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Development of Casing Design Systems for Horizontal Wells

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Abstract:

In the petroleum industry, mining of horizontal wells is extensively carried on with a view to improving the efficiency of recovering oil and gas and activating the existing oil wells. Since it has not been cleared yet how such factors as a casing bending and its wear, a friction force between the casing and the well wall and so exert influences on the properties of steel pipe, the safe and economical casing designing technology has not been established. From this sense, the properties of steel pipe under the conditions of horizontal well load were cleared, and a casting design system incorporated these knowledge bases was developed and started marketing as JCASING of the trade name. This system is possessed of various serviceable functions such as material selection technology on a material with a property of the resistance to the sulfide stress cracking through hydrogen as a medium, multi-string design technology taking account of a kick tolerance, data base storage on the highly functional oil well pipes, and so.

1. Introduction

The petroleum industry is vigorously developing re-entry wells in which a reduction in oil field development cost is attempted through the use of new wells dug horizontally within an existing oil well and slim-hole wells which aims at minimization of ground facilities, consumption of oil well casing and tubing, and cuttings.

Casing used in horizontal drilling is subjected to load not found in vertical wells such as bending, abrasion and torsion. Since the operating characteristics of steel pipes during practical use are unclear, pipe specifications applied tend to be excessive. To cope with this problem, an understanding of the operating characteristics of steel pipes under the load environment found in horizontal drilling and design techniques for horizontal well casing based on a knowledge of the operating characteristics have long been awaited. Slim-hole drilling needs casing designs closely related to oil well drilling techniques such as the determination of casing setting depth and kick tolerance (a safety measure for a well given a blow-out of gas from the bottom of a well).

Given the above, we were commissioned by the Japan National Oil Corporation to develop the current design system with application to the design of horizontal drilling and slim-hole wells[1)].

Characteristics

1) Consideration of the influence of torque and drag generated during pipe raising and lowering operations peculiar to horizontal

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and directional drilling.

2) Quantification of the influence of casing abrasion and bend on the collapse and operating characteristics of systems of steel pipe joints.

3) Potential for abrasion prediction.

4) Implementation of new functions for assessing a corrosive environment and material selection that take into account the influence of pH and the partial pressure of Hydrogen Sulfide.

5) Implementation of functions such as a determination of well path, determination of locations for burying casing, analysis of kick tolerance.

6) Installation of a data base for special oil well casing tubing (premium joint, anti-collapse, sour resistance)

7) Minimization of casing cost.

2. Overview of the Casing Design System for Horizontal Wells

Fig. 1 shows the computational flow of the current system. Design of the well path is executed first and then casing setting depth is determined with reference to information such as formation pressure and fracture gradient. Next, detailed plan of casing combination is executed for selected strings. First, after inputting drilling conditions, the amount of abrasion is predicted. Second, inputting corroding environment conditions allows the list of appropriate steel pipes for the casing to be narrowed down. Third, inexpensive steel pipes well-suited for load conditions of oil wells such as torque and drag are selected. Finally, results such as safety proportion, costs and weights are generated as outputs.

3. Practical Operating Characteristics of Oil Pipes under Horizontal Well Load

3.1 Resistance to collapse

Resistance to collapse of casing pipe in horizontal wells should take into account of casing bending, and its inner wear caused by contact with abrasive surface of tool joint. With regard to abrasion of casing wall, **Fig. 2** shows the result of a destruction test of steel pipes whose interior walls were ground into crescent-shapes by a grinder. The figure shows that the reduction in resistance to collapse is proportional to the reduction in the wall thickness[2,3].

With regard to bending collapse operating characteristics, **Fig. 3** shows the result of collapse tests under a uniform bending moment. The figure shows that the reduction in collapse resistance due to bending is very small. Up to now, since the influence of bending has been replaced with an axial force which amounts to tensile bending stress, the influence of bending has been overestimated. This is because under an axial force, resistance to collapse is governed by the yield condition equation of von Mises[4], a compressive bending stress is in favor of collapse strength. In case of bending, as shown in **Fig. 4**, since tension and compression occur together, an improvement in the collapse pressure due to compression is expected to compensate for the reduction due to tension. Therefore, the overall effect is evaluated by integrating the amount of reduction in collapse pressure due

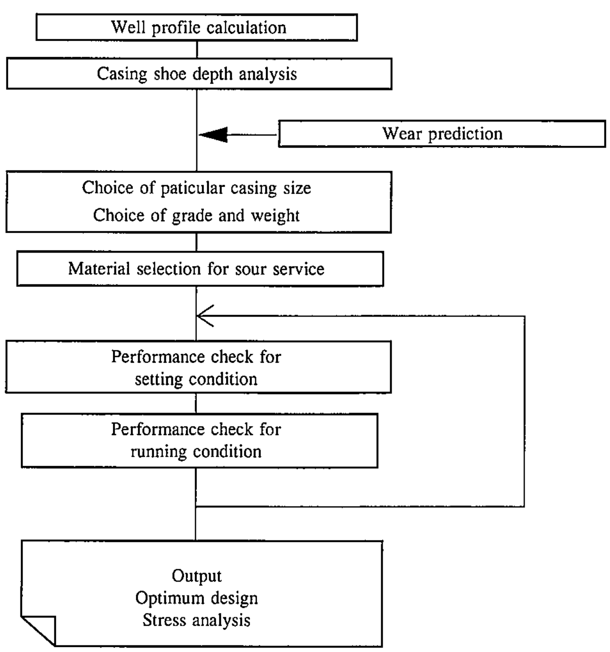

Fig. 1 Computational flow of casing design system

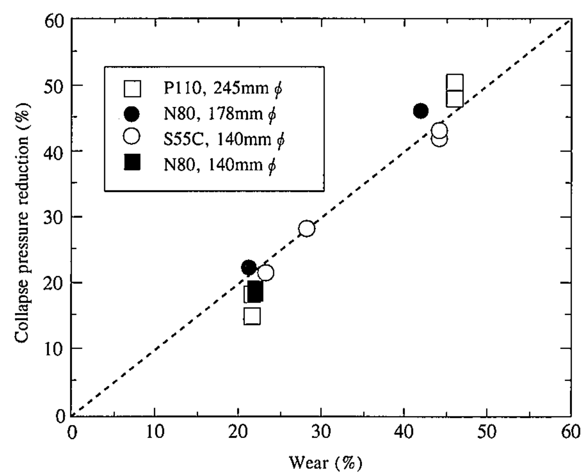

Fig. 2 Influence of abrasion on collapse pressure

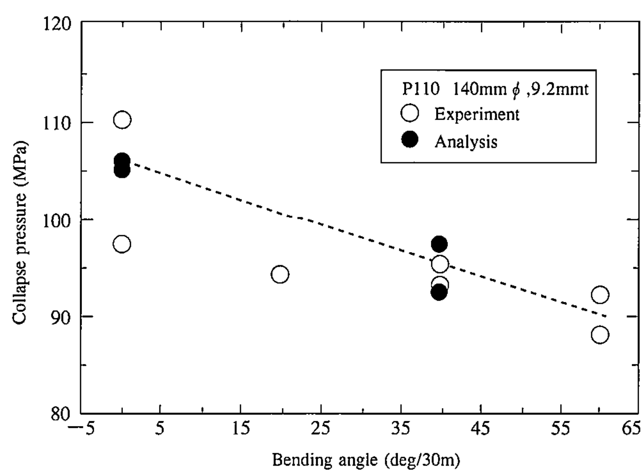

Fig. 3 Influence of bending on collapse pressure

to a bending force along small parts of pipe cross section in the direction of circumference. The evaluating equation and its fit to experimental results are presented in Eq. (1) and **Fig. 3** respectively. The experimental results are very consistent with computed values.

$$P_b = P_0 \int_0^{2\pi} \left\{ \sqrt{1 - 0.75\left(\frac{\sigma_b(\theta)}{Y_P}\right)^2} - 0.5\left(\frac{\sigma_b(\theta)}{Y_P}\right) \right\} d\theta \qquad \cdots\cdots \text{Eq. (1)}$$

where P_b, P_o, $\sigma_b(\theta)$ and Y_p are collapse pressure under bending stress, collapse pressure of straight pipes, bending stress at location θ in the circumferential direction and yield strength, respectively.

3.2 Torque resistance

A large friction force is generated between casing and well wall at the slanted part of horizontal drilling. Particularly crucial is the relationship between the friction force accompanied by steel pipe's rotation when cementing and the makeup torque of joints. Friction forces can be derived from the moment relationship depicted in **Fig. 5** and can be divided into torque (torque increment), vertical displacement (drag increment) and can be evaluated through equations (2) and (3)[5].

$$\Delta M = \mu \cdot F_n \cdot r \qquad \cdots\cdots \text{Eq. (2)}$$

$$\Delta F_t = W \cdot \cos\theta + \mu \cdot F_n \qquad \cdots\cdots \text{Eq. (3)}$$

where ΔM, μ, F_n, r, ΔF_t, W and θ are torque increment, friction coefficient, vertical drag, radius of the steel pipe, drag increment, steel pipe's weight and inclination angle, respectively.

Torque generated by tightening of joints depends on the type of thread. With regard to make up torque of API's (American Petroleum Institute) round thread (LTC), the maximum allowable make up torque is obtained by API RP 5C1. Since there is no recommended value for API's buttless thread (BTC), the corresponding values of API's round threaded joints of the same size and of the same steel grade are used. Generally, premium joint (MTC) show higher torque resistance than API's due to their torque shoulder and are therefore suitable for horizontal wells[6]. For example, since the allowable tightening torque of Premium Joint NS-CC of Nippon Steel Corporation is determined by the maximum torque without breaking leak tightness of metal seal, it has better operating characteristics than an API joint as shown in **Fig. 6**.

3.3 Joint strength

Tension tests were conducted for API's round threaded joints, buttless threaded joints and NS-CC under bending load (40 degrees/30m)[7]. Joints with buttless thread and NS-CC joints equipped with metal seal part showed the same joint strength as straight pipes. On the other hand, round threaded joints showed a reduction in tensile strength. **Fig. 7** shows the variation of bending load and tensile load for a given shape of curve. The bending load of round threaded joints decreases under a lighter tension load than that of buttless threaded joints. Moreover, round threaded joints are broken with a remaining bending load on them. Buttless threaded joints are designed to mesh with incomplete thread parts whereas incomplete ridge in round threaded joints are exposed without being well-fixed due to the incomplete thread at the run-out portion of the external thread because of preventing from galling. This exposed part becomes a source of stress concentration.

3.4 Joint seal capability

Gas and water sealing characteristics of joints subjected to bending loads are studied. Following API RP 5C5, evaluation of sealing capability was studied under compound conditions in

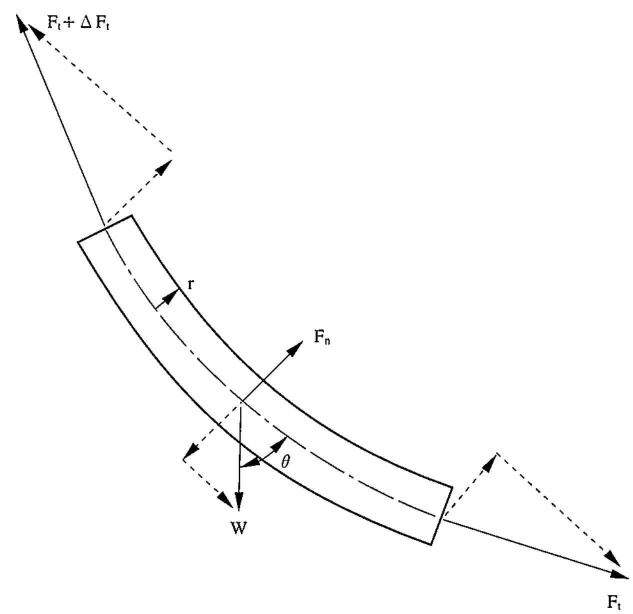

Fig. 5 Torque drag operating on slanted part of oil well.

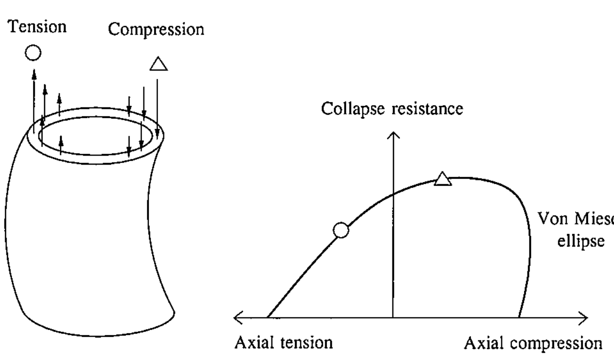

Fig. 4 Relationship between von Mises ellipse and bending tension.

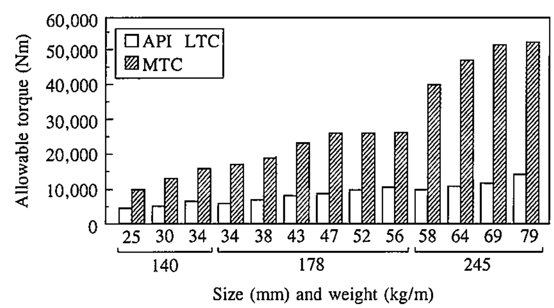

Fig. 6 Allowable tightening torque of joints

which 95% of von Mises's stress due to drag, bending and internal pressure. Bending rates in the study were 20 and 40 degrees per 30m. Results are shown in **Table 1**.

While both API joints showed leakage of gas and water, NS-CC with a metal seal maintained its sealing capability under a 40 degrees/30m bend. In horizontal wells where joint seal performance is required, usage of premium joints with a metal seal is recommended.

3.5 Material selection method against sulfide stress cracking resistance (SSC)

SSC is known to depend on the temperature and the concentration of hydrogen sulfide and hydrogen ions. However, according to current criteria for NACE material selection[8], only temperature is taken into account in evaluating the severity of the corrosive environment without consideration of the other above mentioned factors' influence. To make up for this, evaluation methods of the severity of the corrosive environment and material selection methods for inhibiting sulfide stress cracks were developed under the new assumption that SSC is a hydrogen embrittlement phenomenon with the hydrogen concentration inside the steel governing cracks[9].

3.5.1 Corrosive environment severity evaluation method

The amount of hydrogen infiltrating the steel from the corrosive environment was measured using electrical hydrogen permeation test. The amount of hydrogen infiltrated is determined using Eq. (4) with measured diffusion coefficient D and steady state hydrogen permeation velocity C.

$C = J \times L/D$ ……Eq. (4)

where C, J, L and D are hydrogen concentration, permeation velocity, thickness of test-piece through which hydrogen infiltrates and a diffusion coefficient, respectively.

Infiltration of steel by Hydrogen are caused by hydrogen ions in solution reduced on the steel surface with hydrogen sulfide acting as a catalyst accelerating the infiltration of hydrogen atoms into the steel. **Fig. 8** and Eq. (5) are obtained through a linear regression analysis of the relationship between infiltrated hydrogen atoms under various environmental conditions and the corrosive environmental factors.

$[H]_{Fe} = 13 \times ([H^+] \times [H_2S])^{0.26}$ ……Eq. (5)

where $[H]_{Fe}$, $[H^+]$ and $[H_2S]$ are hydrogen concentration (ppm) in criteria test-piece, hydrogen concentration (pH = -log[H^+]) and concentration (ppm) of hydrogen sulfide, respectively.

$[H]_{Fe}$ is a new index of the severity of a corrosive environ-

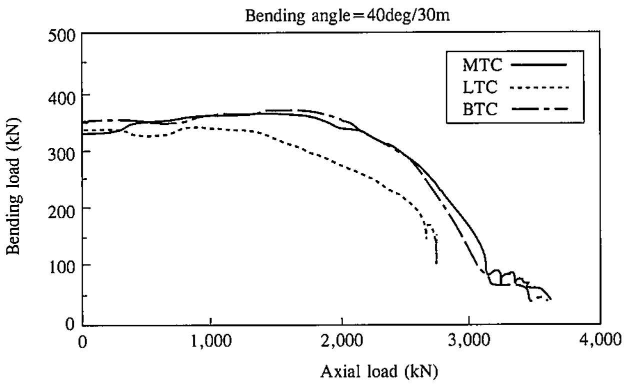

Fig. 7 Bending load and tensile load for a given shape of curve

Table 1 Sealing capability of joints under bending load.

Size	Grande	Joint	Bending angle (deg/30m)	Test result: Water	Test result: Gas
140mm 25kg/m	K55	MTC	0	No leak	No leak
			20		
			40		
140mm 34kg/m	P110	MTC	0		
			20		
			40		
178mm 43kg/m	L80	MTC	0		
			20		
			40		
		BTC	0	Leak	Leak
			20		
			40		
		LTC	0	No leak	No leak
			20		
			40		
245mm 58kg/m	K55	MTC	0		
			20		
			40		
245mm 64kg/m	N80	MTC	0		
			20		
			40		

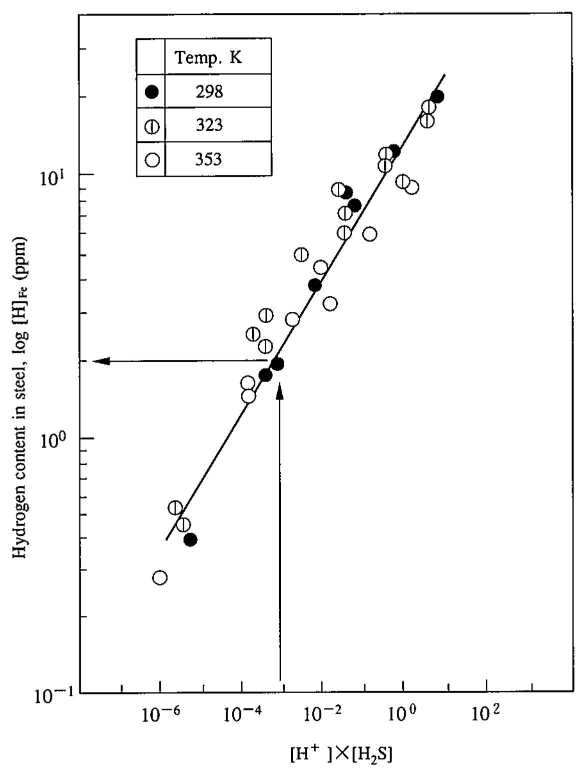

Fig. 8 Relationship between a corrosive environment and the infiltration volume of hydrogen into steel

ment in which hydrogen ion concentration, hydrogen sulfide concentration and temperature are all taken into account.

Since $[H_2S]$ represents concentration inside solution, in order to replace $[H_2S]$ with hydrogen sulfide's partial pressure P_{H_2S} (MPa), Eq. (6) of Henry's law should be used.

$[H_2S] = 10 \times P_{H_2S} \times (K_h \times 34 \times 103)$ ……Eq. (6)

where K_h, the solubility of hydrogen sulfide, is determined through Eq. (7)[10].

$\log K_h = 3321/T - 54.14 + 17.11 \log T$ ……Eq. (7)

where T represents absolute temperature, K.

With regard to $[H^+]$, it is sometimes stated in terms of pH, otherwise it should be estimated using the partial pressure of hydrogen sulfide and that of carbon dioxide and Cl ion concentration. The present system uses the pH estimation method[10] developed by Miyasaka.

3.5.2 Material selection method for resisting sulfide stress cracks

Fig. 9 shows results of a four point bent beam SSC test on API's steels and corrosion resistant materials treated at various levels for quenching and tempering. The corrosive environment is meaured using $[He]_{Fe}$ and the critical hydrogen concentration $[He]_c$ at which cracks are generated is set. $[H]_c$ decreases with increasing yield strength YS. Let us compare the corrosive environment index $[H]_{Fe}$ and critical hydrogen concentration $[H]_c$. If $[H]_c > [H]_{Fe}$, the steel can be used in the correspondingly corrosive environment, otherwise SSC can occur. Comparing the SSC resistive characteristics of steel treated for quenching and tempering, 110SS of Nippon Steel Corporation's corrosion resistant material is found to hold critical hydrogen volume [H]c approximately 20 times that of API P110 which has the same strength standards.

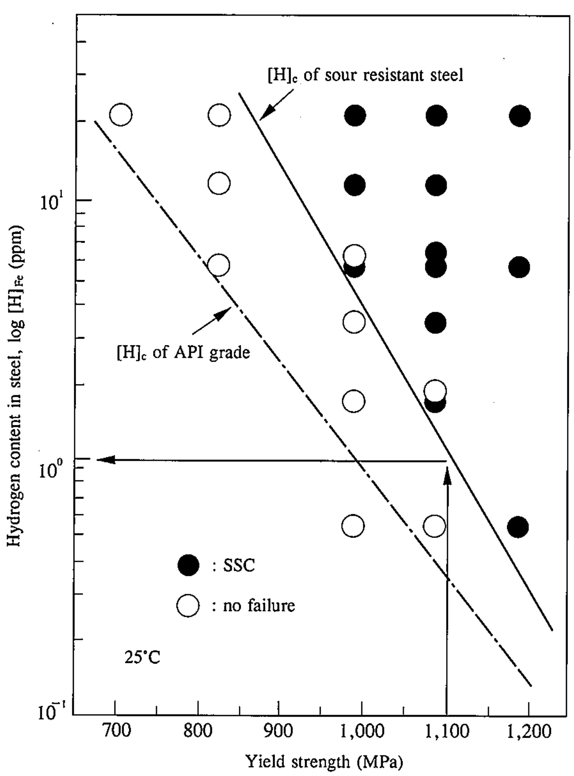

Fig. 9 SSC resisting critical hydrogen concentrations of materials treated for quenching and tempering

4. Casing String Design

4.1 Multi-string design

The current system enables 2-D and 3-D well path design. **Fig. 10** is an example of single bend well used in a solved problem in section 5. After the well form is determined, the next is determination of the locations of casing under the ground. Burying of casing as in **Fig. 11** should be done before stratum strength directly below casing already buried under the ground becomes smaller than mud density b being used. Continued

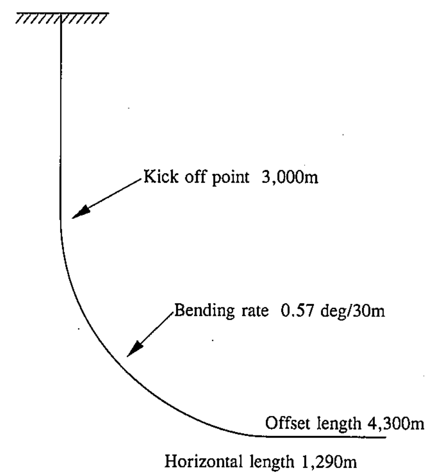

Fig. 10 Example design of well path

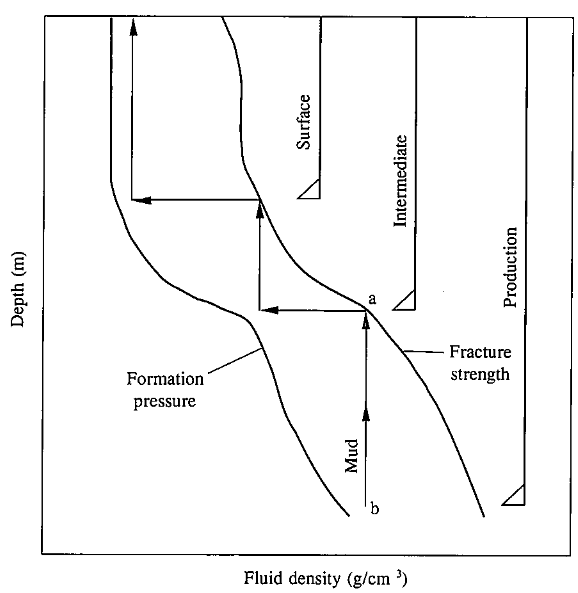

Fig. 11 Method of determining casing's burying locations

drilling without burying casing will increase mud density b due to the suppression of increasing stratum's pressure. As a result, stratum directly below casing will collapse to loss circulation. The number of casing strings and burying depth are roughly determined in this way.

Kick tolerance means allowable amount of gas infiltration inside well. The larger the value of this quantity, the higher the safety against blow-out becomes. **Fig. 12** shows schematically influence of the size of kick tolerance on burying locations of casing. As infiltrated gas infiltrates from the bottom hole to fill the annulus between drilling pipes and well wall, gas rises to the well head with increasing buoyancy over time. The pressure of a rising gas column equals that of mud at the bottom with the gas head being at higher pressure. Therefore, when the volume of infiltrated gas is smaller than the kick tolerance, it is not dangerous because the gas column reaches inside the casing. Otherwise, when gas pressure increases beyond the strength of the stratum, it can lead to a terrible accident due to collapse of the well wall. In order to increase kick tolerance, the number of strings increases with narrower buried casing intervals.

A short-cut for a slim hole is to reduce the gap between casings. However, a small amount of infiltrated gas can lead to a rising gas column making such a well dangerous. Thus, kick tolerance is an essential technical factor for multi-string design. For steel pipe manufacturers, it is closely related to over-sized and special-clearance casting specifications.

4.2 Features of the string design function

The first feature is that because the current system is linked with the abrasion prediction program[11], an estimation of abrasion to the interior of the casing and dynamic safety evaluation taking account of abrasion can be made. Abrasion prediction is based on Eq. (8) as a fundamental principle[12].

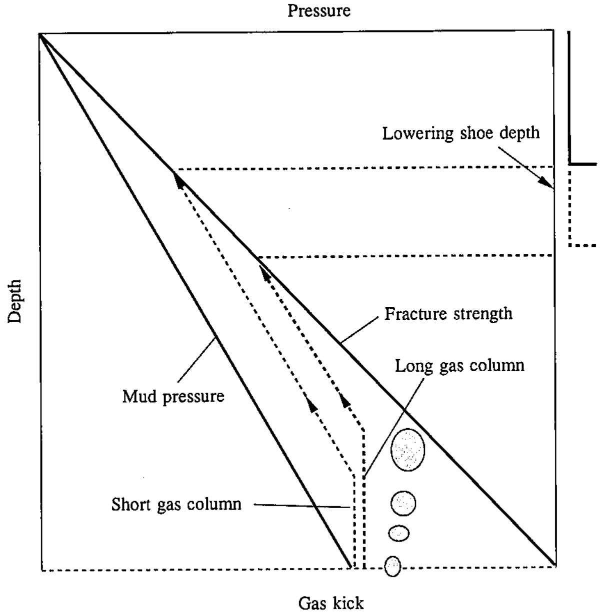

Fig. 12 Conceptual illustration of kick tolerance

$$V = (K/H) \cdot \mu \cdot D \cdot L$$

where V, K/H, μ, D and L stand for volume of metal shaved off by abrasion, abrasion efficiency measured experimentally, friction coefficient, contact length and vertical drag, respectively.

The second feature is that it incorporates a checking function for compression, torque and von Mises breakdown conditions as well as a conventional safety check for collapse, burst and tension which were considered to be counter measures against dynamic load condition such as torque and drag indispensable for horizontal drilling. Furthermore, as shown in **Fig. 13**, a dynamic safety check given these dynamic loads can be examined for any combination of casing string and friction conditions (torque and drag) anywhere directional and curved steel pipes penetrate[13]. Due to this function, the following operations are made possible: preventive operation against pipe sticking, in which steel pipes are moved up and down, cementing operation of horizontal part, which involves rotation, and load simulation peculiar to the horizontal well.

The third feature is an economic string design function taking account of the above mentioned dynamic load checking. In addition to minimize the cost of casing, it is recommended to use steel pipes whose operating tolerances exceed load conditions. In line with this idea, the current system uses combination string design which divides casing strings, whose load conditions vary across various locations, into several intervals to adopt the least expensive steel pipes for each. To describe it in detail, as shown in **Fig. 13**, one string is divided into small intervals of 30m. Then conducting safety check against static and dynamic load from the bottom to the top of string for every casing's segment in all the small intervals, inexpensive steel pipes are chosen.

5. Casing Design Example

Fig. 10 shows an example of casing design for a horizontal well in a corrosive environment at a depth of 6000m and an offset of 3000m.

Fig. 14 shows the results of multi-string design for kick tolerance 0.16m^3 (10BBL) and 0.32m^3 (20BBL). Comparing the number of strings, the former has 5 and the latter has 6. As a result, assuming that steel pipe with an external diameter of 178mm (7 inches) is used as the innermost production casing, well head diameters will be 508mm (20inches) and 762mm (30inches) at the

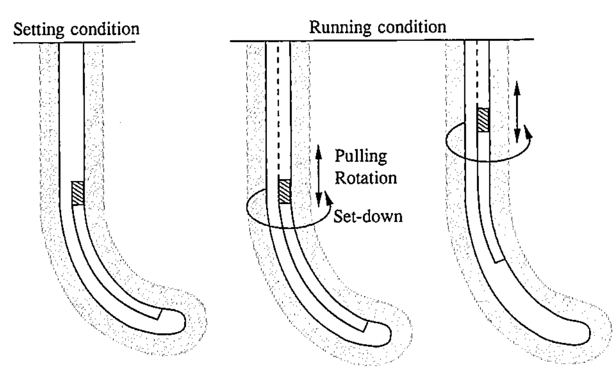

Fig. 13 Dynamic safety check method for casing

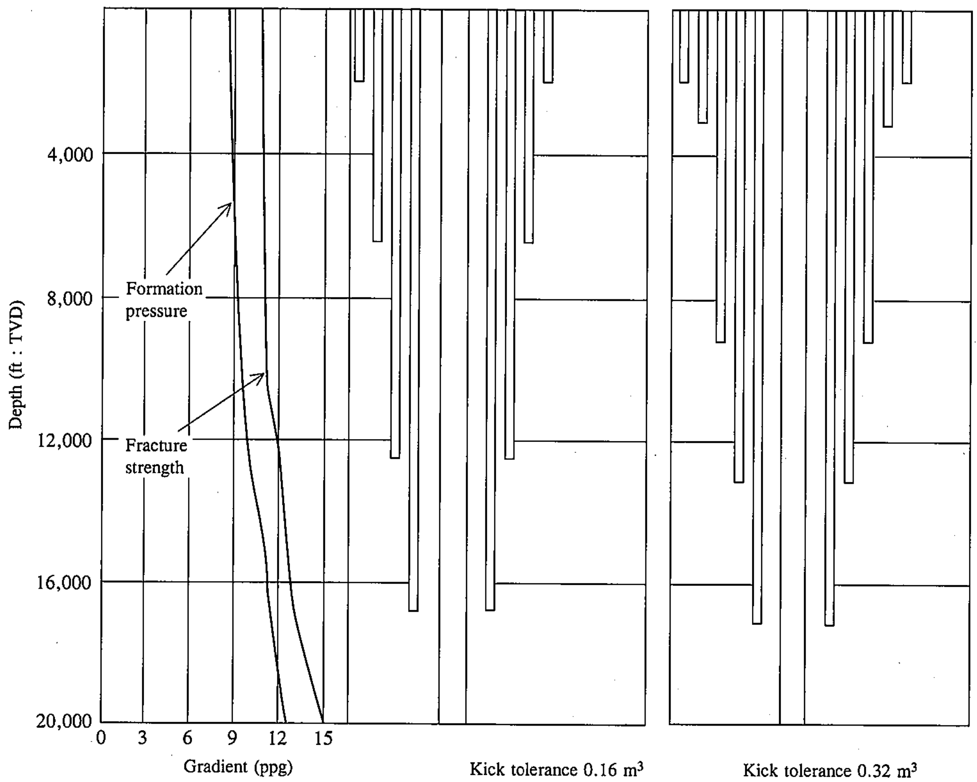

Fig. 14 Well design examples with different kick tolerances

ground surface. As a result, safe well depth and well width become larger thus increasing the development cost.

As an example of single string design, 2nd to the innermost casing with an outside diameter of 245mm (9-5/8inches) is investigated. **Table 2** shows the results of the casing design used by the current system such as influence of abrasion, that of torque and drag and SSC resistant material evaluation. **Table 3** shows, as a comparison, the results of conventional casing design which applies NACE method using SSC resistant material selection and temperatures without consideration of abrasion or torque and drag.

Fig. 15 shows the distribution of abrasion along casing string. Abrasions are observed below the bending point. The amount of maximum abrasion is predicted to be 12.3% of thickness. The influence of abrasion is revealed as a difference in the steel pipe's thickness and strength of the bottom part of strings. To compensate for the reduction in collapse pressure, high collapse resistant pipes are selected (Nippon Steel Corporation standard 95HS, 110HS).

Fig. 16 shows the relationship between the distribution of torque accompanied with casing rotation and torsion strength of steel pipe joints. Since torque is smaller at a depth of more than 4500m (15000ft), API buttless joints (BTC) suffice. However, when it is shallower, due to the decrement in torque in proportion to the depth, premium joints (MTC) with higher torsion resistance is required. The influence of torque is manifested as a difference in the types of joints used.

According to the measure of corrosive environment using hydrogen, the predicted pH at the ground surface where corroding condition is the severest is 3 and the allowable hydrogen con-

Table 2 Casing design with additional load conditions specific to horizontal well

NO	Top (ft: MD)	Bottom (ft: MD)	Length (ft: MD)	OD (in)	Weight (lbs/ft)	Thickness (in)	Grade	Joint	Type	Cplg OD (in)	Pipe ID (in)	Drift OD (in)
1	0	3,400	3,400	9.625	53.50	0.545	110SS	MTC	Reg	10.625	8.535	8.379
2	3,400	5,900	2,500	9.625	53.50	0.545	N-80	MTC	Reg	10.625	8.535	8.379
3	5,900	9,700	3,800	9.625	53.50	0.545	N-80	MTC	Reg	10.625	8.535	8.379
4	9,700	12,300	2,600	9.625	53.50	0.545	95HS	MTC	Reg	10.625	8.535	8.379
5	12,300	14,900	2,600	9.625	58.40	0.595	95HS	MTC	Reg	10.625	8.435	8.279
6	14,900	17,500	2,600	9.625	58.40	0.595	110HS	BTC	Reg	10.625	8.435	8.279

Table 3 Casing design using conventional methods

NO	Top (ft: MD)	Bottom (ft: MD)	Length (ft: MD)	OD (in)	Weight (lbs/ft)	Thickness (in)	Grade	Joint	Type	Cplg OD (in)	Pipe ID (in)	Drift OD (in)
1	0	2,500	2,500	9.625	59.40	0.609	T-95	MTC	Reg	10.625	8.407	8.279
2	2,500	5,000	2,500	9.625	53.50	0.545	T-95	BTC	Reg	10.625	8.535	8.379
3	5,000	7,500	2,500	9.625	53.50	0.545	N-80	BTC	Reg	10.625	8.535	8.379
4	7,500	10,000	2,500	9.625	53.50	0.545	N-80	BTC	Reg	10.625	8.535	8.379
5	10,000	12,500	2,500	9.625	53.50	0.545	95HS	BTC	Reg	10.625	8.535	8.379
6	12,500	17,500	5,000	9.625	53.50	0.545	95HS	BTC	Reg	10.625	8.535	8.379

centration of SSC resistant material 110SS is 22.9ppm. Based on these values, allowable hydrogen sulfide partial pressure is calculated through Eq. (5) to be 0.3MPa (43.8psi). Since the partial pressure of hydrogen sulfide in the solved problem turns out to be 0.25MPa (36psi), 110SS is applicable. However, according to NACE, the upper limit of high strength materials that can be used in hydrogen sulfide corroding environment with the temperatures of less than 338K is API standard T95. This choice of material is more conservative than when the corrosive environment is evaluated with precision.

Finally, for the comparison of string costs, when the influence of the horizontal well is not taken into account, the cost emerges as $382,000 (see **Table 3**). When the influence of the horizontal well is taken into account, the cost becomes $412,000 (see **Table 2**). Though the increase in the cost is approximately 8%, the accurate assessment of the safety of the horizontal well casing design became possible. Moreover, since special well pipes with premium joints, corrosion resistance and high collapse pressure are used where appropriate, economic design was achieved.

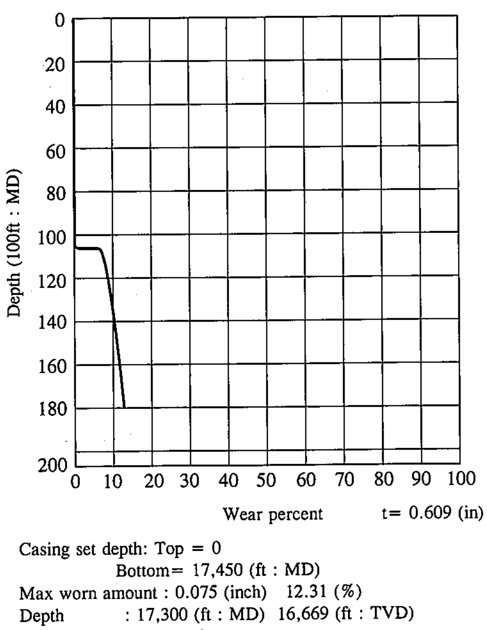

Fig. 15 Distribution of abrasion amount along casing strings

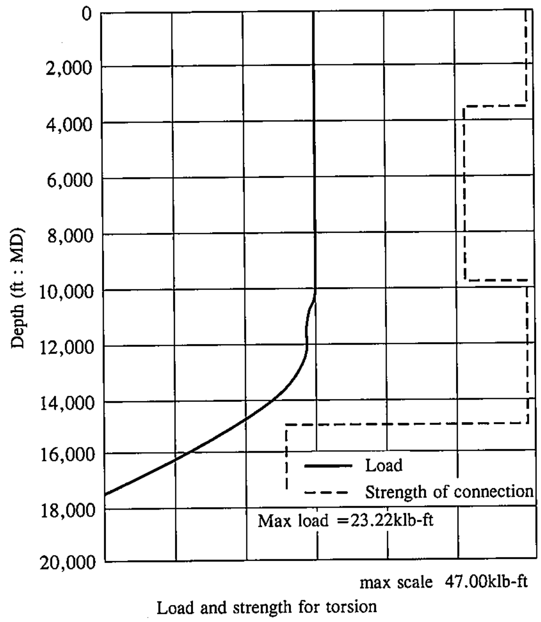

Fig. 16 Results of safety evaluation against torque of casing

6. Conclusion

We developed casing design system (JCASING) equipped with a practical operating characteristics analysis function for well pipes used in horizontal wells and with multi-string design.

Acknowledgment

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