DRILLING STRING DESIGNS FOR DEEP DRILLING OPERATIONS

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Before 1950, drilling strings contained few drill collars, and the hole depth was shallow enough so that grade-E drill pipe easily satisfied most requirements for drilling and drill-stem testing. In 1957, when Great Western Drilling Company drilled the Phillips Petroleum Company Montgomery A-1 to 23,400 feet, engineered drilling strings became necessary. Between 1957 and the time the API published RP7G, drilling-string design was a daily necessity for drilling engineers to avoid operational problems and to satisfy contractural requirements. Each engineer designed his drilling strings based on his knowledge and training, and the procedures were based on techniques previously used in the design of casing. In the vacuum created by operational necessity and the lack of API recommended practice we developed a philosophy and two report forms for our use which have worked well. Examples of the use of these report forms and a comparison between our philosophy and the API RP7G recommended approach are presented in this paper.

API Recommended Practices 7G, 7th Edition, April 1976, Section 5.1 states that "The following design criteria must be established:"

a. Anticipated total depth with this string.
b. Hole size.
c. Expected mud weight.
d. Desired Factor of Safety in tension and/or margin of overpull.
e. Desired Factor of Safety in collapse.
f. Length of drill collars, OD, ID, and weight per foot.
g. Desired drill pipe sizes and inspection class.
Section 5.3 reads as follows.

> The design of the drill string for static tension loads requires sufficient strength in the topmost joint of drill pipe to support the submerged weight of all the collars, stabilizer, and bit. It is important to note that the tension values shown in the tables are the theoretical values based on minimum areas, wall thickness, and yield strengths. The yield strength as defined in API specifications is the stress at which a certain total deformation has occurred. This deformation includes all of the elastic deformation as well as some plastic (permanent) deformation.

The specific description of the amount of deformation and stress is in API specification 5A Section 4.2.

API RP7G states, "Slip crushing is not a problem if slips and master bushings are maintained." We believe that this statement is essentially true if the drilling rig is equipped with solid master bushings and 16-1/2-inch long slips in good condition.

We design our drilling strings to have 100,000 pounds pull above the minimum yield strength for the class of pipe in service. We use the minimum yield values and the adjusted pipe weight in lb/ft as reported in RP7G. A drilling string designed this way has additional strength not considered because the yield strength of most pipe is closer to the nominal pipe strength, and the remaining wall in most drill pipe exceeds the minimum requirements. The API points out that if pipe is loaded to the minimum yield value, some permanent stretch may occur; the API Recommendation is to limit the design load to 90 percent of the minimum yield or to use a specific factor recommended by the pipe supplier. RP7G reads as follows.

> The selection of the proper safety factor and/or margin of overpull is of critical importance and should be approached with caution. Failure to provide an adequate safety factor can result in loss or damage to the drill pipe, while an overly

TABLE 1—DRILLING STRING AND WIRE LINE CAPACITY PROGNOSIS, SUMMARY OF API EXAMPLES 5, 7

MUD WEIGHT 10 #/GAL
BUOYANCY FACTOR 0.847

HOOK LOAD WIRE LINE SAFETY FACTOR
23495 NOM. STRENGTH 1 1/4" EIP= 159800
ACCUM WT 8 LINES 10 LINES 12 LINES
PLUS TRAV 0.1469 0.1224 0.1062
EQUIP 1,087,815 1,305,555 -

DESCRIPTION																
NUMBER	LENGTH	OD	THREAD TYPE	ID	NOM. WT.	GRADE	WT/ FT	WEIGHT IN AIR	WT. IN FLUID	ACCUM WT.	MIN YLD STRENGTH	OVER-PULL	HOOK LOAD ACCUM WT PLUS TRAV EQUIP	8 LINES	10 LINES	12 LINES
27	810	6 1/4	4 1/2 XH	2 1/4	90	-	90	72900	61746	61746	938125					
244	7564	4 1/2	4 1/2 XH	3 1/4	16.6	E	17.84	134942	114296	176042	260100	84058	107553			
117	3627	4 1/2	4 1/2 XH	3	16.6	X95	18.19	65975	55881	231923	418700	186777	255418	4.26	5.11	
	12000							273817	231923							

TRAVELING EQUIPMENT LIST

ITEM		CAPACITY	WEIGHT
TRAVELING BLOCK	545 H 350	700000	9380
HOOK	4300	600000	6000
SWIVEL	P-400	536000	4570
ELEVATOR LINKS	2 3/4 x 108	700000	870
ELEVATORS	4 1/2 MGG	450000	495
KELLY	5 1/4 HEX	960000	2180
			23495

CALCULATED OVERPULL USING 90% OF MINIMUM TENSILE YIELD STRENGTH
260100 x 0.9 = 234090#
234090 - 176011 = 58079# OVERPULL

conservative choice will result in an unnecessarily heavy and more expensive drill string. The designer should consider the overall drilling conditions in the area, particularly hole drag and the likelihood of becoming stuck. The designer must also consider the risk which is acceptable for the particular well for which the drill string is being designed.

In deep drilling operations this information is considered by the operator, and a minimum overpull is specified in the contract. From an operational standpoint it is very important that the strength of the drilling string be described by overpull available and not by its safety factor. The reason for this precaution is that a driller cannot read a safety factor from his weight indicator.

Included are some design sheets to illustrate the format our company uses to design drill pipe strings to be used for drilling and for drill stem tests. These sheets are planned to eliminate omissions in logic and to reduce errors in calculations.

Table 1 shows the solution to the example problem 5.7 in API RP7G. The traveling equipment list is about what a rig doing 12,000-foot work would need, and it is included to demonstrate how the form shows the driller what his hook load should be at the top of each weight and grade of drill pipe and to show what the wire-line safety factor should be at total depth. Normally, we use the physical properties of drill pipe which we find in the tables in RP7G. When one encounters pipe which is not in the tables in RP7G, as in the API example, the adjusted weight of the drill pipe must be calculated. At this

TABLE 2—DRILLING STRING AND WIRE LINE CAPACITY PROGNOSIS, COMPARISON TO API EXAMPLE 5, 7

MUD WEIGHT 10 #/GAL
BUOYANCY FACTOR 0.847

HOOK LOAD WIRE LINE SAFETY FACTOR
23,495 NOM. STRENGTH 1 1/4 EIP= 159,800
ACCUM WT 8 LINES 10 LINES 12 LINES
PLUS TRAV 0.1469 0.1224 0.1062
EQUIP 1,087,815 1,305,555

DESCRIPTION																
NUMBER	LENGTH	OD	THREAD TYPE	ID	NOM. WT.	GRADE	WT/ FT	WEIGHT IN AIR	WT. IN FLUID	ACCUM WT.	MIN YLD STRENGTH	OVER-PULL	HOOK LOAD ACCUM WT PLUS TRAV EQUIP	8 LINES	10 LINES	12 LINES
27	810	6 1/4	4 1/2 XH	2 1/4	90	-	91	73710	62432	62432	-	-				
20	620	4 1/2	4 1/2 XH	3	20.0	E	22.18	13752	11648	74080	322950	248870	97575			
178	5518	4 1/2	4 1/2 XH	3 1/4	16.6	E	18.40	101531	85997	160077	260100	100023	183572			
163	5053	4 1/2	4 1/2 XH	3	16.6	X95	18.51	93531	79221	239298	418700	179402	262793	4.14		
	12000							282524 x 0.847 = 239298								

CALCULATED OVERPULL USING 90% OF MINIMUM TENSILE YIELD STRENGTH.
260,100 x 0.9 = 234,090#
234,090 - 160,093 = 73,997# OVERPULL

TABLE 3—DRILL STEM TEST, SUMMARY OF API EXAMPLE 5, 7

MUD WEIGHT 10 #/GAL
BUOYANCY FACTOR 0.847
PRESSURE GRADIENT 520 PSI/1000 FT

PIPE TYPE	LENGTH	DEPTH	HYDROSTATIC PRESSURE	ID	NOM. WT.	GRADE	WT/ FT.	WEIGHT IN AIR	WT. IN FLUID	ACCUM WT.	MIN YLD STRENGTH	OVER-PULL	% MIN Y.P.	% COLLAPSE	COLLAPSE 100%	COLLAPSE CORRECTED FOR TENSION	FACTOR OF SAFETY
27 DC																	
6 ¼ x 2 ¼	810	12000	6240	2.25	90	DC	90										
		11190	5819	2.25	90	DC	90	72900	61746	61746	-						
244	7564	11190	5819	3.826	16.6	E	17.84			61746	260100		23.74	86	7550	6493	1.12
16.6E		3626	1886	3.826	16.6	E	17.84	134942	114296	176042	260100		67.68	48	7550	3624	1.92
117	3627	3626	1886	3.826	16.6	X95	18.19			176042	418700		42.04	72	8850	6372	3.38
16.6 X 95		0	-	3.826	16.6	X95	18.19	65975	55881	231923	418700		55.39	60	8850	5310	-

time, the most accurate method of calculation is through use of the API Specification 5A and the Hughes Tool Company book titled *Length and Weight Added to Drill Pipe by Flashweld Tool Joints*.

Table 2 is an example of a typical drilling-string design where the objective is 100,000-pound overpull and where class 2, grade E pipe and new X95 is used. In this example, we also included 20 lengths of 20-pound grade E, class 2 pipe above the drill collars to be used as transition pipe to reduce fatigue damage in the 16.6-pound grade E pipe.

Table 3, from section 9.11 in RP7G, shows the factors affecting the design of drill pipe strings for drill stem tests. In the example problem using 5-inch outside-diameter drill pipe in 15 lb/gal mud with a design to pull 50,000 pounds to unseat the packer, the maximum depth at which a DST could be run was 8,338 feet. Many knowledgeable people are reluctant to DST any high pressure formation for two main reasons. No one has ever tested the pressure capability of a tool joint, and since a tool joint seals on the shoulders and the shoulders of used tool joints are normally damaged by tool joint pins and spinning chains, the results is a very unreliable pressure vessel. Tubing would be more reliable. However, it is not usually satisfactory for opening DST tools Table 3 shows what would be the result

TABLE 4—DRILLING STRING AND WIRE LINE CAPACITY PROGNOSIS, LINER EXAMPLE

EXAMPLE OF 7 3/4" OD. 46.1 # LINER
SET AT 20,500'. TOP OF LINER @ 15,500'.
MUD WEIGHT 9.2 #/GAL. BUOYANCY FACTOR 0.85%
100,000# OVERPULL. ALL PIPE PREMIUM CLASS.

HOOK LOAD 45648 — WIRE LINE SAFETY FACTOR: NOM. STRENGTH 1 3/8 EIP =192000

NUMBER	LENGTH	OD	THREAD TYPE	ID	NOM. WT.	GRADE	WT/ FT	WEIGHT IN AIR	WT. IN FLUID	ACCUM WT.	MIN YLD STRENGTH	OVER-PULL	ACCUM WT PLUS TRAV EQUIP	8 LINES 0.1469 1,307,011	10 LINES 0.1224 1,568,627	12 LINES 0.1062 1,807,909
	5000	7 3/4			46.1		46.1	230500	198000	198000	-	-				
42	1302	4 ½	4 ½ XH	3.00	20.0	E	22.18	28878	24806	222806	322950	100144	368598			
294	9114	4 ½	4 ½ XH	2.75	16.6	S135	18.54	168974	145149	367955	468180	100225	513828			
164	5084	4 ½	4 ½ XH	2.25	20.0	S135	22.56	114695	98523	466478	581310	114832	626958	2.0	2.5	2.8
	20500							543047 x 0.859 = 466477								

TRAVELING EQUIPMENT ITEM	DESCRIPTION			CAPACITY - TONS	WEIGHT
TRAVELING BLOCK		BETHLEHEM	B-55	600	22030
HOOK		BJ	5500	500	9950
SWIVEL		EMSCO	L650	471	7220
ELEVATORS		BJ	GG	350	550
LINKS		BJ	3 ½ x 144	500	1524
KELLY	API	RP7G	5 ¼ HEX	480	4374
					45648

TABLE 5--DRILL STEM TEST FOR EXAMPLE IN TABLE 4

EXAMPLE OF 7 3/4" OD, 46.1 LINER
SET @ 20,500', TOP OF LINER @ 15,500'
MUD WEIGHT 9.2 #/GAL HYDROSTATIC GRADIENT 478.4 PSI/1000 FT.

PIPE TYPE	LENGTH	DEPTH	HYDROSTATIC PRESSURE	ID	NOM. WT.	GRADE	WT/ FT.	WEIGHT IN AIR	WT. IN FLUID	ACCUM WT.	MIN YLD STRENGTH	OVER-PULL	% MIN Y.P.	% COLLAPSE	COLLAPSE 100%	COLLAPSE CORRECTED FOR TENSION	FACTOR OF SAFETY
DESCRIPTION																	
7 3/4	5000	20500	9807		46.1		46.1				-	-					
		15500	7415		46.1		46.1	230500	198000	198000	-	-					
4 1/2	1302	15500	7415	3.640	20.0	E	22.18	230500	198000	198000	322950	-	61.3	54	10980	5929	.80
		14198	6792					28878	24806	222806	322950	-	69.0	45	10980	4941	.73
4 1/2	9114	14198	6792	3.826	16.6	S135	18.54			222806	468180	-	47.6	47.5	11990	5695	.84
		5084	2432					168974	145149	367955	468180	-	78.6	34	11990	4077	1.68
4 1/2	5084	5084	2432	3.640	20.0	S135	22.56			367955	581310	-	63.3	52	18840	9797	4.03
	20500							114695	98523	466478	581310	-	80.2	32	18840		

of attempting a drill stem test using the drilling string design in Table 1.

Assume that a 405-foot interval is being tested and there are 405-feet of drill collars above the packer. The weakest point in this string would be the first joint of 4-1/2-inch outside-diameter drill pipe above the drill collars and the factor of safety in collapse would be 0.764. We would advise against attempting a DST if the factor of safety at any point in the string is below 1. We vary from API recommendations in that we compare accumulated weight to minimum yield strength remaining in the pipe. In example 9.11, the API recommends comparing the tensile load to the average yield strength. The effect on this problem would be that whereas API would estimate 88 percent of the collapse resistance available, we would predict 86 percent.

Table 4 is an example of the type of severe test of drill-pipe dependability encountered in a deep well.

Table 5 shows that when a deep liner is run the importance of filling the drill pipe on the way in the hole should not be ignored.

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