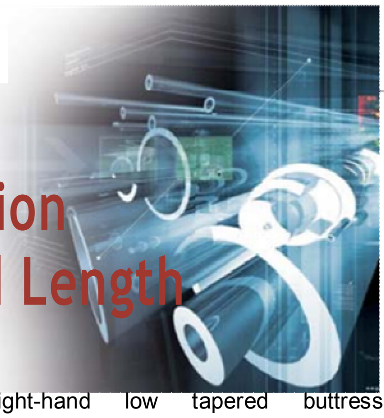

Prospects of Aluminum Drill Pipe Application in Drilling of Horizontal Wells of Extended Length

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PROSPECTS ALUMINUM DRILL PIPE APPLICATION IN DRILLING OF HORIZONTAL WELLS of EXTENDED LENGTH

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Keywords: aluminum alloy, buckling, drill pipe, horizontal well

Year by year the extent of drilling of wells with long horizontal site is increasing both in domestic and in foreign drilling practice.

In 2015 NK Rosneft JSC being a part of Sakhalin-1 Project Consortium successfully completed the drilling of the most extended horizontal well (HWGL) 0-14 [1] drilled in extreme south east end direction of Chaivo field using Orlan drilling platform. The length of borehole is 13,500 m and horizontal borehole section is 12,033 m.

As field experience of HWGL drilling shows the main obstacles in drilling of such wells are:

– difficulties of bringing axial stress and torque moment to drilling instrument while reducing resistance force of drill stem (DS) motion and rotation and while its longitudinal stability is lost;

– problems of horizontal hole cleanup of drilling cuttings (mud);

– progressive wear of tool joints and drill pipe (DP) bodies;

– problems of hydraulic energy supply to bottomhole motor and assurance of required parameters of well cleanout (consumption and pressure).

The review of domestic and foreign process engineering as well as techniques applied for HWGL drilling allows for the conclusion that sustainable drill stem (DS) assembly and operational characteristics of drill pipes are the drivers affecting efficiency of drilling of such wells.

Use of combined DS including lightweight drill pipes (LDP) allows us both to reduce loads sufficiently on lifting parts of drilling rigs in HWGL drilling and extend the length of horizontal hole (HH) of such wells. [2].

Main requirements to LDP design are available in ISO-15546:2007 "Aluminum Alloy Drill Pipes for Petroleum and Gas Industries", international standard, being effective since 2007, and GOST 23786-79 "Aluminum Alloy Drill Pipes".

LDP consists of aluminum pipe and steel joint parts screwed on its ends.

The right-hand low tapered buttress shouldered thread of TT type with conical stabilizing groove is used to connect tool joint to its aluminum pipe. Ensured radial interferences along the thread, stabilizing groove and shouldered connection are provided by "temperature" method of tool joint and pipe assembly performed per special technique. Conical stabilizing groove within the connection partially relieves the thread from cyclic bending stresses, and, therefore, increases the fatigue strength and joint reliability.

Due to this design, we achieve the higher reliability of all LDP couplings under cyclic loads that enables us to perform process operations with tool rotation efficiently and carry out the forced releasing of the stuck pipes.

LDP billets are manufactured from corrosion-resistant high-strength D16T or 1953T1 aluminum alloys through hot extrusion method. They have thickened internal upset ends with pipe thread of TT type screwed. From the box, the pipe is provided with elongated internal collar that enables safe casing slip or spider.

Standard LDP design assures stable nominal external diameter of billets. Besides, aluminum drill pipes of the following modifications can be delivered:

In 2015 NK Rosneft JSC being a part of Sakhalin-1 Project Consortium successfully completed the drilling of the most extended horizontal well (HWGL) 0-14 [1] drilled in extreme south east end direction of Chaivo field using Orlan drilling platform. The length of borehole is 13,500 m and horizontal borehole section is 12,033 m.

- LDP-P with protector designated for protection against wearing of main pipe body, higher longitudinal DS stability as well as its better centralization in the bore hole;
- With spiral finning of LDP-S external surface designated for better hole cleaning of drilling cuttings and higher longitudinal stability in HWGL drilling. The main part of external pipe surface is thickened by external right-hand spiral finning.

The main advantages of aluminum DP are resulted from specific physical and mechanical properties of D16T or 1953T1 aluminum alloys shown in Table 1.

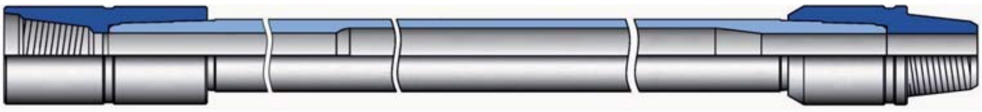

Fig. 1. LDP – standard design

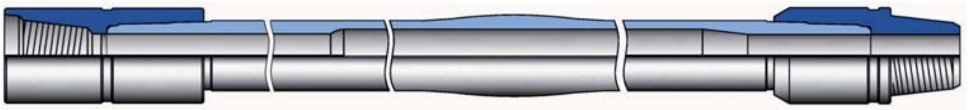

Fig. 2. LDP-P – design with protector collar in the center of a pipe.

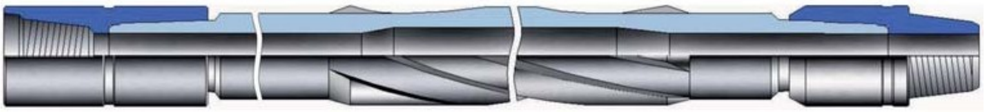

Fig. 3. LDP-S – design with spiral finning of the external surface of a pipe.

While drilling HWGL, almost the entire DS is subjected to compression strain meanwhile in drilling of vertical and directional wells with small inclination angles the DS body is expanded.

The most adverse consequence of compression load effect is the local loss by the drill stem of longitudinal stability incipient in sliding drilling, i.e. without drilling tool rotation in the form of plain sine wave transforming into helix through the increasing compression load; it is so-called “buckling” of type I or II correspondingly.

While drilling with DS rotation and compressive longitudinal and centrifugal transverse loads combination effect, the same forms of “buckling” are implemented in the form of varying plain sinusoidal or dimensional helical “S-turn” planetary revolving around its own axis and axis of the well.

Increased resistance force and torques in HWGL are formed by a load forcing the DS elements to the walls of the well and without buckling they depend firstly on drill stem deadweight with regards to its weight reduction in drilling mud. The hazard of “buckling” is higher in nonrotating DS as far as during rotation the longitudinal resistance forces are significantly lower.

Protector of aluminum drill pipes as well as distance reduction between tool joints and protector increase the pipe longitudinal stability significantly. Calculations demonstrate that finning of external surface of aluminum pipe contributes to higher longitudinal stability by reinforcement and length reduction intensifies this effect. As the “buckling” start criterion is DS longitudinal stability loss in the form of sine wave, then in drilling practice it shall be followed that the allowed effective compressive load in different DS cross sections was lower than the critical load of sinusoidal buckling the excess of which causes the significant increase of DS contact force with the hole walls.

The review of domestic and foreign process engineering as well as techniques applied for HWGL drilling allows for the conclusion that sustainable drill stem (DS) assembly and operational characteristics of drill pipes are drivers which affect efficiency of drilling of such wells.

DS stability loss in HW depends on pipe stiffness and weight in liquid and also on general radial space between the DS and the hole wall.

Based on the current views, DP may lose longitudinal stability on the horizontal borehole section in the form of sine wave under the effect of critical compressive load P $_{cr}$, the value of which is evaluated [3, 4] by the formula below:

$$P_{cr} = 2K_L\sqrt{\frac{EIw}{\delta}}, \qquad (1)$$

where E is Young`s modulus of pipe material; I is axial moment of inertia across the cross section of the main pipe body; w is the weight of pipe linear meter in drilling mud; δ is general radial space between the hole wall and DS;

Table 1. Comparative physical and mechanical properties of aluminum alloys and steels

Pipe Material	Parameters of physical and mechanical properties of DP material				
	Density	Modulus		Coefficient of linear expansion	Minimal Yield strength
		Young	Shear		
Dimensions	kg/m^3	MPa	MPa	1/°C	MPa
Steels for DP	7850	21,0x104	7,9x10^4	11,4x10^{-6}	380-1030
D16T Alloy	2780	7,1x104	2,7x10^4	22,6 x10^{-6}	325
1953T1 Alloy	2780	7,1x104	2,7x10^4	22,6 x10^{-6}	480

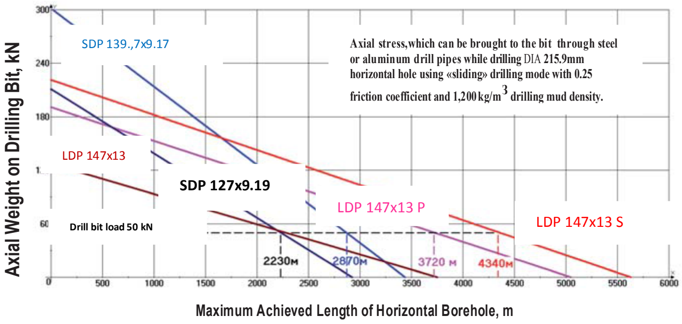

Fig. 4 Maximum achieved HW length and ∅215.9mm bit load ratio in well sliding drilling and 1,200 kg/m^3 drilling mud density with the use of uniform-sized sections, assembled of LDP or SDP.

K_L is coefficient of pipe length taking into account the distance between pivotal sections of DP.

Theoretical researches by Akvatik CJSC demonstrated that for practical evaluation of buckling occurrence in compressed DP the value of K_L depending on the working pipe length and protector availability may change within the range of
$1.0 \leq K \leq 1.5$.

While drilling with drilling stem rotation and compressive longitudinal and centrifugal transverse loads combination effect the same forms of “buckling” are implemented in the form of varying plain sinusoidal or dimensional helical “S-turn” planetary revolving around figure axis and well axis.

In Table 2, as an example, the calculated values of critical forces of sinusoidal “buckling” for the most applicable in HWGL drilling aluminum drill pipes of 147x13 LDP standard size with 12 m working length including protector (P) design, and also 147x11 LDP of 9.3 m in length with external spiral finning are shown. In the same table, critical forces of sinusoidal “buckling” for steel drill pipes (SDP) of the similar standard sizes are compared. All calculations apply to HW drilling with ∅215.9 mm drill bit with drilling mud density equal to 1,200 kg/m3.

147x13 LDP where Young modulus and weight per unit length in drilling mud are lower than of those SDP with similar standard sizes working in the same conditions may lose longitudinal stability under smaller values of compression loads. Protector implementation contributes to 50% increase of their buckling resistance and spiral finning increases the effect through the achieved level of longitudinal stability of these pipes slightly exceeding of 127x9.19 SDP.

However, the main effect of LDP inclusion into the DS assembly instead of SDP during HWGL drilling relates to lower resistance in transfer and rotation of DS in HW that are fairly enough illustrated by the example below.

While drilling HW with axial weight on drilling bit G_b in a sliding mode, i.e. without DS rotation, the maximum borehole length L_{max} which can be achieved without DS longitudinal stability loss can be defined by the formula below:

$$L_{max} < (P_{\text{кр}} - G_{\text{Д}})/(f\,w), \qquad (2)$$

where f is generalized DS drag coefficient.

In Fig. 4 calculated by the formula (2) maximum length L_{max} and ∅215,9 mm bit load Gb relations are presented, they can be achieved in sliding mode without DS longitudinal stability loss with the use of DP given in Table 2. In calculations the generalized open hole resistance (friction) coefficient was taken equal to f=0,25.

As it follows from the charts in Figure 4 using sliding drilling with the same axial weight on ∅215,9 mm drilling bit with the use of LDP fitted with protector or with external spiral finning it is possible to increase the maximum HW length if DS longitudinal stability condition is followed.

The charts show that for HW of small design lengths, the use of SDP allows us to apply higher axial loads to the drill bit. However, with greater lengths such advantage is referred to aluminum DP.

Physical explanation of the resulted ratios is based on the fact that LDP lighter than SDP of the similar standard sizes with well deepening have lower drag losses; it enables retention of resources of compression strain to maintain the required drill bit load.

Problems of efficient HWGL clean-up of drill cuttings are triggered by intensive mud accumulation on a ledge wall of a horizontal well that may cause trough-shaped galling and correspondingly to a sharp increase of resistance (friction) coefficient to DS movement and rotation up to its hanging up in the well hole and further drilling or round-trip operation impossibility.

Based on the recommendations [5], the key factors of efficient HWGL clean-up consist in DS rotation frequency, drill mud consumption and rheological parameters, external DP surface configuration, and the use of back reaming practice which assumes rotatory DS descent and

Table 2. Calculated critical loads of sinusoidal “buckling”

Drill pipe standard size	*Drill pipe material*	*Critical force of sinusoidal buckling, kN*
LDP 147x13	*D16T or 1953T1 aluminium alloys*	*127.1*
LDP 147x13П	*D16T or 1953T1 aluminium alloys*	*190.1*
LDP 147x11C	*D16T or 1953T1 aluminium alloys*	*221.5*
SDP 127x9.17	*Steels of all strength groups*	*210.9*
SDP 139.7x9.19	*Steels of all strength groups*	*301.5*

Problems of efficient HWGL clean-up of drill cuttings are triggered by intensive mud accumulation on a ledge wall of a horizontal well that may cause trough-shaped galling and correspondingly to a sharp increase of resistance (friction) coefficient to DS movement and rotation up to its hanging up in the well hole and further drilling or round-trip operation impossibility.

Figure 5. Pilot batch of LDP 103x11S at Tatneft JSC

ascent with simultaneous drill mud circulation.

It may be considered established that the best frequency depends to the fullest extent on P - HAR(Pipe-Hole-Area-Ratio) parameter equal to borehole and DP cross sections areas ratio:

$P\text{-}HAR=(Dh/Dp)^2$,

where: Dh, Dp is diameters of borehole and DP correspondingly.

The optimal frequency N_{opt} of DS rotation is recommended to be choosen on the basis of P-HAR parameter following the rule:

If P-HAR>6.5, then N_{opt} = 150-180 rpm,

If 3.25<P-HAR<6.5 then N_{opt} =120-150 rpm,

If P-HAR<3.25, then N_{opt} =90-120 rpm.

Hole cleaning efficiency can be increased by the use of drill mud flow energizer in the off-center radial HW space, for example in the form of DP with spiral finning of external surface or so-called Hydroclean^{TM} developed by VAM Drilling [7].

The functional principle of Hydroclean^{TM} or DP external finning is that bit cuttings brought up from the ledge wall of HW by blades rotating simultaneously with DS are falling into moving turbulent flow of drilling mud and are carried out to certain distance after which such cuttings are either picked up by the energizer generated flow or settle on the well wall.

Minimum required circulation rate Q_{min} is referred to each standard DP size for acceptable HW clean-up depending on drill-string borehole annulus configuration, drilling mud rheological parameters, bit cuttings buoyancy features, pipe rotation frequency, and external finning availability and parameters.

The pilot lot of LDP 103x1-S shown in Figure 5 was manufactured and tested by Tatneft JSC in drilling of HW showed good results in terms of cutting transport.

Increased cutting transport in conjunction with stable rotation torque has confirmed the efficiency of LDP 103x11S used for improvement of hole cleaning of drill cuttings.

Progressive wear of external surface of DP supporting elements (tool joints, protector, and DP body) in the course of HWGL drilling and round-trip operations is of abrasive nature and controlled by pressing forces applied to DS from hole walls. These forces in HW first of all depend upon DP weight in drilling mud as well as axial load on the bit, centrifugal forces in rotation of DS located off center, buckling, and other factors.

The evaluation of DP surface supporting elements wear rate which is widely agreed that proportional to friction power can be pursuant to the formula:

$R= C_w T fV$ (4)

where: R is DP surface supporting elements wear rate which is measured as the rate of external diameter loss, loss of wearable part size and mass;

T is normal force pressing DP supporting element to the wall of a well;

f is generalized coefficient of friction on the wearing surface;

V is linear speed of DP supporting element slipping against the well wall with DS progressive motions and rotations;

C_w is size factor specifying tool joint or pipe material resistance to abrasive wear.

Regardless of centrifugal forces and buckling, T values with account of DP lighting in drilling mud for SDP, LDP, and LDP-P pressing forces on the horizontal area of the well may be defined in the following way:

$T_{SDP} = 1/2\ q_{sdp} L_p\ (1 - \rho_m / \rho_{st})$ for SDP, with two supports at the tool joints;

$T_{Al} = 1/2\ q_{Al} L_p\ (1 - \rho_m / \rho_{eq})$ for LDP with two supports at the tool joints; (5)

$T_{Al} = 1/3\ q_{Al} L_p\ (1 - \rho_m / \rho_{eq})$ for LDP – P with two supports at the tool joints and one support at the protector collar in the center of a pipe.

In formulas (5) the following designations are used:

q_{sdp}, q_{Al} are weight in air of 1m of SDP or LDP correspondingly;

L_p is working DP length;

ρ_{st}, ρ_{eq}, ρ_m are steel density, equivalent density of aluminum pipe assembled with the steel tool joint and drilling mud density correspondingly.

Ratios (4) and (5) provide for comparative evaluation of relative wear rate of pipe tool joints and body for aluminum and steel DP with the same working length and operating in the same geological and process conditions of straight horizontal borehole section drilling.

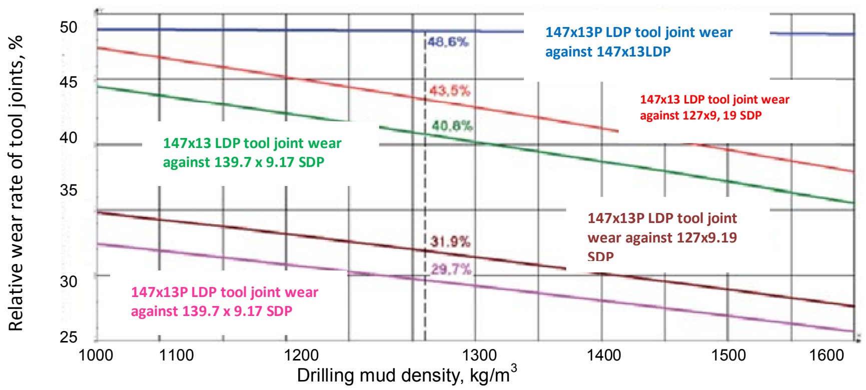

Figure 6. Interrelation of relative wear rate of LDP and SDP tool joints and drilling mud density while drilling HWGL

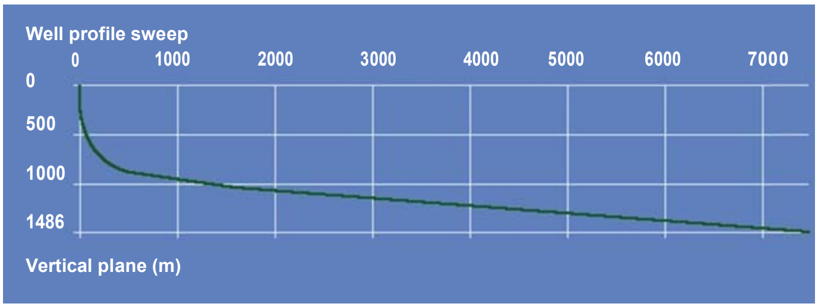

Figure 7. Borehole No.277 design profile in drilling for PS-168.3 mm.

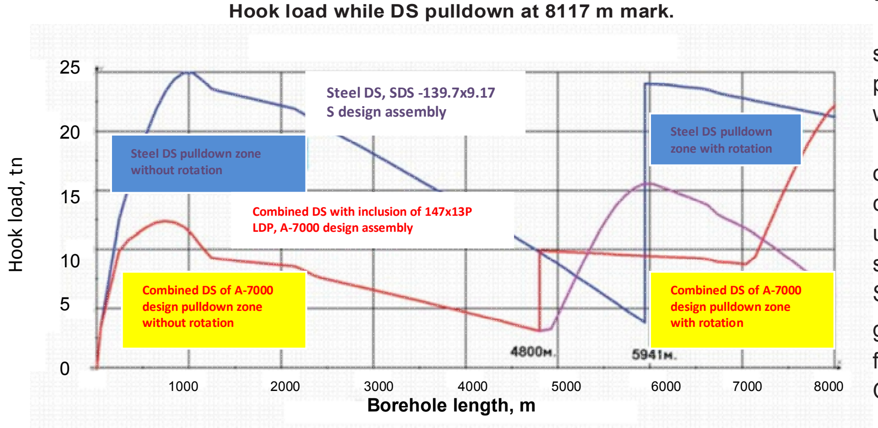

Рис. 8 Comparative dynamics of hook load variation in depth in A-7000 and S assemblies of DS pulldown at 8117m design reference mark.

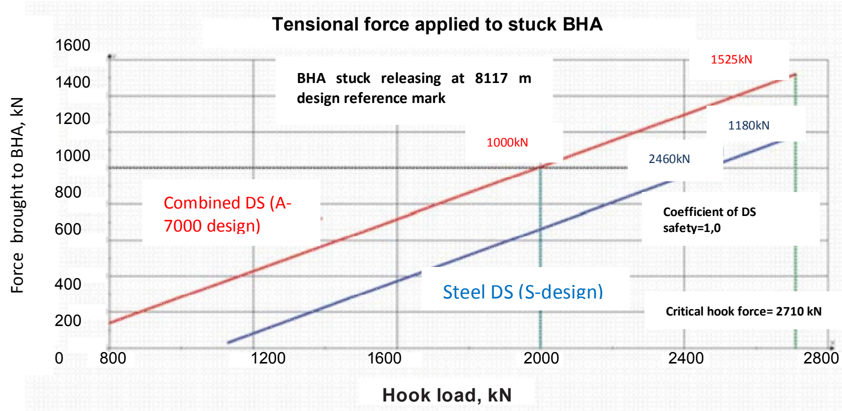

Figure 9 Comparison of tensional forces to be applied to BHA gummed in at 8117 m design reference mark through steel or combined DS assemblies.

In Figure 6, as an example, the charts calculated per the formulas (4) and (5) show the relative wear rate of tool joints for LDP 147x13 (P), SDP 127x9.19 and SDP 137.9x9.17 depending on the density of drilling mud in HWGL drilling. The charts analysis in Figure 6 results in the following:

- LDP 147x13P fitted with protector have the lowest wear rate of tool joints, and the tool joints of SDP 139.7x9.17, the heaviest of the compared DP, more than others are exposed to wear;

- With regards to the greatest lightening of lightweight drill pipes compared to the steel ones, as far as drilling mud density is increasing, the wear rate of LDP tool joints compared to SDP is dropping. For example, with drilling mud density of 1000 kg/m^3 LDP 147x13P tool joints wear rate compared to SDP 139.7x9.17 is 34.8%, while with drilling mud density of 1600 kg/m ^{3} this parameter is going down to 27.5%.

- LDP 147x13 tool joints wear rate comparatively to LDP 147x13P actually remains unchanged as the buoyancy of aluminium DP slightly depends upon the density of drilling mud.

As for LDP147x13S, spiral finning of which increasing the bearing face in HW contributes to more intensive tool joints pressing forces relief and reducing the intensity of their abrasive wear thereby.

It also should be noted that the most vulnerable supporting element of drill pipes LDP 147x13P is the protector as aluminum alloys resistance to abrasive wear is worse than of steel.

The results of calculations performed with the use of 3 – DDTBH program are given below. These are the calculations of LDP 147x13P of 1953T1 alloy efficient use being a part of combined DS in comparison with the steel assembly designed by Exxon Mobil combined of SDP-5.5" x 21.90# (139.7x9.17) of steel G-105 strength group while rotary cutting with PDC-∅ 215.9 mm drill bit for PS–168.3 mm HWGL No. 277 production string at Odoptu-More field (Sakhalin island).

The source data for comparative calculations are derived from the materials provided by RN-Burenie LLC. Design borehole profile is shown in Figure 7, the full borehole length is 8117 m, vertical depth is 1486 m, horizontal displacement is 7480 m.

In calculation, the friction coefficients in interacting pairs were taken as equal to 0.20 in cased borehole section; and 0.25 in open hole.

The main rated parameters of rotary cutting at 8117 m design reference mark are as follows: DS rotation frequency is 120 rpm; bit weight is 120 kN; and drilling mud density is 31.8 l/sec.

BHA for the compared DS assemblies was assumed as identical and consisted of a drill bit, rotary steerable system, calibrator, MWD for visual and instrumentation control of 3D position of borehole, non-magnetic drill pipes, non-magnetic drill collars, drilling hydro mechanical jars, adapters. The total BHA length was assumed equal to 102 m and the full weight was 95.5 kN.

Steel DS assembly (S design):

BHA + SDP – 139.7 x 9.17 of G-105 steel, 8015 m in length.

Combined DS assembly (A-7000 design):

BHA+LDP – 147x13P of 1953T1 aluminum alloy, 7000 m in length + SDP – 139.7 x 9.17 of G-105 steel, 1015 m in length.

A – 7000 assembly is composed under the condition of maximum lightening of DS to achieve significant decrease of its stress condition and service loading on a drilling rig.

In Table 3 and in Figures 8 and 9 some calculation results of the main parameters of compared DS assemblies used for No. 277 HWGL drilling are demonstrated.

In Figure 8 the diagrams are given to show hook load variation in pulldown of compared DS assemblies to 8117 m design reference mark.

In Figure 9 the comparison of tensional forces to be brought to BHA gummed-in at 8117 m design reference mark through steel or combined DS assemblies is shown.

Key factors of efficient HWGL clean-up consist in DS rotation frequency, drill mud consumption and rheological parameters, external DP surface configuration, and the use of back reaming practice which assumes rotatory DS descent and ascent with simultaneous drill mud circulation.

You can see from Table 3 that inclusion of 147x13P_1953T1 LDP aluminum pipes 7000 m in length into combined DS assembly instead of SDP-139.7 x 9.17 of G-105 steel in drilling at 8117 m design reference mark could cause double reduction of total DS weight in drilling mud. Due to this lightening and corresponding decrease of rotating resistance and drilling equipment drag, the rotation torque at the rotary drive and the hook load would reduce as much as 1.7 times in DS pulling out. Herewith the minimum safety coefficient of the whole DS would increase for 50 to 70%.

Due to certain increase of flow area the use of aluminum DP instead of SDP would reduce the stand pipe pressure down to 6.4 MPa.

As it follows from Figure 8 and Table 3 combined DS pulldown without rotation is possible down to 4742 m in depth, and the steel one is down to 5941 m. Rotation ensures for both assemblies smooth pulldown of drilling equipment to the design reference mark, however, for the steel DP pivoting it is required to apply the rotation torque as much as twice for the combined drill stem.

As it follows from Figure 9 with the same combined DS hook load up to BHA stuck-off at the design reference mark it is possible to apply the higher tensional strain. For example, at hook load of 2000 kN at combined DS 1000 kN strain is applied to BHA and 630 kN at the steel one.

Table 3. Comparative design parameters of stress strained DS

List of main design parameters of stress strained DS	DS assembly designs	
	S-steel	A-7000, combined
1.DS weight in air, kN	3065	197.8
2. DS weight in drilling mud, tnf	2565	130.9
Rotary bit drilling at 8117m design reference mark		
3. Hook load, kN	280	19.8
4. Rotation torque at rotary actuator, kNm	49.6	28.6
5.Minimum safety coefficient along DS length	1.94	2.89
6. Pressure loss, MPa	26.2	19.8
DS pulling out from design reference mark		
7. Hook load, kN	1140	65.8
8. Total drag, tnf	69.1	30.1
9. Minimum safety coefficient along DS length	2.41	4.22
10. Maximum DS extension, m	7.865	10.360
DS pulldown to design reference mark m		
11. Maximum pulldown depth without rotation, m	5941	4742
12. Hook load, kN	21.1	23.0
13. Rotation torque at DS rotary actuator, kNm	41.7	20.2

This significant technological advantage specified by the use of aluminum DS becomes especially relevant both for forced releasing of the stuck pipes and when back reaming is required while HWGL drilling.

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