FACULTY OF SCIENCE AND TECHNOLOGY

Department of Petroleum Engineering

SUBJECT: PET 600 – Well Completion

DATE: 18 December 2015

TIME: 0900-1300

AID: Calculator

THE EXAM CONSISTS OF TWO SECTIONS ON 22 PAGES (INCLUDING FRONT PAGE). AFTER EACH SECTION YOU FIND USEFUL EQUATIONS AND OTHER INFORMATION.

DO NOT WRITE YOUR ANSWERS ON THE EXAM SHEET. YOU MUST USE ORDINARY ANSWER SHEETS SO THAT WE HAVE TWO COPIES OF YOUR ANSWERS.

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----- EXAM SECTION A -----

PART I

Five short questions each with three alternative answers (multiple choice). Please indicate on your answer sheet the answer that you think is most correct.

Maximum score is 10 points.

Question I-1: Flow efficiency and skin factor

(2p) Injection pressure decreases …

Options:

A. … if the skin factor remains constant.
B. … if the skin factor decreases.
C. … if the skin factor increases.

Question I-2: Well deviated from vertical

(2p) Well deviation skin factor correlations are those of …

Options:

A. … Cinco and Besson.
B. … Karakas and Tariq.
C. … Vogel and Fetkovich.

Question I-3: Perforation length

(2p) Perforations extending beyond the damaged zone …

Options:

A. … are to be avoided due to low productivity.
B. … give the same skin effect as those terminating inside the damaged zone.
C. … give low skin value if deep enough.

Question I-4: Slot recovery

(2p) Slot recovery means to …

Options:

A. … remove completion, set cement plugs and remove wellhead.
B. … remove completion, plug and abandon the original well path, set whipstock and sidetrack.
C. … remove completion, set deep and shallow barrier plug in production casing and recover the wellhead.

Question I-5: Clean-up of long horizontal reservoir section

(2p) During clean-up of long horizontal reservoir sections …

Options:

A. … the heel has a disadvantage due to low flow velocity.
B. … high-permeability zones close to the heel clean up with initial high drawdown.
C. … the filter cake lift-off pressure is optimised at the toe.

PART II

Provide short answers on your answer sheet.

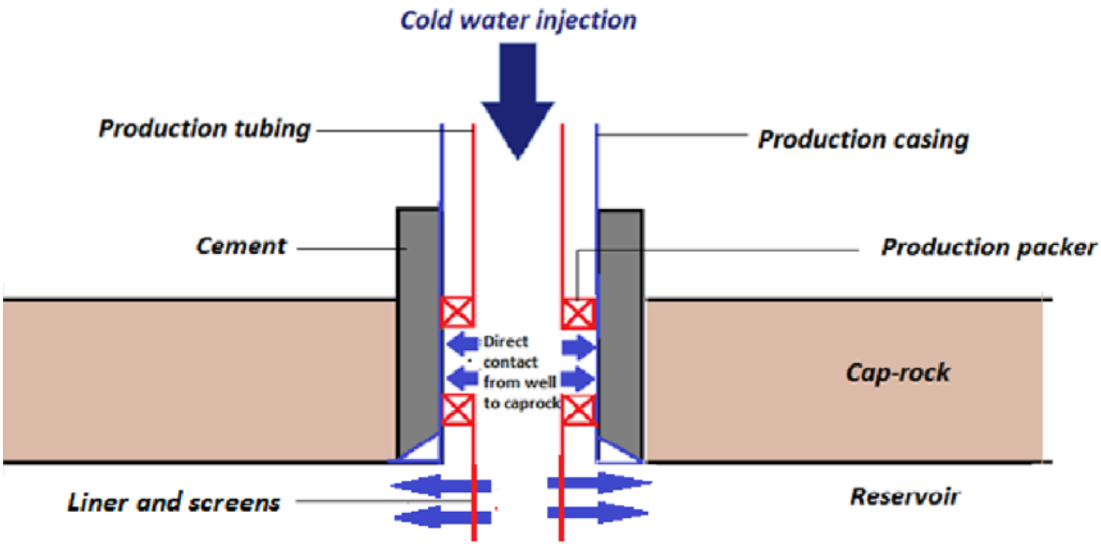
Maximum score is 10 points.

Question II-1: Relationship between UCS and TCS2

- Linear Mohr-Coulomb failure envelope
  - TCS2 = UCS + 2*tanβ*tanβ (MPa)
  - $\beta = 45° + \varphi/2$
  - φ = internal angle of friction

(2p) For a sandstone reservoir section, assume a reasonable value of friction angle and produce an equation to calculate TCS2 from UCS.

Question II-2: Super-injector 9900 m^3/day

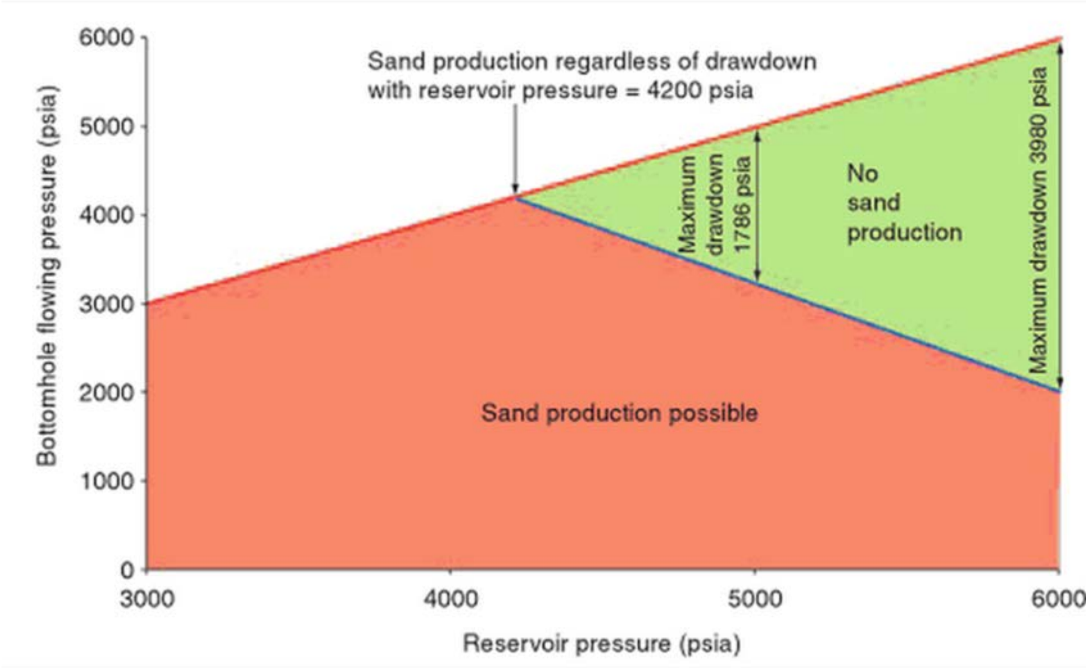


(1p) In which way does the temperature in the cap-rock change?
(1p) How does the cap-rock temperature change affect the cap-rock fracturing pressure?

Question II-3: Well clean-up and flow initiation

(2p) Give at least two reasons to perform a well clean-up.

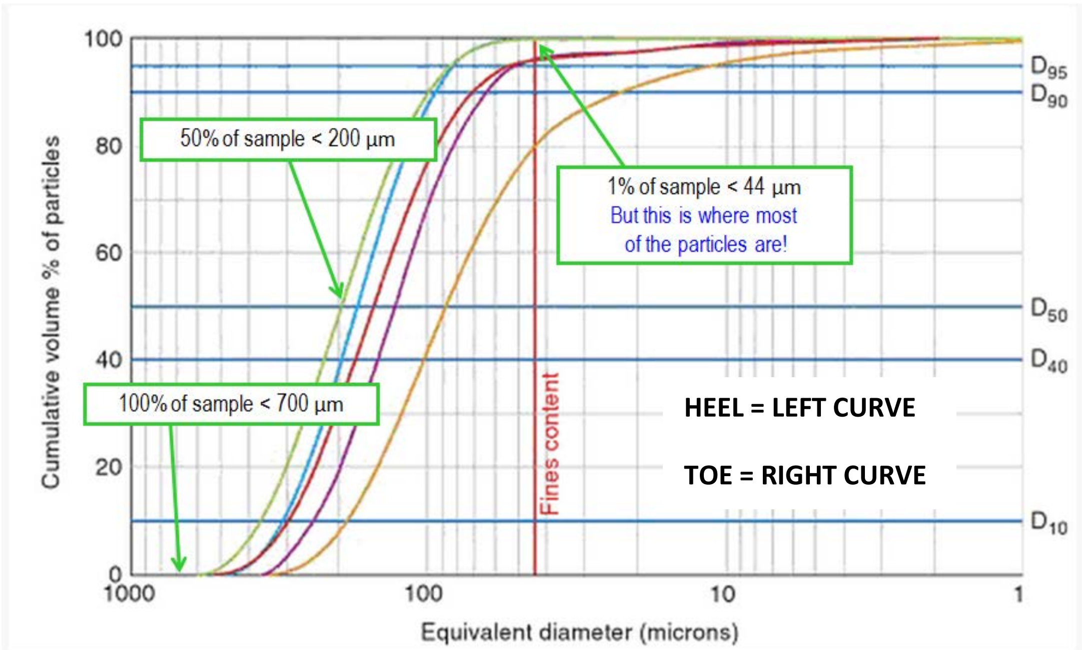
Question II-4: Consider an oil reservoir with an active water drive



Bellarby, 2009

(1p) Would you install sand control? State yes or no.
(1p) Explain why you make this choice.

Question II-5: Grain size distribution for five 10-meter reservoir intervals



Adapted from Bellarby, 2009

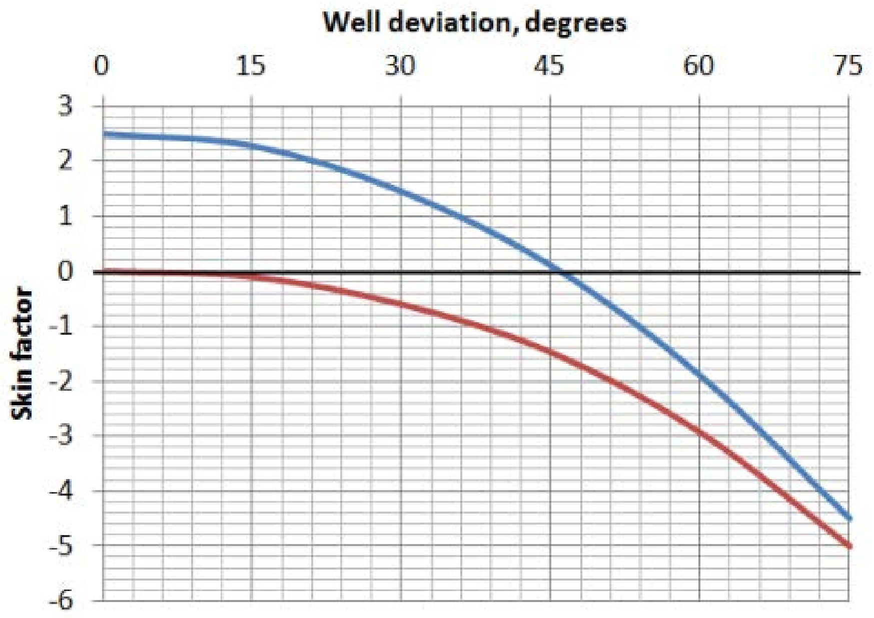
(1p) For the rightmost curve, report your observations pertaining the grain size distribution.
(1p) For the selected SAS lower completion, explain how you would complete the toe section (rightmost curve) differently than the other four intervals.

PART III

Provide answers on your answer sheet.

Maximum score is 15 points.

In your homework you plotted skin factor versus well deviation angle from vertical as exemplified below. The lower completion is C&P.



Question III-1: Combined perforation and damage skin factor

(2p) State the value of the combined perforation skin and damage skin (S_{dp}) in vertical well. (3p) Explain how to read S_{dp} in a 45-degree well and state value.

Question III-2: Skin and well deviation

(5p) What do you conclude from the observation that the two lines get closer the more horizontal the well is?

Question III-3: Crushed zone skin

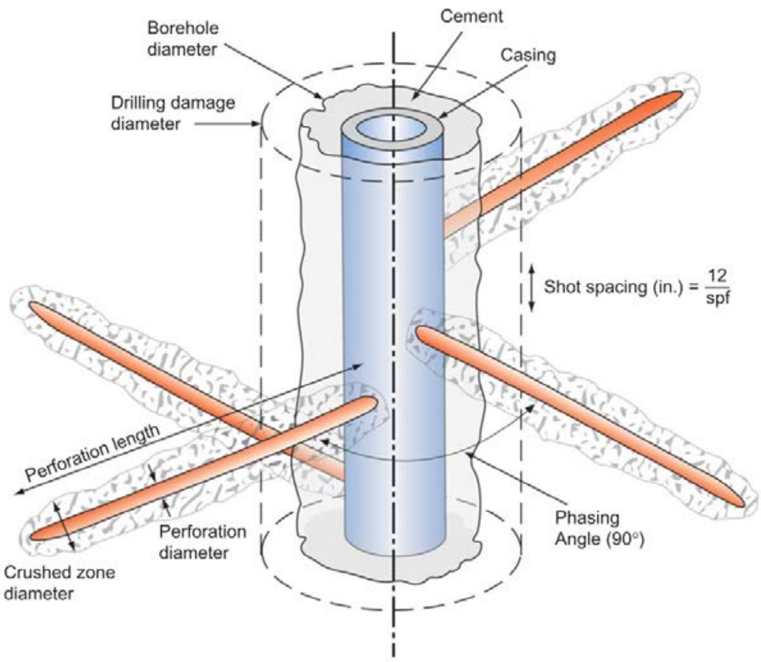
(3p) Explain how the crushed zone skin factor depends upon well deviation. (2p) How does it plot on the figure above?

PART IV

Provide answers on your answer sheet.

Maximum score is 15 points.

Consider one foot of perforation length as shown below. The shot-density is 4 shots per foot (spf) and the axial shot spacing is 3 inch. The perforation diameter is 1.65 cm, the crushed zone diameter is 2.54 cm and the perforation length is 47 cm. The total perforated interval is 100 ft and the oil production rate is 500 Sm3/day.



After Bellarby (2009)

Question IV-1: Perforation calculations

(1½p) What is the flow velocity as the oil leaves a perforation tunnel and entering liner?
(1½p) What is the total volume of the crushed zone considering the entire perforated length?

Question IV-2: Karakas & Tariq vertical well C&P skin model

(1p) Explain what the parameters S_h, S_{wb} and S_v represent.
(1p) Identify assumptions made for these parameters.
(1p) For each of the three parameters, state if $S>0$, $S<0$ or both.

Question IV-3: Crushed zone skin factor

(3p) Prepare sketch and derive equation for the crushed zone skin factor (S_c) as a function of axial shot spacing, perforation length, reservoir permeability, crushed zone permeability, crushed zone radius and perforation radius. Darcy's law: $\Delta p = q\mu B/kh\ (\ln r_1/r_2 + S)$

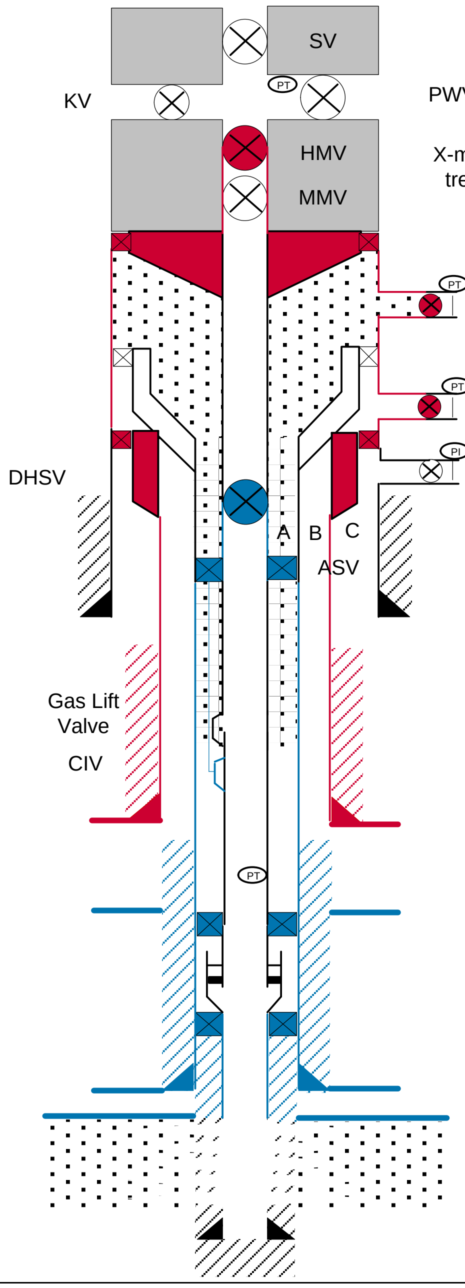
Question IV-4: Completion sequence

(3p) Please sort in the correct execution order the following operational steps in the completion program for a gas-lifted oil producer.

Operational steps in alphabetic order
Close FIV
Displace to packer fluid
Hand well to production
Install sand screens
Install Xmas tree
Open FIV
Perform OHGP
Retrieve barrier plug
Rig down BOP stack
Rig down WL
Rig up WL
Run tubing
Set shallow barrier plug

Question IV-5: Well barriers without ASV

(3p) Prepare a list of primary and secondary well barriers after failed ASV. Does this change cause any noticeable effects for the periodic barrier testing scheme? Below is WBS for initial case with functioning ASV.



Section A bonus question

Provide answers on your answer sheet.

Maximum score is 4 points.

NORSOK Standard

D-010

Rev. 4, June 2013

NOTE For wells that are injecting with a higher downhole pressure than the cap rock barrier integrity, the maximum reservoir pressure shall be stated on the WBS. Design requirements: Production packer to be set below cap rock.

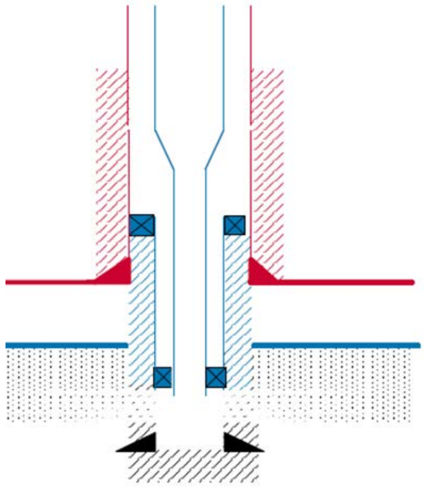


Figure 7.7.4.1

7.7.4 Injection / disposal wells

Injection / disposal wells are designed and used to inject liquids (water, brines, slurries or similar) and/or gases (including WAG, SWAG) into dedicated formation(s).

The well shall be constructed such that the injected media will be contained within the targeted formation zone (reservoir) without risk of out of zone injection.
For wells injecting at a pressure greater than the fracture closure pressure at the injection depth, the following applies:

a) the production packer shall be installed at a depth ensuring the injection or a casing leak below the production packer will not lead to fracturing of the cap rock or leak to shallower formation when applying maximum injection pressure (see figure 7.7.4.1);
b) the casing/liner cement shall be logged and as a minimum have bonding from upper most injection point to 30 m MD above top reservoir;
c) it shall be documented that the injection will not result in a reservoir pressure exceeding the strength of the cap rock.

Question B-1: Sizing

(½p) For 9⅝" production casing, what is maximum size for liner?

(½p) What size production tubing could you fit inside a liner of that size?

Question B-2: Production packer below the cap rock

(1p) Why is the production packer installed inside the reservoir?

Question B-3: Physical explanation

(2p) How to document requirement c) above if injecting above cap-rock fracturing pressure?

Used acronyms

ASV – annulus safety valve

BOP – blowout preventer

C&P – cased and perforated

FIV – formation isolation valve

OH – openhole

OHGP – openhole gravel-pack

SAS – stand-alone screen

TCS2 – triaxial compressive strength with 2 MPa lateral support

UCS – unconfined compressive strength

WBS – well barrier schematic

WL – wireline

Equations

$p_i - p_o = \frac{q_o B_o \mu_o l}{1.127 \times 10^{-3} A k_o}$	$J = \frac{0.00708 k_o h}{\mu_o B_o \ln(0.472 r_e / r_w)} = \frac{q_o}{(\overline{p_r} - p_w)}$
$\frac{q_o - q_b}{q_{o(max)} - q_b} = 1 - 0.2\frac{\overline{p_w}}{\overline{p_b}} - 0.8\left(\frac{\overline{p_w}}{\overline{p_b}}\right)^2$	$S = \left(\frac{k}{k_d} - 1\right)\ln\left(\frac{r_d}{r_w}\right)$
$S_h = \ln\left(\frac{r_w}{\alpha(r_w + l_p)}\right)$	$S_h = \ln\left(\frac{4 r_w}{l_p}\right)$
$S_{wb} = C_1 \exp(C_2 r_{wD})$	$S_v = 10^a h_D^{b-1} r_{pD}^b$
$S_t = \frac{h}{h_m} F(S_m + S_a) + S_c$	$S_{dp} = \left(\frac{k}{k_d} - 1\right)\ln\left(\frac{r_d}{r_w}\right) + \left(\frac{k}{k_d}\right)(S_p + S_\chi)$
$S_h = \ln\left[\frac{a + \sqrt{a^2 - (L/2)^2}}{(L/2)}\right] + \frac{\beta h}{L}\ln\left[\frac{\beta h}{2 r_w}\left(1 - \frac{2\ell_\delta}{\beta h}\right)^{-2}\right] - \ln\left(\frac{r_e}{r_w}\right)$	

----- EXAM SECTION B -----

Part I Integrity and upper completion

1 The NORSOK D-010 standard describes well integrity requirements, where well integrity is defined as “the application of __________, _______________, and ________________**solutions** to reduce risk of uncontrolled release of formation fluids throughout the life cycle of the well.

a. What are these **three solutions** to be filled in the blank space above?

b. Which of these solutions deals with design issues?

2 SINTEF and NPD had performed an integrity survey on injection and production well. Which of these shows a higher integrity leak problem?

3 The following two **Figures 1a & 1b** are completed wells, which shows X-mass tress (Yellow) placed on wellhead system. What is the difference between these with regard to X-mass tree? Tell your reason.

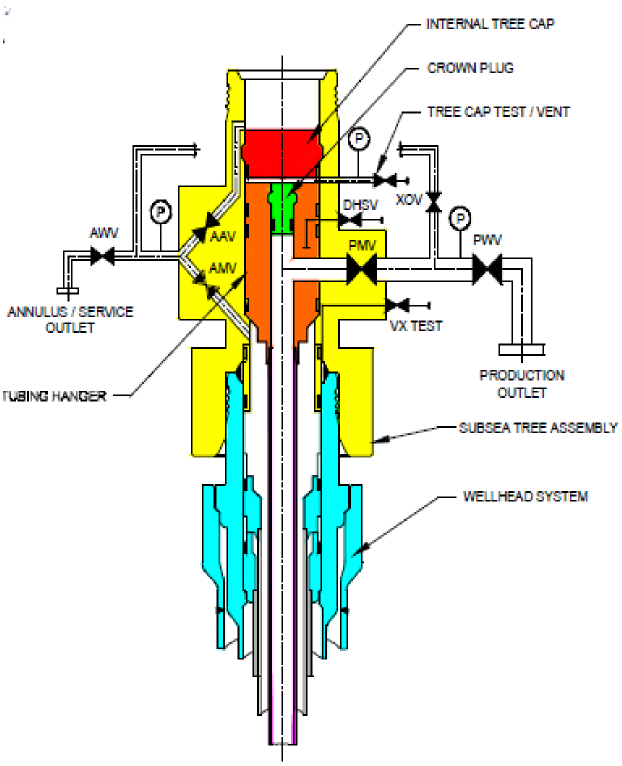


Figure 1a: Completed well

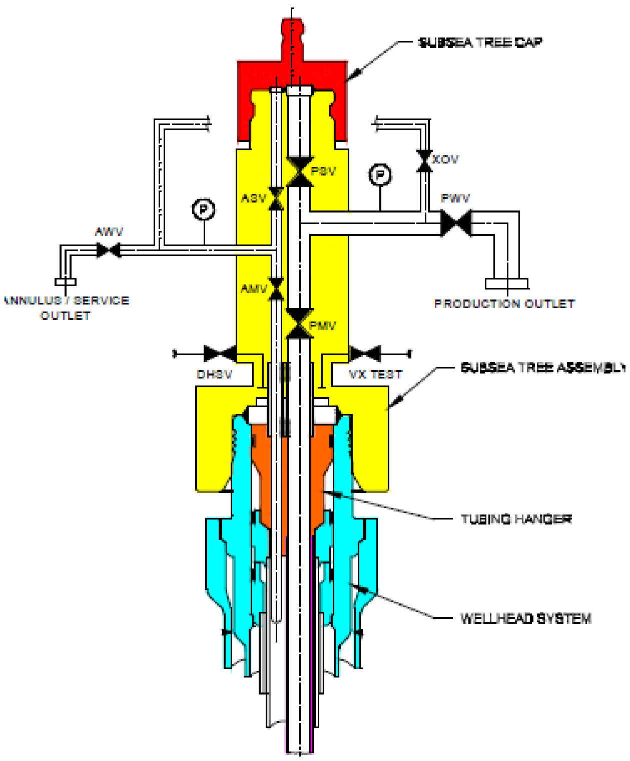


Figure 1b: Completed well

Part II Material testing and properties

4 Given two wires of the same material
The first wire stretched 8mm under a load of 60N.
The second wire with half the diameter and a quarter of the original length of the first wire is stretched by the same load.

Assuming that Hooke's law is obeyed, what is the extension of the second wire?(Choose the correct answer)

a) 1mm b) 4mm c) 8mm d) 16mm d) None of these

5 What is the unit of Young's modulus? (Choose the correct answer)
a) Nm^{-1} b) Nm c) Nm^{-2} d) Nm^{2} e) None of these.

6 **Figure 2** graphs show how force varies with extension and stress varies with strain for the loading of a metal wire

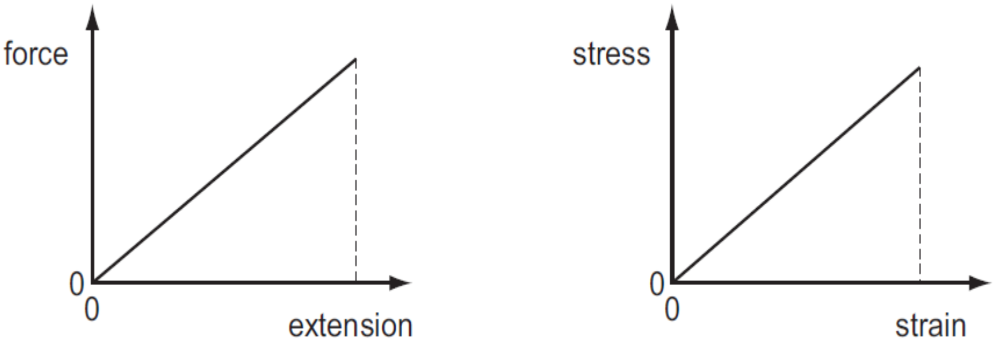


Figure 2

Based on **Figure 2**, the Young's modulus of the wire is equal to (Choose the correct answer)

a) The gradient of the force-extension graph
b) The area between the force-extension graph and the extension axis
c) The gradient of the stress-strain graph
d) The area between the stress-strain graph and the strain axis

7 Using **Figure 3**, <u>identify</u> which material has:
a) The highest yield stress
b) The highest tensile stress
c) The lowest ductility
d) The highest ductility
e) The highest Young's modulus

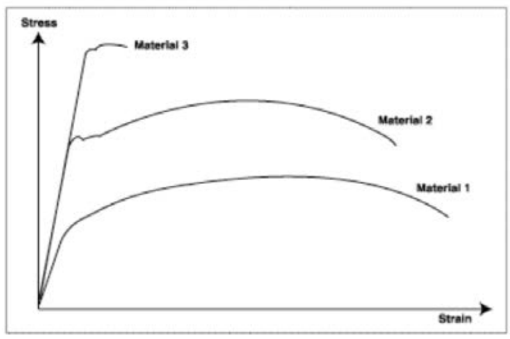


Figure 3

8 **Creep test**
a) Please sketch the expected creep test result showing the <u>four phases of deformation</u>

Part III Material selection

9 Assume a Sea Water (which is not aerated and contains chloride) to be used in an injection well. What kind of stainless steel would you recommend to be used for the tubing? Tell your reason why?

10 Assume the H_2S fractional concentration is 8ppm and the bottomhole pressure is 12,000psi. A company wants to use a low alloy Steel grade N-80. **Figure 4** is the assessment chart. Can this grade tubing be used in an environment where the pH value is

a) pH=5?

b) pH=3?

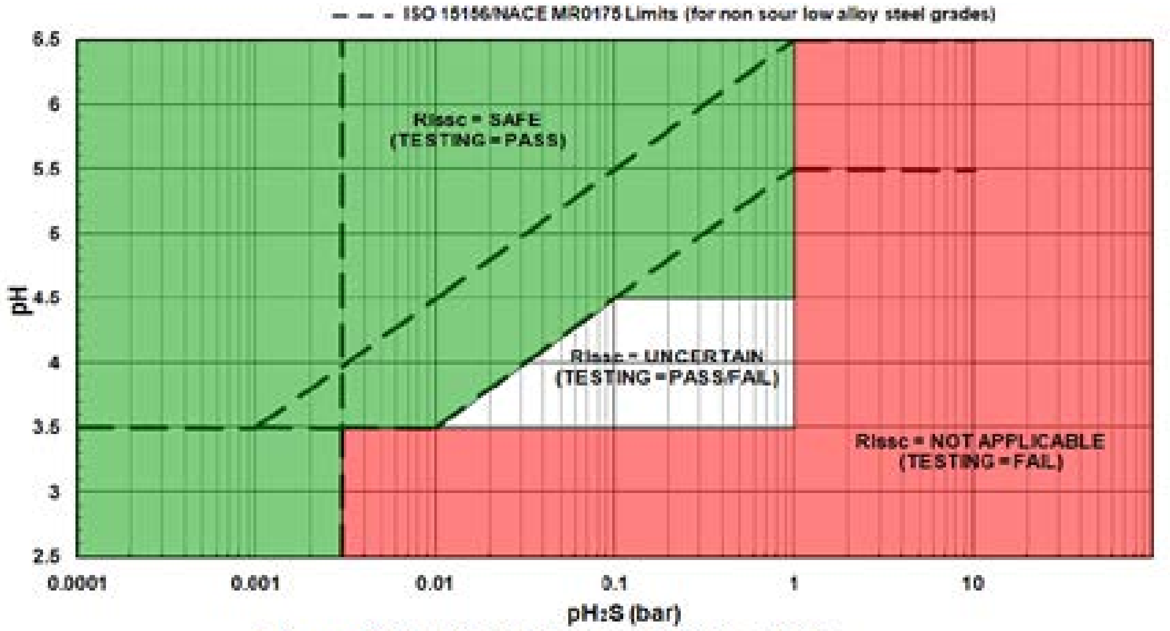


Figure 4: CARBON STEEL - ISO 11960 Grade N80

Part IV Tubing design

11 Assume a closed end thin walled cylinder, which is pressurized at the inner wall only with a pressure, *P*. The wall thickness is ''*t*'' and the inner radius is ''*r*''. Assume that NO SHEAR STRESS. The radial stress is given as $\sigma_r = -P$.

. **Your task**

a) Please derive that the hoop stress is given as the following

$$\sigma_\theta = \frac{Pr}{t}$$

b) Please derive that the axial stress is given as the following

$$\sigma_z = \frac{Pr}{2t}$$

c) Please derive the burst equation according to TRESCA failure criteria

12 Assume an open-ends thin walled cylinder of L-80 tubing is loaded internally only with an internal pressure, P. The tubing is not experiencing shear stress. Assume that the safety factor (SF = 1)

$$\sigma = \begin{bmatrix} \sigma_r & \tau \\ \tau & \sigma_\theta \end{bmatrix} = \begin{bmatrix} -5000 & 0 \\ 0 & 25000 \end{bmatrix} psi$$

Your task

a) What is the value of the axial stress?
b) What is the value of the internal pressure in psi?
c) What are the maximum and the minimum principal stress values in psi?
d) Does the tubing fail according to Maximum principal stress theory?
e) What is the value of the inner radius to wall thickness ratio (r/t) of the tubing?.
[**Hint:** Use Hoop stress]

13 A point in a structural component has a stress state given by the normal and shear stress as shown on the stress tensor. The Normal stresses are $\boldsymbol{\sigma}_{xx}$ = 50, $\boldsymbol{\sigma}_{yy}$ = 70MPa.

$$\sigma = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{bmatrix} = \begin{bmatrix} 50 & ? \\ ? & 70 \end{bmatrix}$$

The material is ductile and has yield strength of 300 MPa. The maximum and minimum principal stresses are given as ($\boldsymbol{\sigma_1}$= 260) MPa and ($\boldsymbol{\sigma_2}$ = -140) MPa as shown on the failure envelop (**Figure 5**).

Your task

a) What is the name of the failure envelope?
b) What is the condition of the material? (Fail or Safe) tell the reason
c) What was the value of shear stress (σ_{xy}) in the material?

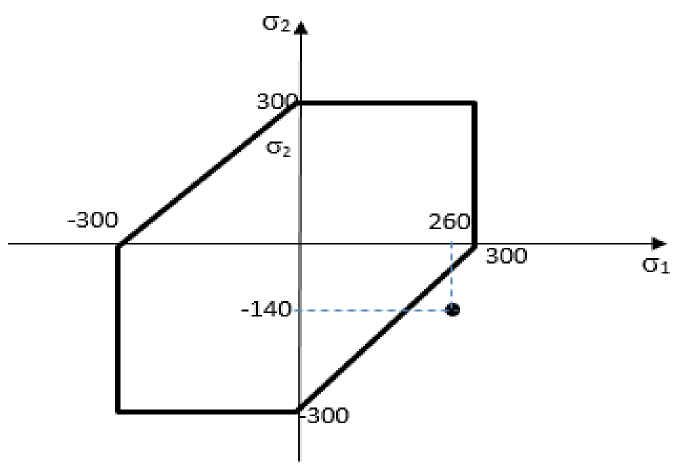


Figure 5: Failure envelop

14 Assume an open-and-closed end cylinder having inner and outer radius 1cm and 3 cm, respectively. Assume that the cylinder is loaded with internal and external pressures. The yield strength of the cylinder is 39MPa. **Figure 6** shows the stress distribution across the wall thickness of the cylinder.

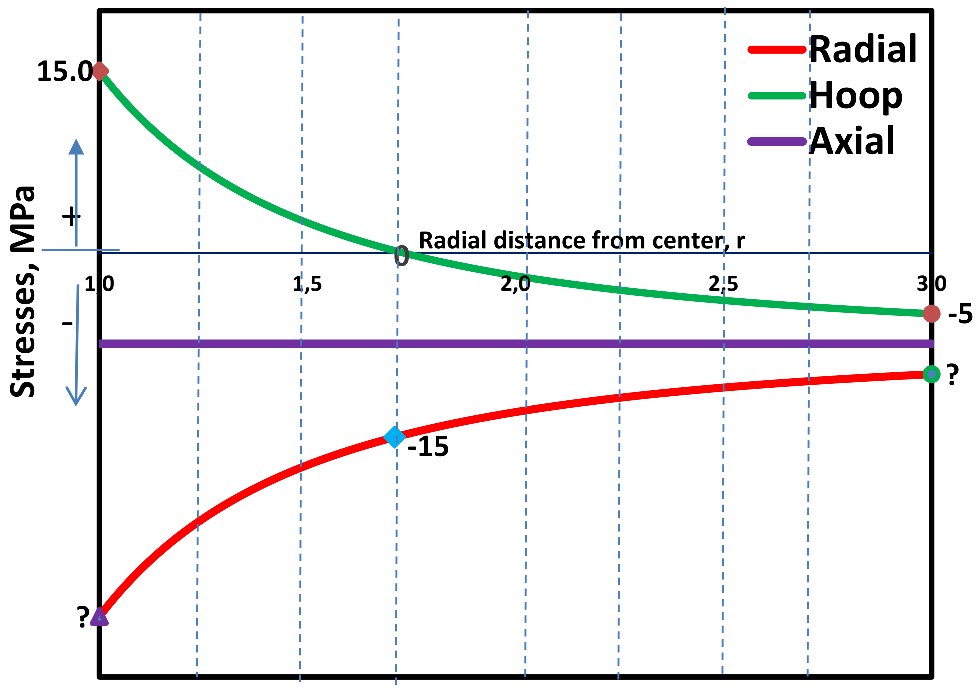


Figure 6: Stress fields in thickness of a thick walled cylinder

Your task

a) What are the values of radial stresses at the inner and the outer radius of the cylinder, in MPa?
b) What is the value of axial stress in the wall thickness of the cylinder in MPa?
c) What are the values of the inner and the outer pressures in MPa?
d) Does the tubing yield according to Tresca failure criteria at the inner wall of the cylinder?

15 Assume an open-end thick walled cylinder, which is loaded internally with an internal pressure P_a. at r = a. The outer pressure at r = b is P_b =0. No shear stress. The radial and hoop stresses at the inner wall the cylinder given as:

$$\sigma_r = -P_a \qquad\qquad \sigma_\theta = \frac{P_a(b^2 + a^2)}{b^2 - a^2}$$

Assume that the b = 2a. According to maximum principal stress theory, the pressure used to cause the inner wall yielding can be give as

$$P_y = \frac{3}{5}\sigma_y$$

Is this correct? Please show your work

16 **In Figure 7**, L-80 (OD=5'' & ID=4.75'') tubing was used as a production tubing. The geometrical factor of this tubing dimension gives approximately $\beta \approx 20.51$. The material property of the L-80 tube has been measured at laboratory temperature (i.e 75 °F). As you know very well, when the tubing is used in high temperature, the yield strength is de-rated and the temperature de-rating of L-80 tubing is 0.05%. A well has been injected through the annulus and suddenly was shut down due to some reason without unloading at the surface. The tube also shut-down at well head. Therefore, the assumed pressure profiles in the annulus and in the tubing along with the temperature profile are shown on **Figure 7**. In addition, the axial stress at Point C (i.e at depth 4000m) is 24769 psi.
(NB: 1 kpsi = 1000 psi)

Your task

a) What is temperature de-rated yield strength of the tubing at point C?

b) Is the tubing safe at point C? (**Hint**: **Use figure 7b** to evaluate the condition of the tubing)

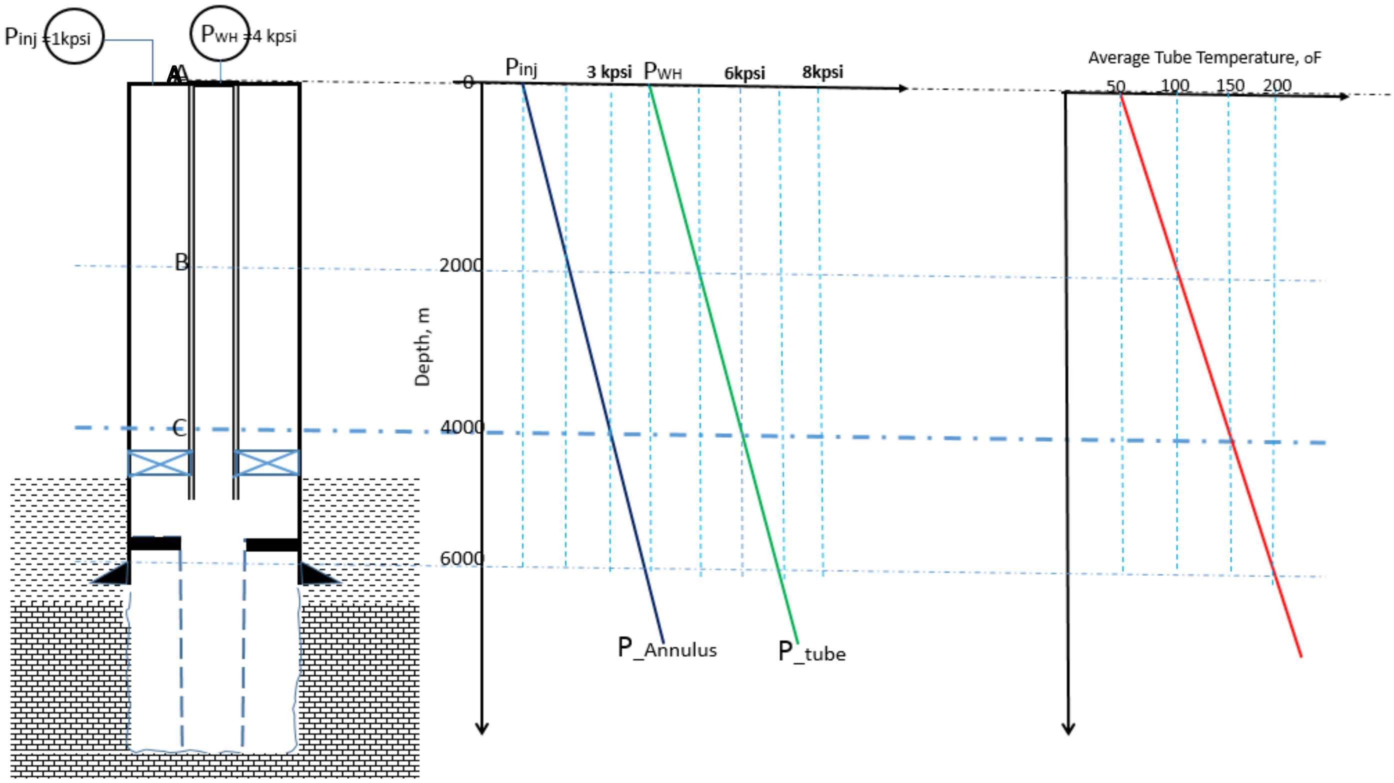


Figure 7a: Completed well & Pressure & temperature profiles

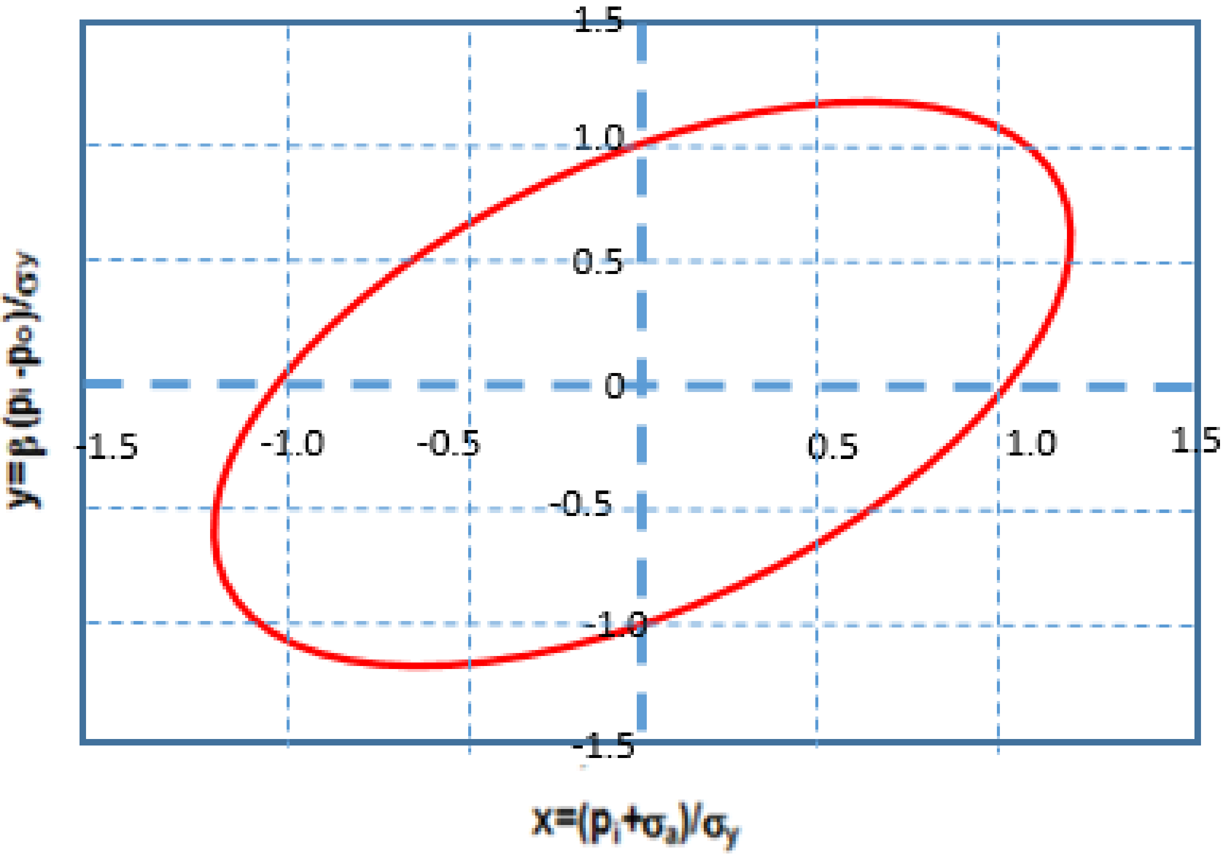


Figure 7b: Failure analysis envelope for tubing in completed well (Figure 7a)

Part V: Simulation

17 In StressCheck[TM]/Landmark, there are three types of connections used for Casing

a) What are the names of these connections?

18 To unseat packer and remove tubing, we need to apply an appropriate extra force on tubing. What is the name of the load that you used during StressCheck simulation?

19 **In Figure 8**, three loadings are shown. What is the condition of tubing due to the given three loading? If failure, what kind of failure (burst or collapse, or tensile) and under what axial load condition (compression or tension)?

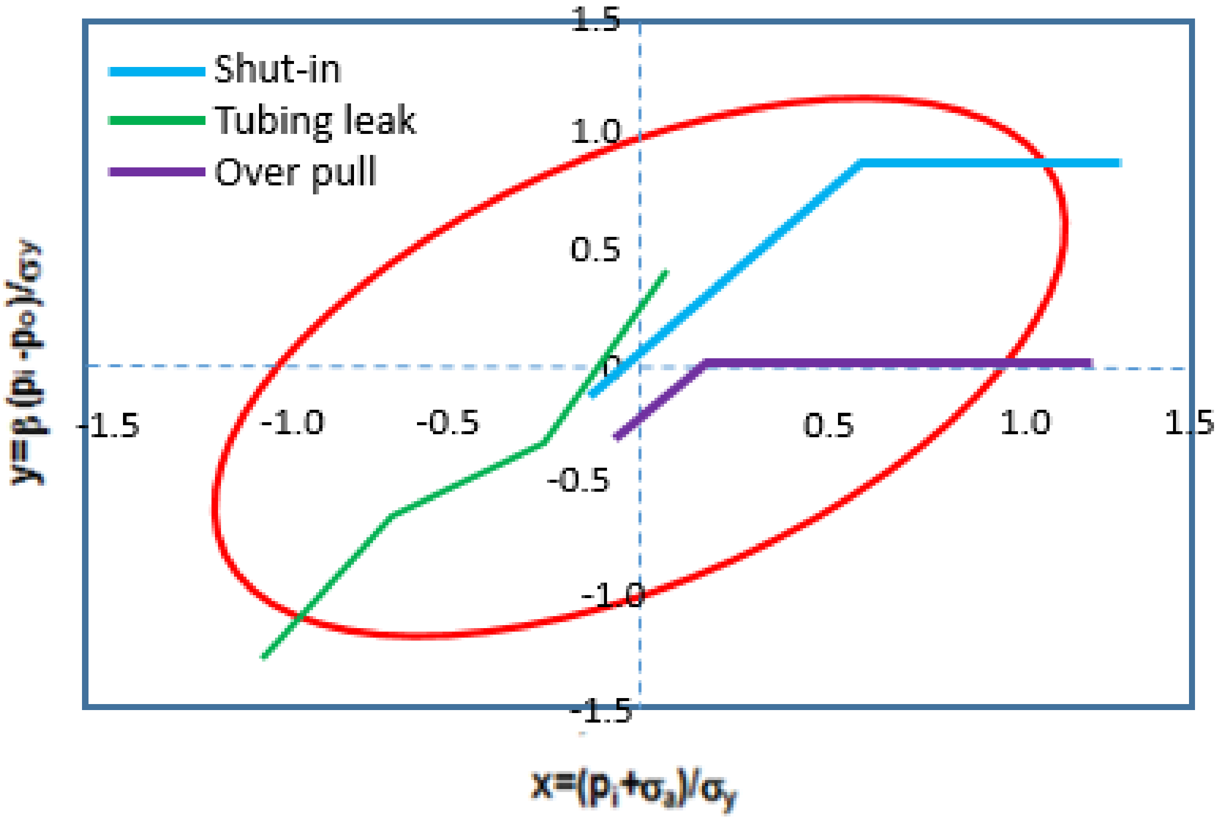


Figure 8: Dimensionless Von-Mises Failure analysis for tubing

Part VI: Corrosion

20 What is corrosion? Please write four elements for corrosion to occur

21 During flow in **Figure 9**, where do you think the tube could be exposed to erosional induced corrosion? Please re-design the geometry to solve the problem

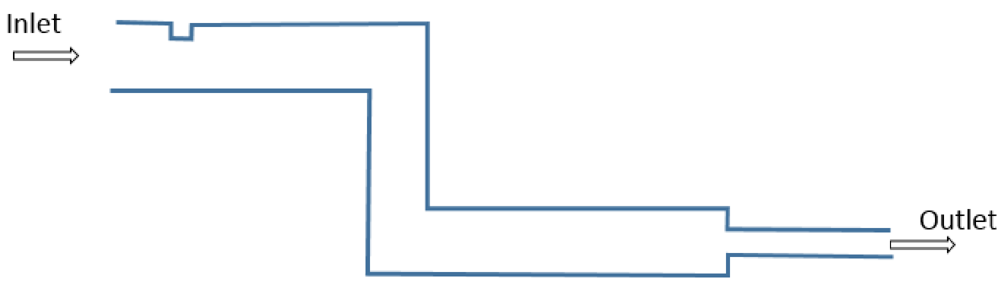


Figure 9: Flow in bended tube

22 Assume that Ti alloy is susceptible to Moisture environment. Under what state of stress state the Ti-alloy should be in order avoid stresses corrosion cracking (SCC)? Choose the right answer

a) Compression b) Tension c) Both tension and compression d) None of these

23 _______________is electrochemical protection technique used to protect structures such as buried pipelines, Subsea X-mass tree, oil-drilling rig, etc against corrosion.

Part VII: Conoco-Halliburton company-IO course (Give short answer)

24 During e-drilling solution visit at Forus, you have observed that the driller depth calculated based on the number of stands. But, actual depth (length of) of a drilling string is different from the driller depth. What do you think could be the reason?

25 During Halliburton and ConocoPhillips visit, you have been informed to know that both companies are investing a lot since the last 10 years on IO. What is IO all about? What is its advantages?

26 During visit at RIO center / Halliburton, an engineer who was in charge for visiting told us about his tasks. What is the primary task of RIO engineer who is working at onshore drilling center?

27 Can Statoil or any oil Company drill a single well alone? If not, which party/company is involved?

Formula sheet

Lame Equation for thick walled cylinder

Radial stress

$$\sigma_r = \frac{p_a a^2 - p_b b^2}{b^2 - a^2} - \frac{a^2 b^2}{(b^2 - a^2) r^2}(p_a - p_b) \qquad \text{A1}$$

Hoop stress

$$\sigma_\theta = \frac{p_a a^2 - p_b b^2}{b^2 - a^2} + \frac{a^2 b^2}{(b^2 - a^2) r^2}(p_a - p_b) \qquad \text{A2}$$

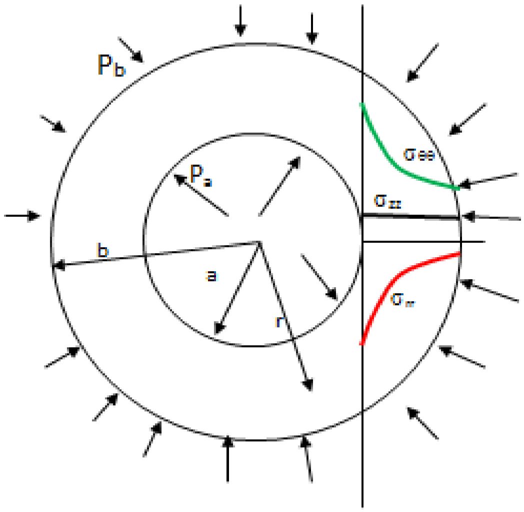


Figure A1: Stress distribution across the wall thickness

Axial stress: (Open and Closed end)

$$\sigma_a = \frac{p_a a^2 - p_b b^2}{b^2 - a^2} = \frac{1}{2}(\sigma_r + \sigma_\theta) \qquad \text{A3}$$

Special cases for Lame equation

a) **Internal pressure only**, (i.e P_b =0). Eq. A1 and A2 reduces to

$$\sigma_r = \frac{P_a a^2}{b^2 - a^2}\left(1 - \frac{b^2}{r^2}\right) \qquad \text{A4}$$

$$\sigma_\theta = \frac{P_a a^2}{b^2 - a^2}\left(1 + \frac{b^2}{r^2}\right) \qquad \text{A5}$$

Axial stresses (σ_z or σ_{zz} or σ_a)

$$\begin{cases} \sigma_z = 0 & Open-Ends \\ \sigma_z = 2\upsilon \dfrac{P_a a^2}{b^2 - a^2} & Closed-Ends \\ \sigma_z = \dfrac{P_a a^2}{b^2 - a^2} & Closed-and-Open-ends \end{cases} \qquad \text{A6}$$

b) **External pressure only**, (P_a =0). Eq. A1 and A2 reduces to

$$\sigma_r = -\frac{P_b b^2}{b^2 - a^2}\left(1 - \frac{a^2}{r^2}\right) \qquad \text{A7}$$

$$\sigma_\theta = -\frac{P_b b^2}{b^2 - a^2}\left(1 + \frac{a^2}{r^2}\right) \qquad \text{A8}$$

$$\begin{cases} \sigma_z = 0 & Open-Ends \\ \sigma_z = -2\upsilon \dfrac{P_b b^2}{b^2 - a^2} & Closed-Ends \\ \sigma_z = -\dfrac{P_b b^2}{b^2 - a^2} & Closed-and-Open-ends \end{cases} \qquad \text{A9}$$

Failure criteria

Tresca-Maximum shear stress theory

$$\sigma_y = \sigma_{\max} - \sigma_{\min} \qquad \text{A10}$$

Von_Mises- Maximum distortional energy theory

(Example for stresses in cylinder)

$$\sigma_y = \sqrt{\frac{1}{2}\left\{(\sigma_\theta - \sigma_r)^2 + (\sigma_r - \sigma_a)^2 + (\sigma_a - \sigma_\theta)^2\right\} + 3\tau^2} \qquad \text{A11}$$

Maximum principal stress ($\sigma_1 > \sigma_2 > \sigma_3$)

$\sigma_1 = \sigma_y$ (Since $\sigma_{max} = \sigma_1$) A12

2D stress and principal stress

2D stress tensor

$$\sigma = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{bmatrix} = \begin{bmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{bmatrix} \qquad \text{A13}$$

Principal stresses (Maximum and Minimum)

$$\sigma_{1,2} = \frac{\sigma_{xx} + \sigma_{yy}}{2} \pm \sqrt{(\frac{\sigma_{xx} - \sigma_{yy}}{2})^2 + \sigma_{xy}^2} \qquad \text{A14}$$

Stress, Strain/Hooke's law /yield stress temperature de-rating

$$\sigma = \frac{Load}{Area} \qquad \text{A15}$$

$$\varepsilon = \frac{\Delta L}{L_o} \qquad \text{A16}$$

$$\sigma = E\varepsilon \qquad \text{A17}$$

$$\sigma_y(T) = \sigma_y(75^o F)[1 - x\%\{T - 75\}] \qquad \text{A18}$$

Partial pressure of H_2S (pH_2S)

pH_2S = Total bottom hole pressure **X** fraction of H_2S present A18