of cementing achieved about 4050m , which refreshed the depth and

Table 9: Statistic of Cement Quality in ChuanDongBei field

Slurry System	Well No.	Casing Size	Casing Shoe Depth(m)	Qualified (%)	Perfect (%)
Leakage proof	LG36	244.5mm CSG	4104	97.6	78.19
	LG21	244.5mm CSG	3118	100	97.87
	LG001-6	127mm Liner	6310	100	55.86
Large temperature difference	LG001-8	177.8mm Liner	4994	97.4	38.6
	LG11	177.8mm Liner	5636	99.4	99.3
	LG68	168.3mm Liner	6950	91.7	59.8
Anti-corrosion	LG36	127mm Liner	6956	100	67.1
	LG001-28	127 mm Liner	5076	100	71.3
	LG001-2	127mm Liner	6747	91.3	40.6

the casing weight of the cementing technology in empty hole in Sichuan Basin.

The above slurry systems have reached over 90% qualified rate according to Cement Bond Logging on dozens of wells referred to Table **9**.

8. BOP AND SOUR GAS MONITORING SYSTEM

The key points for BOP includes three basic factors from pressure rating, component selection of stacks and component arrangement. Due to ultr-deep depth and rich H_2S, the 10,000psi even 15,000psi pressure rating BOP have been used in ChuanDongBei area, which are composed of shear blind ram, fixed pipe ram, double pipe rams and annular preventer reffered to Figure **7** [8]. Shear rams or shear blind rams are necessary to install according to Chinese prescriptive regulation of deep gas well with greater than 5% H_2S. Additionally, on-site applications show the variable bore ram(VBR) is a kind of good ram for tapered string in HTHP wells as a usual connection of 5-$^1/_2$inch, 5inch and 3-$^1/_2$inch drill pipe. A rotating head device is recommended for increasing safery during drilling in high pressure contained with H_2S pay zone.

It is critical to perform pressure test BOP regularly each 14 days during drilling in the gas contained zone. Besides, there are some key points that should be given according to onsite application of ChuanDongBei field and related regulation.

- Minimum requirement is one ram, one double ram, one shear ram.
- Shear ram can't be used as a blind ram in case that blind ram is malfuction.
- Make sure at least one ram is below the shear ram.
- There are two choke lines with 103mm minimum ID.
- The pressure rate of kill and choke lines are matched with BOP stacks.
- There are 4-6 flow lines with at least 100m away far from wellhead.
- Anti-corrosive materials should be used not only for BOP, kill and choke line but also for gas separator. And the ID of separator is more than 1200mm, over 1.6MPa pressure rate and separate gas in excess of 200,000m^3/d.
- Short trip of 5 stands to ensure the hole is not swapped and a pill of scavengers should be spot on bottom.

Fixed H_2S detector should be set up in the cellar, substructure, drilling floor, bell nipple, mud ditch and some portable H_2S monitors would be taken as required along with flammable gas meter. The horn and light warning devices are connected to the H_2S analyzer to warn the crew in case that H_2S has been deteted accordingly. In addition, the Self-contained Breathing Apparatus should be equipped with each staff on the basis of per tour plus 15% back-up

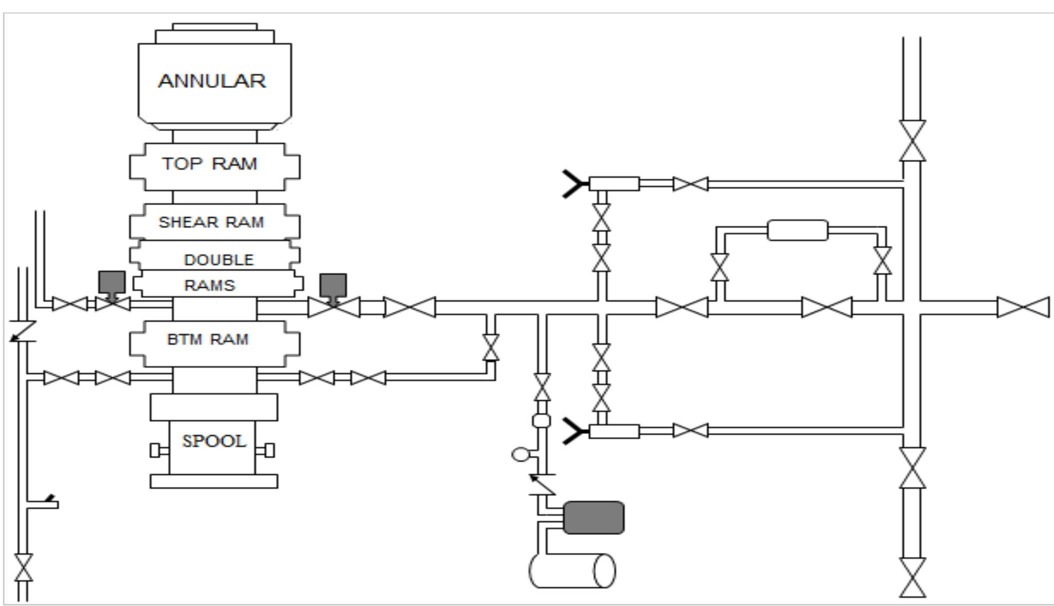

Figure 7: BOP stack and kill and choke maniford in ChuanDongBei.

quantities of total drilling crew, while at least five explosion proof fans, self-ignition tool and enough fire extinguishers must be ready for the emergency handling according to emergency plans and regulations.

9. EMERGENCY PLANS

It is critical that some emergency plans are prepared and trained for any unplanned situation, especially for drilling activities in sour gas field. There are three kinds of situation that must be taken into consideration as follows. (1) A slightly accident that is corrected immediately using standby equipment and tools on the rig site. (2) A serious mishap that is difficult to correct only utilizing the present facility and on-site personnel, then leading to toxic gas exposure. (3) A major mishap which causes uncontrolled blowout even explosion on rig site.

Different emergency response procedures should be taken on the basis of the categorization of accidents including but not limited to:

1. Organization Chart along with reporting procedures and phone number; authority of members in plans should be defined clearly and members have to know each one to whom report, even including the procedures to report to government or related medical and rescue organization.
2. Evacuation plans for on-site personnel in case that any toxic gas comes out largely;
3. Ignition orders after blowout, in the event that uncontrolled H_2S cause severe damage for personnel and environmental pollution.

One of lessons learned from L-16H natual gas blowout mishap of KaiXian County, which was failed to ignite on time, where total 243 deaths, 2,142 hospitalizations and 65,000 evacuations [3]. Toxic gas blowout must be ignited within 15minutes if there are residents not evacuated 500m far away from wellhead in accordance with new released standard for specification of ignition time.

In order to make sure the safe drilling, some strict regulations are attached to those normal emergency plans. For instance, emergency procedure of single well should be checked and approved by not only Design Dept, but also Top Management Burea in case that over 5% H_2S is expected in the single well as a high hydrogen sulfide well. After that, the procedure is registered in the local Government, accompanied with H_2S know-how training and evacuation drill for nerby residents regarding toxic gas exposure accordingly.

10. APPLICATION RESULTS

By means of scaled application of casing program optimization, gas and nitrogen drilling, anti-HT motor plus fit for purpose PDC, anti-HT mud, cementing and MPD, average drilling rate has been increased dramatically by maximum five times to accelerate the exploration and development in ChuanDongBei area. Take well LG01-XY as an instance, which was improved average ROP to 6.4m/h, extended the footage to 1713m in one specialized bit with air hammer with 145 days period, reached “zero pollution, zero harm, zero accident” achievement during H_2S interval, got premium cementing result and wellbore qualify in 2013.

Generally speaking, the well duration of over 6000m deep well has shortened to the time of 4000m well in the past according to statistics data of 11wells that were drilled by a series of key technologies in ChuanDongBei field. The average drilling cycle was 187.1 days, about 323 days less than that of conventional drilling technologies, as shown in Figure **8**.

Moreover, a series of drilling oprtation manual and guideline have been compiled including “Safe and rapid drilling procedures in ChuanDongBei area”, “Gas drilling Manual in Sichuan basin”, “Design scheme of drilling experts system” and “HSE guidelines in deep and HTHP containing sour gas fields” based on the safe drilling records in ChuanDongBei field. In a word, drilling deep safely and rapidly by the key technology and standard in ChuanDongBei have gradually become the representation drilling technology in HTHP contained sour gas fields of China.

11. CONCLUSIONS AND RECOMMENDATIONS

The exploration and development of ChuanDongBei field have proven the drilling technology optimization and innovation of deep and deep wells as a typical and successful case in HTHP and sour gas fields of China.

1. The six interval casing program of Longgan shows that increasing the hole sizes in the upper

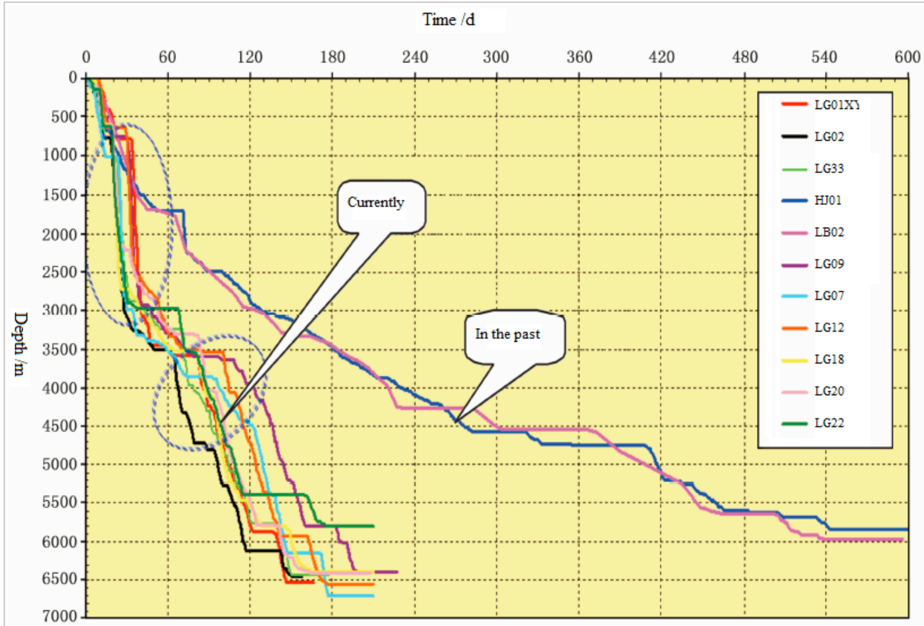

Figure 8: Well periods in ChuanDongBei field.

and non-HTHP section to make sure a contingency hole size to drilling desired TD.

2. As far as gas drilling goes, it is a key technology to improve ROP in ChuanDongBei field associated with feasibility study of single well and dry well cementing technique when seven new records have been obtained as the best one in China.

3. Complicated bottomhole conditions along with high temperature and pressure and sour gas have promoted the research and development of latest technologies such as anti-HT motor, featured PDC bit, MPD and dry well cementing, which provide a series of onsite application experience in ChuanDongBei field.

4. H_2S monitoring, strict regulation and emergency plan learned from sour gas fields in Sichuan have bought out an enough barrier for drilling smoothly in high risk area.

5. The paper has presented an integrated drilling case of unltra-deep HTHP contained sour gas fields, which is easily used for a technical reference as drilling in similar geologically complicated sour gas fields.

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NOMENCLATURE

D	Depth, m
De	Desentiy, g/cm^3
P	Pressure, MPa
T	Temperature, ℃
Tt	Time, d
H	Hour, h
OD	Outer diameter, mm
ID	Inner diameter, mm
I	Iron concentration, mg/L
S	Total salinity, g/L

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