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University of
Stavanger

FACULTY OF SCIENCE AND TECHNOLOGY

SUBJECT: MPE 680 Well Technology

DATE: December 3, 2012

TIME: 0900-1300

AID: Approved calculator

THE EXAM CONSISTS OF 3 PROBLEMS ON 8 PAGES + FORMULA SHEETS

REMARKS: Formula sheet is attached. It is considered a part of the exam for the candidate to make appropriate assumptions if confusions are encountered.

YOU ARE REQUIRED TO STATE ALL ASSUMPTIONS!

You are designing a vertical exploration well (see Figure 1, page 5).
The curves shown in Figure 1 are as follows, listed from left side towards right side:

1. Hydrostatic gradient (vertical at 1.03 s.g.)
2. Pore pressure gradient – low estimate
3. **Pore pressure gradient – medium estimate**
4. Pore pressure gradient – high estimate
5. Fracture gradient – low estimate
6. **Fracture gradient – medium estimate**
7. Fracture gradient – high estimate
8. **Overburden gradient**
9. The two line-dot curve sections are designed for problem 2d+2e.

Note also that the description of the formations, the formation group comes below the horizontal dotted lines (i.e. the first dotted line is marking the top of the Rogaland group, so that the Rogaland group is BETWEEN the first two dotted lines, and so on).

Problem 1: Casing strength under combined load (25%)

Assume a 9 5/8" casing of P110 quality and 53,5 lb/ft (see other specifications on attached data sheet). Such a casing has a minimum tensile yield strength of 110 000 psi. For this problem you may assume this yield strength is valid for all type of failures.

Now an axial load is applied simultaneously as an internal pressure. You are now supposed to define the failure envelope for this casing (i.e. internal pressure vs. axial load at failure) during a pressure testing scenario.

Internal pressure should have the unit of bar, and axial load should have unit kN.

Remember to state all other assumtions you make!
Make large figures, and include failure envelopes in problem a) and b) in the same figure!

a) Define the failure envelope using Rankine (σ_{max}) failure criteria (**make figure!**)

b) Define the failure envelope using Tresca (τ_{max}) failure criteria. (**make figure!**)

c) Which of the two failure envelopes are largest, and why? (*Hint: think on the general stress tensor and which part of it that governs the failure*).

d) Which of the two failure criteria do you consider the most correct to use for a combined load, and why?

Problem 2: Pore pressure/fracture gradient/casing design/stuck pipe (43,75%)

a) Looking at the water depth, we expect that a jack-up rig is being used. Do we have to account for the riser margin? Explain what the riser margin means, and then explain why or why not you would like to account for it!

b) Should the 13 3/8" casing be designed for full or reduced well integrity? Explain your answer. (see Table 1 for details).

c) What is the maximum allowable pore pressure if the 13 3/8" casing should have full well integrity? Also, what is the minimum and maximum allowable LOT-value below the 13 3/8" casing shoe?

d) You feel that the fracture gradient curves are poorly documented, and you need to do a quick estimate of the fracture gradient in the Shetland group and the Vestland group. You should assume the medium pore pressure gradient curve, BUT at the depths of interest, you should imagine that the pore pressure is continuously increasing (see the line-dot curve). You may assume that that the minimum horizontal stress equals 85% of the overburden. The geology suggests that there is an isotropic horizontal in-situ stress field. Calculate the fracture gradient at 2400 mTVD and at 3000 mTVD.

e) Now you should use the real medium pore pressure gradient to calculate the real fracture gradient. This means that the drop in pore pressure is a result of depleted pressure, and you should use the compaction model to calculate the fracture gradient. Calculate the expected real fracture gradient at 2400 mTVD and at 3000 mTVD.

f) It is a possibility that you need to plan for a sidetrack to this well. Calculate the expected fracture gradient at 2400 mTVD and at 3000 mTVD if the sidetrack has a 30 degree inclination.

g) Imagine that you actually drill the sidetrack and go stuck. Calculate the depth of stuck point if

- Kick off point @ 1080 mTVD
- DLS = 3 deg/30m
- Pipe elongation @ pull test = 2,70 m
- Pull force @ pull test = 841 kN
- 5" drill pipe, 19,5 ppf (see table 1 on page 4 and Figure 4 on page 8)

What is the name of the formation where the pipe is stuck?

Problem 3: Casing design (31,25%)

Perform design calculations for the 9 5/8" liner for this well (Figure 1).

PS! See input data in Table 1 and Figure 2+3 on the next pages.

Evaluate different collapse, burst and tension design criteria and calculate the following design factors:

PS! *You must explain if you should or should not account for biaxial stresses, wear, corrosion and bending moments*

a) Full well integrity or reduced well integrity? Explain.
b) Collapse design factor
c) Burst design factor
d) Tension design factor
e) Based on casing mechanical properties alone, is there another casing grade that would be a better choice than the P110? (assuming same nominal weight)

YOU ARE REQUIRED TO MAKE FIGURES FOR ALL DESIGN CRITERIA

Table 1 – Input data for all problems

The following well data applies:

Water depth:	90	m
Depth to sea level, MSL:	30	m
Mud weight:	1.72	s.g.
Cement density:	1.92	s.g.
Friction coefficient:	0.23	
Poisson ratio:	0.20	
Formation fluid density @ kick:	0.50	s.g.

The following casing data applies (See Figure 2+3 Casing data):

- 13 3/8" grade P110, 72.00 lb/ft casing (setting depth 1050 mTVD)
- 9 5/8" grade P110, 53.50 lb/ft liner
  - setting depth 2750 mTVD
  - top of liner @ 900 mTVD
  - top of cement @ 1900m
- Open hole section to 3200 mTVD

burst pressure = internal yield pressure

The following minimum casing design factors applies:

Tension	1.3
Burst	1.1
Collapse	1.1

Drill pipe and casing Youngs modulus:	200 kN/mm^2

Maximum allowable test pressure = 90% of casing strength

Some conversion factors:

- 1 kN/mm^2 = 10 000 bar = 1000 MPa = 1 GPa = 145 038 psi

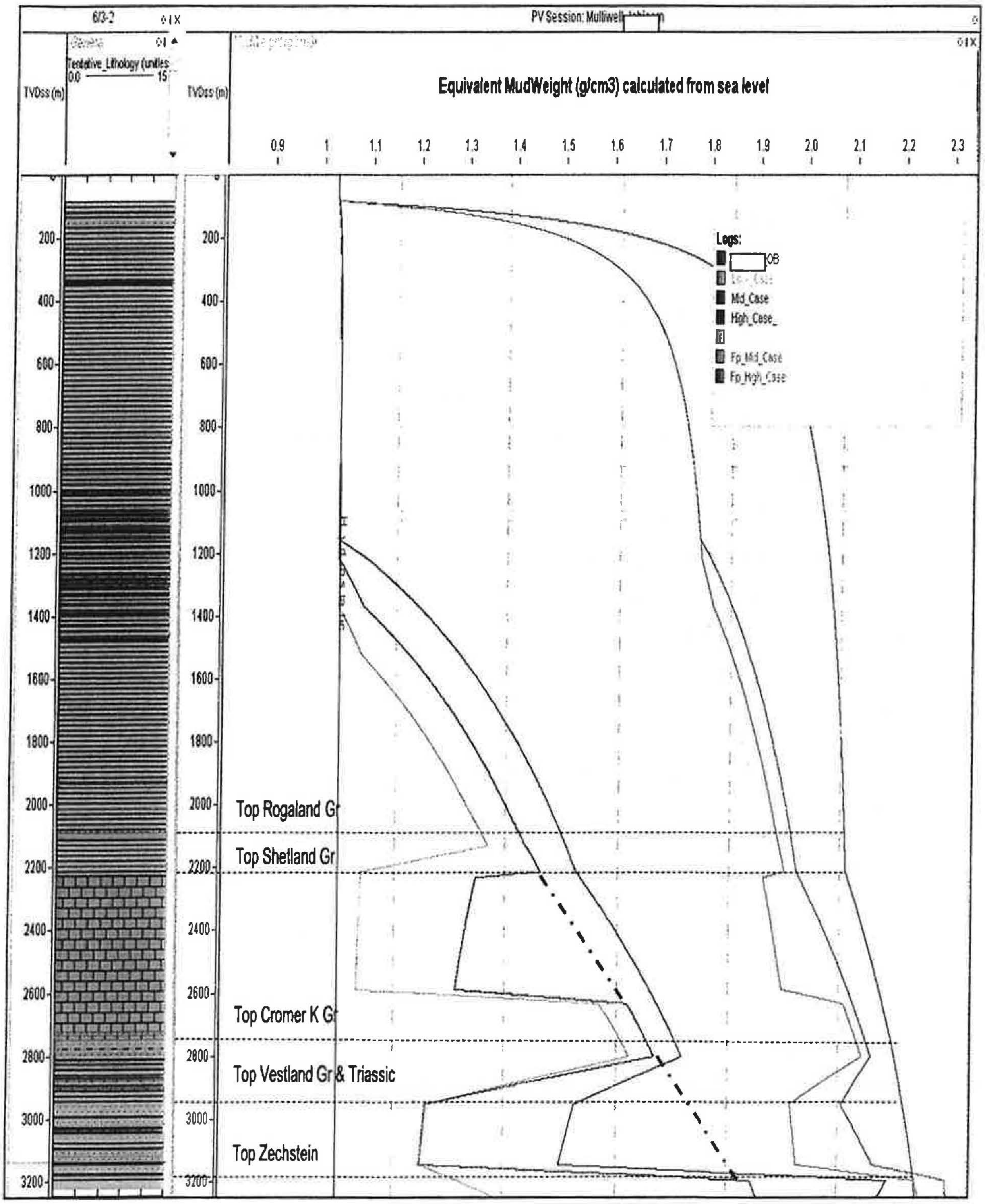
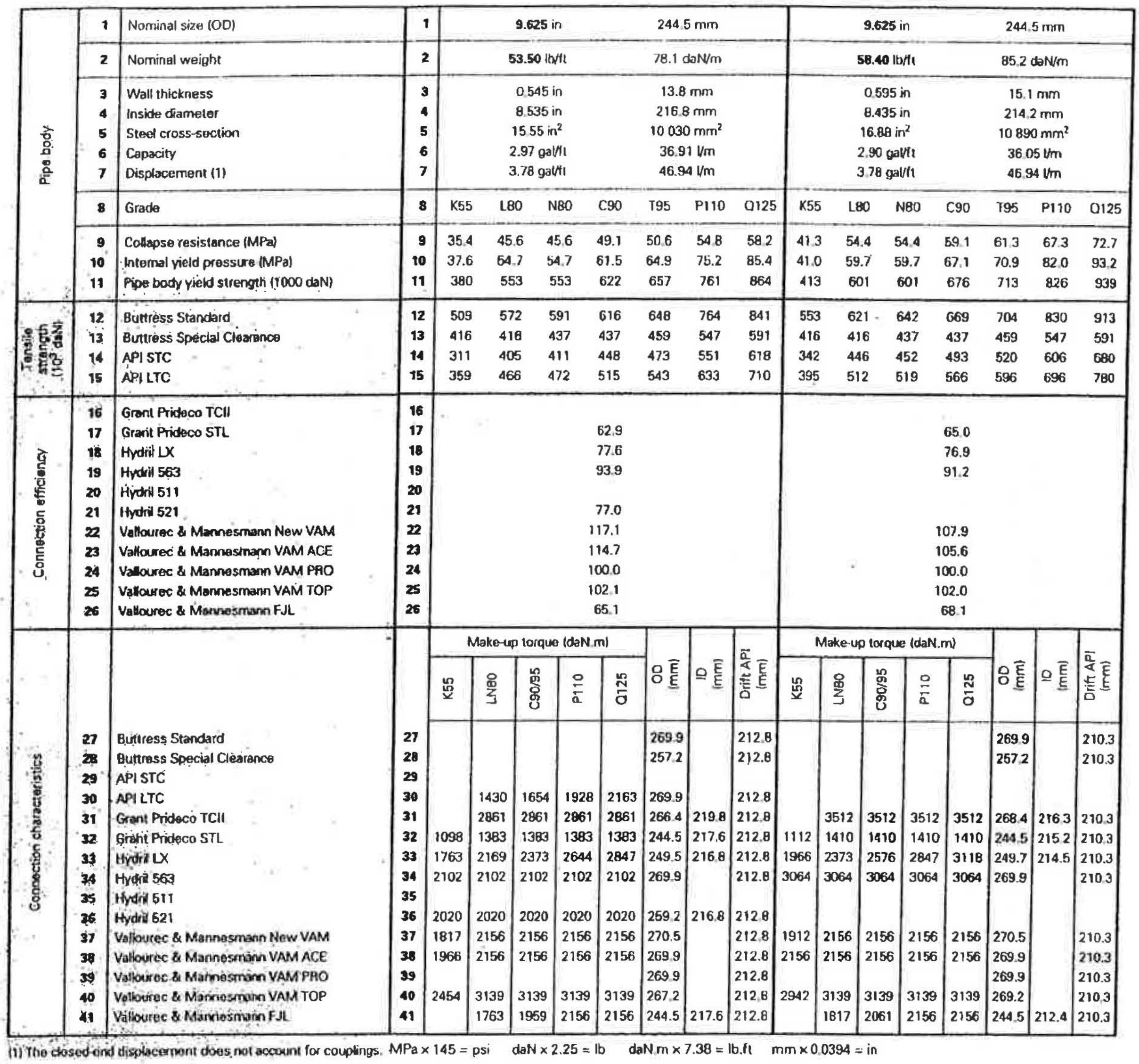


Figure 1 – Pore pressure gradient and fracture gradient curves

GEOMETRICAL CHARACTERISTICS AND MECHANICAL PROPERTIES OF CASING (continued)



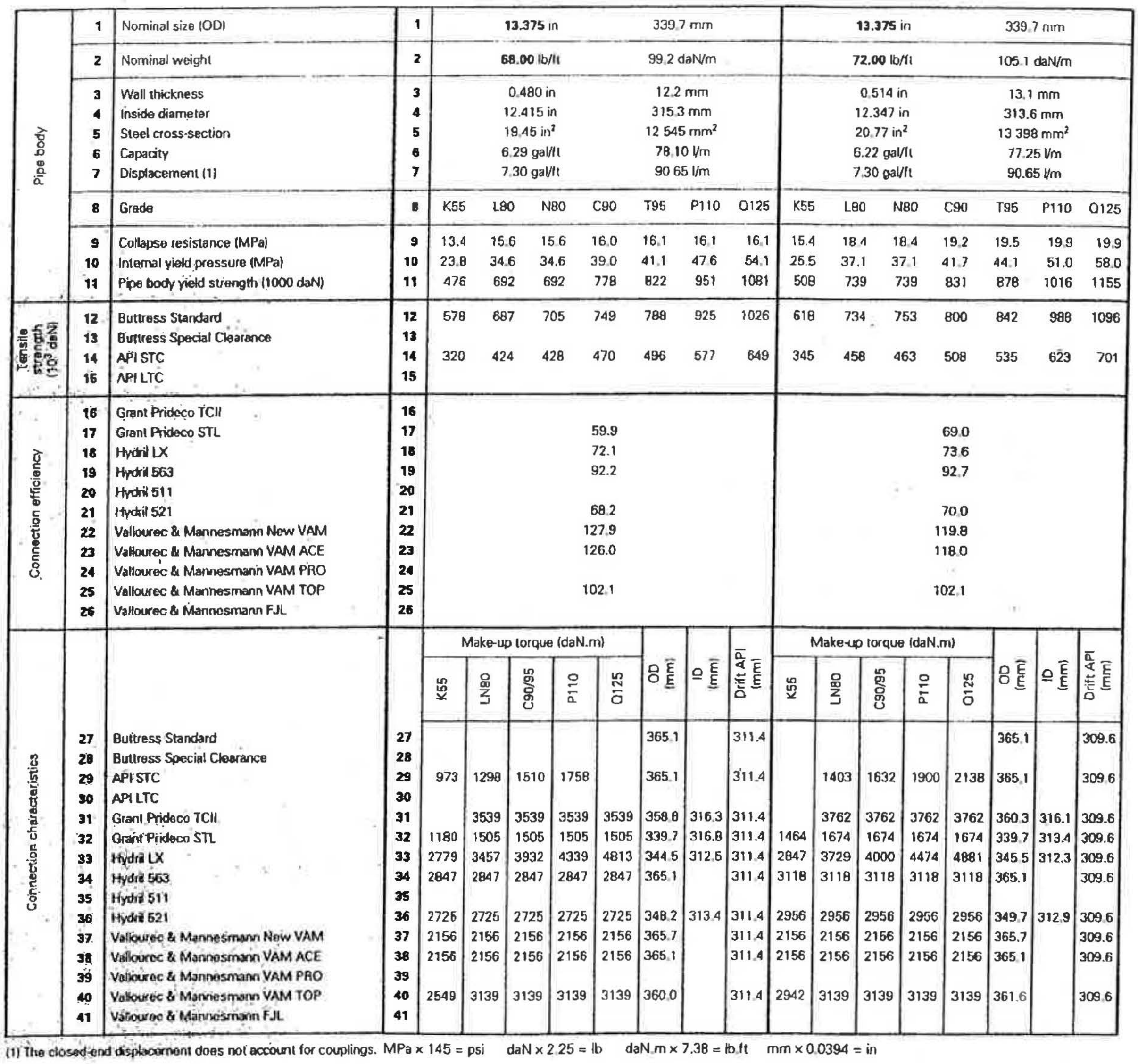
Pipe body	1	Nominal size (OD)	1	**9.625** in	244.5 mm	**9.625** in	244.5 mm
	2	Nominal weight	2	**53.50** lb/ft	78.1 daN/m	**58.40** lb/ft	85.2 daN/m
	3	Wall thickness	3	0.545 in	13.8 mm	0.595 in	15.1 mm
	4	Inside diameter	4	8.535 in	216.8 mm	8.435 in	214.2 mm
	5	Steel cross-section	5	15.55 in^2	10 030 mm^2	16.88 in^2	10 890 mm^2
	6	Capacity	6	2.97 gal/ft	36.91 l/m	2.90 gal/ft	36.05 l/m
	7	Displacement (1)	7	3.78 gal/ft	46.94 l/m	3.78 gal/ft	46.94 l/m

	8	Grade	8	K55	L80	N80	C90	T95	P110	Q125	K55	L80	N80	C90	T95	P110	Q125
Pipe body	9	Collapse resistance (MPa)	9	35.4	45.6	45.6	49.1	50.6	54.8	58.2	41.3	54.4	54.4	59.1	61.3	67.3	72.7
	10	Internal yield pressure (MPa)	10	37.6	54.7	54.7	61.5	64.9	75.2	85.4	41.0	59.7	59.7	67.1	70.9	82.0	93.2
	11	Pipe body yield strength (1000 daN)	11	380	553	553	622	657	761	864	413	601	601	676	713	826	939
Tensile strength (10^3 daN)	12	Buttress Standard	12	509	572	591	616	648	764	841	553	621	642	669	704	830	913
	13	Buttress Special Clearance	13	416	416	437	437	459	547	591	416	416	437	437	459	547	591
	14	API STC	14	311	405	411	448	473	551	618	342	446	452	493	520	606	680
	15	API LTC	15	359	466	472	515	543	633	710	395	512	519	566	596	696	780
Connection efficiency	16	Grant Prideco TCII	16														
	17	Grant Prideco STL	17	62.9							65.0						
	18	Hydril LX	18	77.6							76.9						
	19	Hydril 563	19	93.9							91.2						
	20	Hydril 511	20														
	21	Hydril 521	21	77.0													
	22	Vallourec & Mannesmann New VAM	22	117.1							107.9						
	23	Vallourec & Mannesmann VAM ACE	23	114.7							105.6						
	24	Vallourec & Mannesmann VAM PRO	24	100.0							100.0						
	25	Vallourec & Mannesmann VAM TOP	25	102.1							102.0						
	26	Vallourec & Mannesmann FJL	26	65.1							68.1						

				Make-up torque (daN.m)					OD (mm)	ID (mm)	Drift API (mm)	Make-up torque (daN.m)					OD (mm)	ID (mm)	Drift API (mm)
				K55	LN80	C90/95	P110	Q125				K55	LN80	C90/95	P110	Q125			
Connection characteristics	27	Buttress Standard	27						269.9		212.8						269.9		210.3
	28	Buttress Special Clearance	28						257.2		212.8						257.2		210.3
	29	API STC	29																
	30	API LTC	30		1430	1654	1928	2163	269.9		212.8								
	31	Grant Prideco TCII	31		2861	2861	2861	2861	266.4	219.8	212.8		3512	3512	3512	3512	268.4	216.3	210.3
	32	Grant Prideco STL	32	1098	1383	1383	1383	1383	244.5	217.6	212.8	1112	1410	1410	1410	1410	244.5	215.2	210.3
	33	Hydril LX	33	1763	2169	2373	2644	2847	249.5	216.8	212.8	1966	2373	2576	2847	3118	249.7	214.5	210.3
	34	Hydril 563	34	2102	2102	2102	2102	2102	269.9		212.8	3064	3064	3064	3064	3064	269.9		210.3
	35	Hydril 511	35																
	36	Hydril 521	36	2020	2020	2020	2020	2020	259.2	216.8	212.8								
	37	Vallourec & Mannesmann New VAM	37	1817	2156	2156	2156	2156	270.5		212.8	1912	2156	2156	2156	2156	270.5		210.3
	38	Vallourec & Mannesmann VAM ACE	38	1966	2156	2156	2156	2156	269.9		212.8	2156	2156	2156	2156	2156	269.9		210.3
	39	Vallourec & Mannesmann VAM PRO	39						269.9		212.8						269.9		210.3
	40	Vallourec & Mannesmann VAM TOP	40	2454	3139	3139	3139	3139	267.2		212.8	2942	3139	3139	3139	3139	269.2		210.3
	41	Vallourec & Mannesmann FJL	41		1763	1959	2156	2156	244.5	217.6	212.8		1817	2061	2156	2156	244.5	212.4	210.3

(1) The closed-end displacement does not account for couplings. MPa × 145 = psi daN × 2.25 = lb daN.m × 7.38 = lb.ft mm × 0.0394 = in

Figure 2 – Casing data



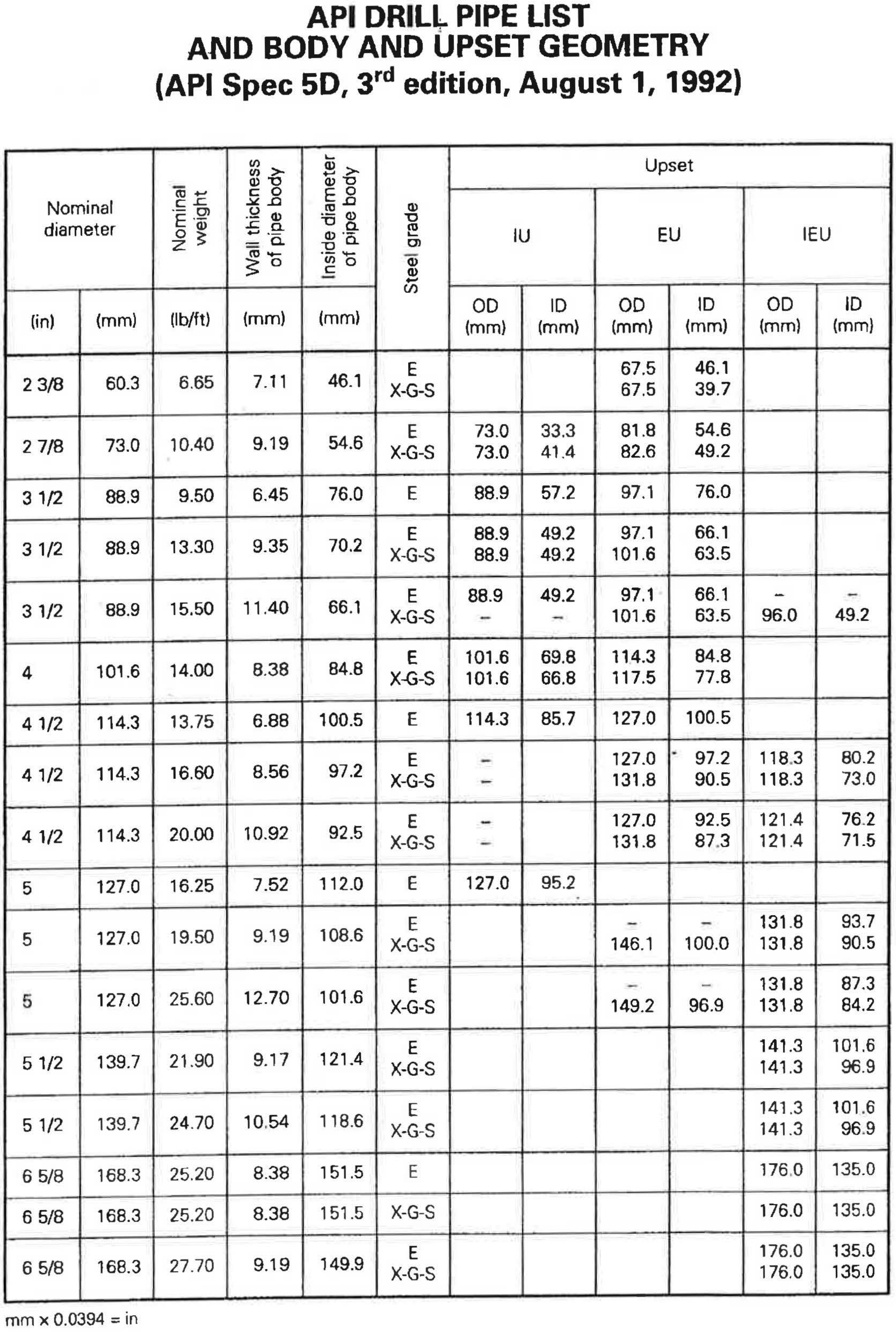
GEOMETRICAL CHARACTERISTICS AND MECHANICAL PROPERTIES OF CASING (continued)

Pipe body	1	Nominal size (OD)	1	**13.375** in 339.7 mm							**13.375** in 339.7 mm						
	2	Nominal weight	2	**68.00** lb/ft 99.2 daN/m							**72.00** lb/ft 105.1 daN/m						
	3	Wall thickness	3	0.480 in 12.2 mm							0.514 in 13.1 mm						
	4	Inside diameter	4	12.415 in 315.3 mm							12.347 in 313.6 mm						
	5	Steel cross-section	5	19.45 in² 12 545 mm²							20.77 in² 13 398 mm²						
	6	Capacity	6	6.29 gal/ft 78.10 l/m							6.22 gal/ft 77.25 l/m						
	7	Displacement (1)	7	7.30 gal/ft 90 65 l/m							7.30 gal/ft 90.65 l/m						
	8	Grade	8	K55	L80	N80	C90	T95	P110	Q125	K55	L80	N80	C90	T95	P110	Q125
	9	Collapse resistance (MPa)	9	13.4	15.6	15.6	16.0	16.1	16.1	16.1	15.4	18.4	18.4	19.2	19.5	19.9	19.9
	10	Internal yield pressure (MPa)	10	23.8	34.6	34.6	39.0	41.1	47.6	54.1	25.5	37.1	37.1	41.7	44.1	51.0	58.0
	11	Pipe body yield strength (1000 daN)	11	476	692	692	778	822	951	1081	508	739	739	831	878	1016	1155
Tensile strength (10^3 daN)	12	Buttress Standard	12	578	687	705	749	788	925	1026	618	734	753	800	842	988	1096
	13	Buttress Special Clearance	13														
	14	API STC	14	320	424	428	470	496	577	649	345	458	463	508	535	623	701
	16	API LTC	15														
Connection efficiency	16	Grant Prideco TCII	16														
	17	Grant Prideco STL	17	59.9							69.0						
	18	Hydril LX	18	72.1							73.6						
	19	Hydril 563	19	92.2							92.7						
	20	Hydril 511	20														
	21	Hydril 521	21	68.2							70.0						
	22	Vallourec & Mannesmann New VAM	22	127.9							119.8						
	23	Vallourec & Mannesmann VAM ACE	23	126.0							118.0						
	24	Vallourec & Mannesmann VAM PRO	24														
	25	Vallourec & Mannesmann VAM TOP	25	102.1							102.1						
	26	Vallourec & Mannesmann FJL	26														

				Make-up torque (daN.m)					OD (mm)	ID (mm)	Drift API (mm)	Make-up torque (daN.m)					OD (mm)	ID (mm)	Drift API (mm)
				K55	LN80	C90/95	P110	Q125				K55	LN80	C90/95	P110	Q125			
Connection characteristics	27	Buttress Standard	27						365.1		311.4						365.1		309.6
	28	Buttress Special Clearance	28																
	29	API STC	29	973	1298	1510	1758		365.1		311.4		1403	1632	1900	2138	365.1		309.6
	30	API LTC	30																
	31	Grant Prideco TCII	31		3539	3539	3539	3539	358.8	316.3	311.4		3762	3762	3762	3762	360.3	316.1	309.6
	32	Grant Prideco STL	32	1180	1505	1505	1505	1505	339.7	316.8	311.4	1464	1674	1674	1674	1674	339.7	313.4	309.6
	33	Hydril LX	33	2779	3457	3932	4339	4813	344.5	312.5	311.4	2847	3729	4000	4474	4881	345.5	312.3	309.6
	34	Hydril 563	34	2847	2847	2847	2847	2847	365.1		311.4	3118	3118	3118	3118	3118	365.1		309.6
	35	Hydril 511	35																
	36	Hydril 521	36	2725	2725	2725	2725	2725	348.2	313.4	311.4	2956	2956	2956	2956	2956	349.7	312.9	309.6
	37	Vallourec & Mannesmann New VAM	37	2156	2156	2156	2156	2156	365.7		311.4	2156	2156	2156	2156	2156	365.7		309.6
	38	Vallourec & Mannesmann VAM ACE	38	2156	2156	2156	2156	2156	365.1		311.4	2156	2156	2156	2156	2156	365.1		309.6
	39	Vallourec & Mannesmann VAM PRO	39																
	40	Vallourec & Mannesmann VAM TOP	40	2549	3139	3139	3139	3139	360.0		311.4	2942	3139	3139	3139	3139	361.6		309.6
	41	Vallourec & Mannesmann FJL	41																

(1) The closed-end displacement does not account for couplings. MPa × 145 = psi daN × 2.25 = lb daN.m × 7.38 = lb.ft mm × 0.0394 = in

Figure 3 – Casing data



API DRILL PIPE LIST AND BODY AND UPSET GEOMETRY

(API Spec 5D, 3rd edition, August 1, 1992)

Nominal diameter		Nominal weight	Wall thickness of pipe body	Inside diameter of pipe body	Steel grade	Upset					
						IU		EU		IEU	
(in)	(mm)	(lb/ft)	(mm)	(mm)		OD (mm)	ID (mm)	OD (mm)	ID (mm)	OD (mm)	ID (mm)
2 3/8	60.3	6.65	7.11	46.1	E X-G-S			67.5 67.5	46.1 39.7		
2 7/8	73.0	10.40	9.19	54.6	E X-G-S	73.0 73.0	33.3 41.4	81.8 82.6	54.6 49.2		
3 1/2	88.9	9.50	6.45	76.0	E	88.9	57.2	97.1	76.0		
3 1/2	88.9	13.30	9.35	70.2	E X-G-S	88.9 88.9	49.2 49.2	97.1 101.6	66.1 63.5		
3 1/2	88.9	15.50	11.40	66.1	E X-G-S	88.9 –	49.2 –	97.1 101.6	66.1 63.5	– 96.0	– 49.2
4	101.6	14.00	8.38	84.8	E X-G-S	101.6 101.6	69.8 66.8	114.3 117.5	84.8 77.8		
4 1/2	114.3	13.75	6.88	100.5	E	114.3	85.7	127.0	100.5		
4 1/2	114.3	16.60	8.56	97.2	E X-G-S	– –		127.0 131.8	97.2 90.5	118.3 118.3	80.2 73.0
4 1/2	114.3	20.00	10.92	92.5	E X-G-S	– –		127.0 131.8	92.5 87.3	121.4 121.4	76.2 71.5
5	127.0	16.25	7.52	112.0	E	127.0	95.2				
5	127.0	19.50	9.19	108.6	E X-G-S			– 146.1	– 100.0	131.8 131.8	93.7 90.5
5	127.0	25.60	12.70	101.6	E X-G-S			– 149.2	– 96.9	131.8 131.8	87.3 84.2
5 1/2	139.7	21.90	9.17	121.4	E X-G-S					141.3 141.3	101.6 96.9
5 1/2	139.7	24.70	10.54	118.6	E X-G-S					141.3 141.3	101.6 96.9
6 5/8	168.3	25.20	8.38	151.5	E					176.0	135.0
6 5/8	168.3	25.20	8.38	151.5	X-G-S					176.0	135.0
6 5/8	168.3	27.70	9.19	149.9	E X-G-S					176.0 176.0	135.0 135.0

mm x 0.0394 = in

Figure 4 – Drill pipe data

MPE 680 WELL TECHNOLOGY - FORMULA SHEETS

STRESS AND STRAIN

$$[\sigma]=\begin{bmatrix}\sigma_x & \tau_{xy} & \tau_{xz}\\ \tau_{xy} & \sigma_y & \tau_{yz}\\ \tau_{xz} & \tau_{yz} & \sigma_z\end{bmatrix}$$

$$I_1=\sigma_x+\sigma_y+\sigma_z$$

$$I_2=\tau_{xy}^2+\tau_{xz}^2+\tau_{yz}^2-\sigma_x\sigma_y-\sigma_x\sigma_z-\sigma_y\sigma_z$$

$$I_3=\sigma_x\left(\sigma_y\sigma_z-\tau_{yz}^2\right)-\tau_{xy}\left(\tau_{xy}\sigma_z-\tau_{xz}\tau_{yz}\right)+\tau_{xz}\left(\tau_{xy}\tau_{yz}-\tau_{xz}\sigma_y\right)$$

$$\sigma^3-I_1\sigma^2-I_2\sigma-I_3=0$$

$$\text{Center}=\frac{1}{2}\left(\sigma_{xx}+\sigma_{yy}\right),\ \text{Radius}=\sqrt{\frac{\left(\sigma_{xx}-\sigma_{yy}\right)^2}{4}+\tau_{xy}^2},\ \tan(2\theta)=\frac{2\tau_{xy}}{\sigma_{xx}-\sigma_{yy}}$$

$$\sigma_{oct}=\frac{1}{3}(\sigma_1+\sigma_2+\sigma_3)\qquad \tau_{oct}=\frac{1}{3}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2}\qquad \sigma_m=\frac{1}{3}(\sigma_1+\sigma_2+\sigma_3)$$

$$\varepsilon_{xx}=\frac{\partial u}{\partial x},\ \varepsilon_{yy}=\frac{\partial v}{\partial y},\ \varepsilon_{zz}=\frac{\partial w}{\partial z},\ \gamma_{xy}=2\varepsilon_{xy}=\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}$$

$$\sigma_{rr}=\frac{p_i r_i^2-p_o r_o^2}{r_o^2-r_i^2}-\frac{r_i^2 r_o^2}{r^2\left(r_o^2-r_i^2\right)}(p_i-p_o)$$

$$\sigma_{\theta\theta}=\frac{p_i r_i^2-p_o r_o^2}{r_o^2-r_i^2}+\frac{r_i^2 r_o^2}{r^2\left(r_o^2-r_i^2\right)}(p_i-p_o)$$

$$\sigma_{zz}=\frac{p_i r_i^2-p_o r_o^2}{r_o^2-r_i^2}+\frac{F}{\pi\left(r_o^2-r_i^2\right)}$$

$$\sigma_{rr}=\frac{\alpha E(T_i-T_o)}{2(1-\nu)\ln\left(\frac{r_o}{r_i}\right)}\left[-\ln\frac{r_o}{r}+\frac{r_i^2\left(r_o^2-r^2\right)}{r^2\left(r_o^2-r_i^2\right)}\ln\frac{r_o}{r_i}\right]$$

$$\sigma_{\theta\theta}=\frac{\alpha E(T_i-T_o)}{2(1-\nu)\ln\left(\frac{r_o}{r_i}\right)}\left[1-\ln\frac{r_o}{r}-\frac{r_i^2\left(r_o^2+r^2\right)}{r^2\left(r_o^2-r_i^2\right)}\ln\frac{r_o}{r_i}\right]$$

$$\sigma_{zz}=\sigma_{rr}+\sigma_{\theta\theta}$$

$$u_{(\text{closed end})}=\frac{r}{E\left(r_o^2-r_i^2\right)}\left[(1-2\nu)\left(p_i r_i^2-p_o r_o^2\right)+\frac{(1+\nu)r_i^2 r_o^2}{r^2}(p_i-p_o)-\nu\frac{F}{\pi}\right]$$

$$u_{(\text{open end})}=\frac{r}{E\left(r_o^2-r_i^2\right)}\left[(1-\nu)\left(p_i r_i^2-p_o r_o^2\right)+\frac{(1+\nu)r_i^2 r_o^2}{r^2}(p_i-p_o)\right]$$

ROCK MECHANICS

$$J_2 = \frac{1}{6}\left[(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2\right]$$

$$\sigma_m - P_o = \frac{1}{3}(\sigma_1+2\sigma_3)-P_o$$

$$\tau = \tau_0 + \sigma' \tan\phi$$

$$\tau = \frac{1}{2}\left(\sigma_1'-\sigma_3'\right)\cos\phi$$

$$\sigma' = \frac{1}{2}\left(\sigma_1'+\sigma_3'\right)-\frac{1}{2}\left(\sigma_1'-\sigma_3'\right)\sin\phi$$

$$\sigma_r = P_w$$
$$\sigma_\theta = \sigma_x+\sigma_y-P_w-2\left(\sigma_x-\sigma_y\right)\cos(2\theta)-4\tau_{xy}\sin(2\theta)$$
$$\sigma_z = \sigma_{zz}$$
$$\tau_{\theta z} = 2\left(\tau_{yz}\cos\theta-\tau_{xz}\sin\theta\right)$$
$$\tau_{rz} = \tau_{r\theta} = 0$$

$$\sigma_x = \left(\sigma_H\cos^2\beta+\sigma_h\sin^2\beta\right)\cos^2\gamma+\sigma_v\sin^2\gamma$$
$$\sigma_y = \left(\sigma_H\sin^2\beta+\sigma_h\cos^2\beta\right)$$
$$\sigma_{zz} = \left(\sigma_H\cos^2\beta+\sigma_h\sin^2\beta\right)\sin^2\gamma+\sigma_v\cos^2\gamma$$
$$\tau_{xz} = \frac{1}{2}\left(\sigma_H\cos^2\beta+\sigma_h\sin^2\beta-\sigma_v\right)\sin(2\gamma)$$
$$\tau_{yz} = \frac{1}{2}\left(\sigma_h-\sigma_H\right)\sin(2\beta)\sin\gamma$$
$$\tau_{xy} = \frac{1}{2}\left(\sigma_h-\sigma_H\right)\sin(2\beta)\cos\gamma$$

Borehole fracturing

$$P_{wf} = \sigma_x+\sigma_y-P_0-2\left(\sigma_x-\sigma_y\right)\cos(2\theta)-4\tau_{xy}\sin(2\theta)-\frac{\tau_{\theta z}^2}{\sigma_z-P_0}$$

which for symmetric conditions and no shear stresses becomes $P_{wf} = 3\sigma_{min}-\sigma_{max}-P_0$

Borehole collapse

$$\sigma_1 = \frac{1}{2}(\sigma_\theta+\sigma_z)+\frac{1}{2}\sqrt{(\sigma_\theta-\sigma_z)^2+4\tau_{\theta z}^2}$$

The direction of failure is determined by the size of σ_x and σ_y (i.e. $\theta = 0^o$ or $\theta = 90^o$)

$$\frac{P_{LOT}+P_0}{\sigma_v}+\sin^2\gamma = \left(3\sin^2\beta-\cos^2\beta\cos^2\gamma\right)\frac{\sigma_k}{\sigma_v}+\left(3\cos^2\beta-\sin^2\beta\cos^2\gamma\right)\frac{\sigma_l}{\sigma_v}$$

which on short form becomes:

$P' = a\dfrac{\sigma_k}{\sigma_v}+b\dfrac{\sigma_l}{\sigma_v}$ where σ_H is the largest of σ_k, σ_l

PRESSURE

$P[\text{bar}] = 0.098\cdot MW[\text{s.g.}]\cdot D[\text{m}]$

1 bar = 0.1 MPa

GEOMETRICAL PLANNING

$$\gamma = \tan^{-1}\left(\frac{H_t - R}{V_t - V_{KOP}}\right) + \sin^{-1}\left(\frac{R\cos(x)}{V_t - V_{KOP}}\right), \text{where } \tan(x) = \left(\frac{H_t - R}{V_t - V_{KOP}}\right) \text{ and } DLS = \frac{5400}{\pi R}$$

BUOYANCY

$$\beta = 1 - \frac{\rho_o A_o - \rho_i A_i}{\rho(A_o - A_i)}$$

$$\beta = 1 - \frac{\sum_{k=1}^{n} D_k(\rho_o R_k^2 - \rho_i r_k^2)}{\rho_{steel} \sum_{k=1}^{n} D_k(R_k^2 - r_k^2)}$$

TORQUE AND DRAG

$$F_2 = F_1 + \beta \Delta L w\{\cos\alpha \pm \mu \sin\alpha\}$$

$$T = \mu r \beta w \Delta L \sin\alpha$$

$$F_2 = F_1 e^{\pm\mu|\theta_2 - \theta_1|} + \beta w \Delta L \left\{\frac{\sin\alpha_2 - \sin\alpha_1}{\alpha_2 - \alpha_1}\right\}$$

$$T = \mu r N = \mu r F_1 |\theta_2 - \theta_1|$$

$$\psi = \tan^{-1}\left(\frac{V_h}{V_r}\right) = \tan^{-1}\left(\frac{60 V_h (m/s)}{2\pi N_r (rpm) r(m)}\right)$$

$$F_2 = F_1 + \beta w \Delta L \cos\alpha \pm \mu \beta w \Delta L \sin\alpha \sin\psi$$

$$T = r \mu \beta w \Delta L \sin\alpha \cos\psi$$

$$F_2 = F_1 + F_1(e^{\pm\mu|\theta_2 - \theta_1|} - 1)\sin\psi + \beta w \Delta L \left\{\frac{\sin\alpha_2 - \sin\alpha_1}{\alpha_2 - \alpha_1}\right\}$$

$$T = \mu r N = \mu r F_1 |\theta_2 - \theta_1| \cos\psi$$

STUCK PIPE

$F_{FREE} = \mu(\beta w h \sin(\gamma) + d h \Delta P)$ where h is the effective length of stuck pipe

SURVEY CALCULATION

$$\theta = \cos^{-1}(\sin\alpha_1 \sin\alpha_2 \cos(\beta_2 - \beta_1) + \cos\alpha_1 \cos\alpha_2)$$

$$\Phi = \frac{2}{\theta}\tan\left(\frac{\theta}{2}\right)$$

$$\Delta N = \Phi \frac{\Delta L}{2}(\sin\alpha_1 \cos\beta_1 + \sin\alpha_2 \cos\beta_2)$$

$$\Delta E = \Phi \frac{\Delta L}{2}(\sin\alpha_1 \sin\beta_1 + \sin\alpha_2 \sin\beta_2)$$

$$\Delta V = \Phi \frac{\Delta L}{2}(\cos\alpha_1 + \cos\alpha_2)$$

GEOMECHANIC EVALUATION

$$LOT = 2\sigma_a - P_0$$

$$P_{wf}(\alpha) = P_{wf}(0) + \tfrac{1}{3}(P_0 - P_0^*)sin^2\alpha$$

$$P_{wf}(0) = \frac{P_{wf}(\alpha) + \left(\sigma_o - \tfrac{1}{2}P_0\ \right)sin^2\alpha}{1 + \tfrac{1}{2}sin^2\alpha}$$

$$\Delta\sigma_a = \frac{1 - 2\nu}{1 - \nu}\Delta P_0$$

$$\Delta P_{wf} = \frac{1 - 3\nu}{1 - \nu}\Delta P_0$$

DATA NORMALIZATION

$$d_1^{RKB} = \frac{D}{D - \Delta h} d_2^{RKB}$$

$$d_2^{wf} = \frac{D_1}{D_2} d_1^{wf} + \frac{D_2^w - D_1^w}{D_2} d^{sw}$$

RISER MARGIN

$$d_{min} = \frac{d_{P_0} D - 1.03 h_w}{D - h_f - h_w}$$

CASING DESIGN

$$P_{burst} = \frac{2t}{OD}\sigma_{tensile}$$

$$P_{collapse} = \frac{2CE}{1 - \nu^2}\left[\frac{1}{\left(\frac{OD}{t} - 1\right)^2 \frac{OD}{t}}\right]$$

$$\frac{\sigma_t}{\sigma_{yield}} = \frac{\sigma_a}{2\sigma_{yield}} \pm \sqrt{1 - \frac{3}{4}\left(\frac{\sigma_a}{\sigma_{yield}}\right)^2}$$

SOME UNITS

1 bar = 14.5 psi

1 ft = 12 in = 0.3048 m

1 lbf = 4.45 N

PRESSURE LOAD SUMMARY FOR CASING DESIGN

Note that the full casing design manual contains many more special cases and different correction criteria.

PIPE	*LOADING*	*INTERNAL PRESSURE*	*EXTERNAL PRESSURE*
Surface and intermediate casing	Burst while drilling	Gas gradient of 0.2 s.g. or actual	* Hydrostatic head from MSL before wellhead is installed. * Hydrostatic head from surface after wellhead is installed. Mud (previous section) above top of cement (TOC) Rock on outside: Pore pressure gradient below TOC Casing on outside: Seawater gradient below TOC
Surface and intermediate casing	Burst while in production	Mud plus trapped annular pressure	
Production casing	Burst	Leaking tubing: Shut-in tubing pressure plus 70 bar at top of completion fluid.	
Tubing	Burst	Shut-in tubing pressure plus 70 bar at surface plus gas gradient to reservoir.	Completion fluid gradient inside casing.
Surface and intermediate casing	Collapse during installation	1. Lost circulation: mud gradient 2. while cementing: displacing fluid gradient	* Hydrostatic head from MSL before wellhead is installed. * Hydrostatic head from surface after wellhead is installed. 1. Mud gradient 2. Cement gradient below TOC
Surface and intermediate casing	Collapse while drilling	Based on lost circulation while drilling next section.	* Hydrostatic head from MSL before wellhead is installed. * Hydrostatic head from surface after wellhead is installed. Mud (previous section) above top of cement (TOC) Rock on outside: Pore pressure gradient below TOC Casing on outside: Seawater gradient below TOC
Surface and intermediate casing	Collapse while in production	Mud base gradient	
Production casing	Collapse while in production	Plugged perforations / full evacuation to formation fluid	
Production casing	Collapse during installation	Mud gradient to fluid level.	Mud gradient to surface.
Tubing	Collapse	Full evacuation to formation fluid.	Completion fluid gradient inside casing.

BIAXIAL LOADING

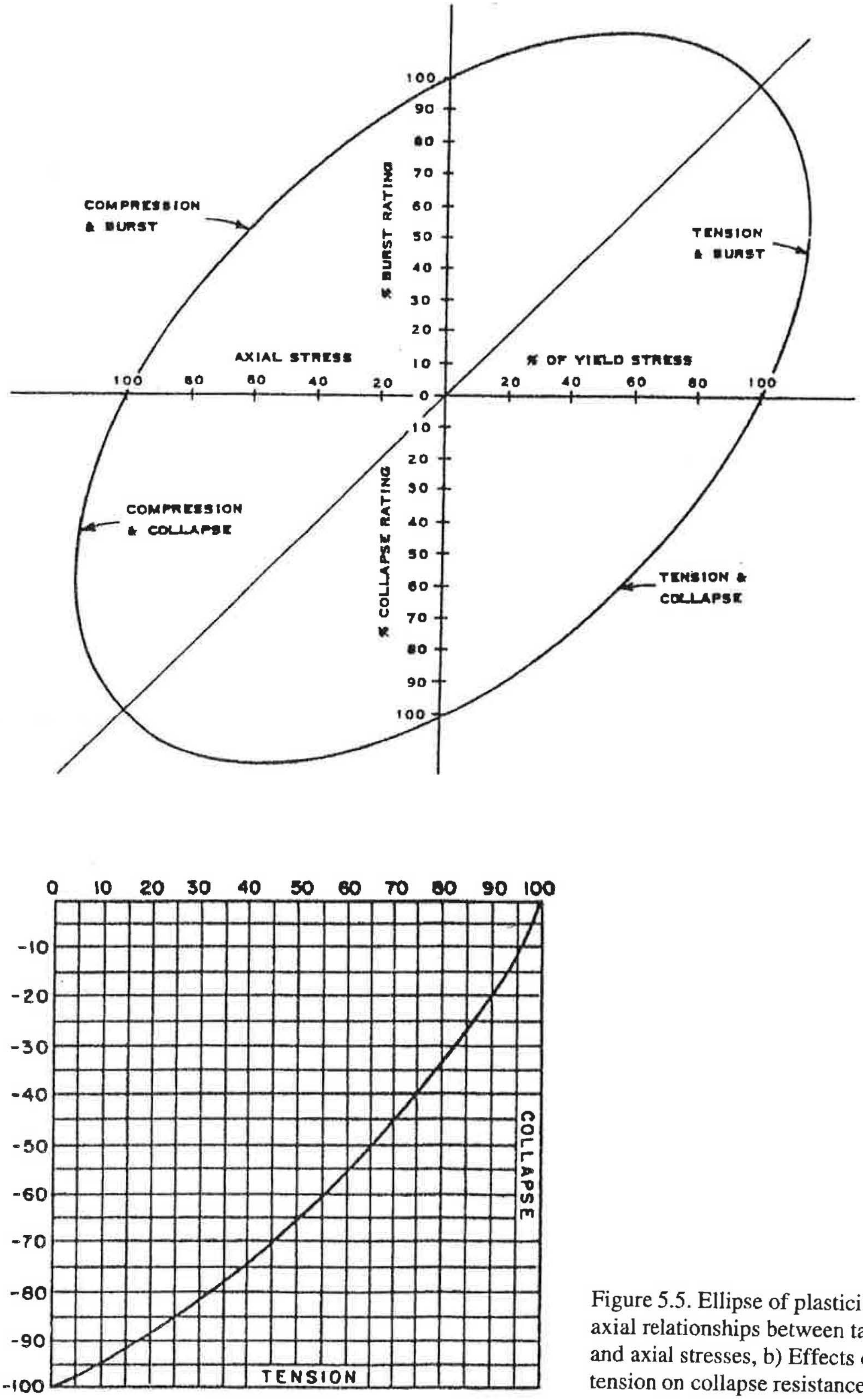


Figure 5.5. Ellipse of plasticity. a) Bi-axial relationships between tangential and axial stresses, b) Effects of axial tension on collapse resistance.