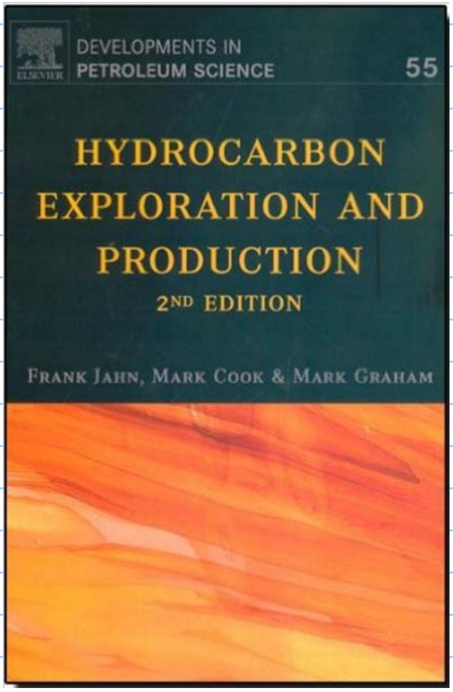
ME683 - Field development and operations . Prof. Milan Stanko (NTNU)

- 3.12.2018 – 07.12.2018 09:00 → 14:00
- excel exercises
- evaluation
  - Prof. Liberato Haule
  - 10% delivery of exercises
  - 2x15% mini quiz (2018, 2019)
  - 60% final exam (2019)
- Reference material :



Frank Jahn, Mark Cook, Mark Graham

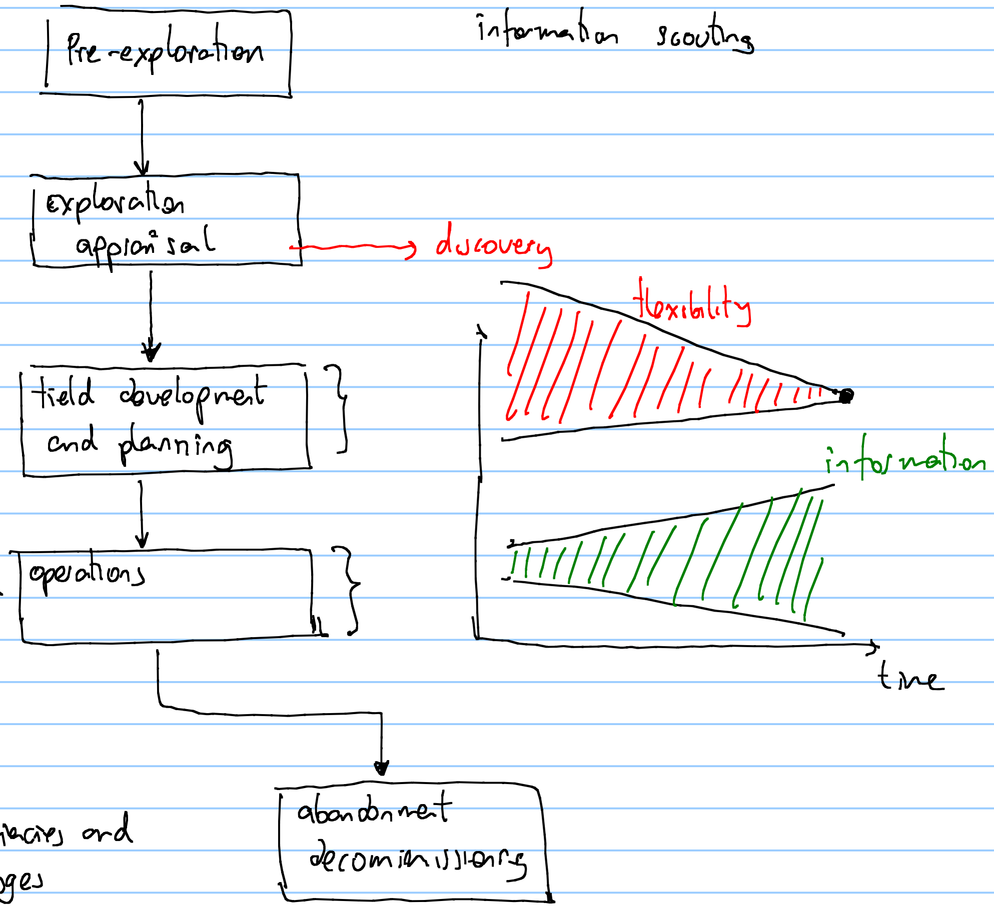
- material from previous courses : http://www.ipt.ntnu.no/~stanko/files/Courses/ME683

http://www.ipt.ntnu.no/~stanko/files/Courses/TPG4230

Milan's youtube channel → "playlist" → TPG4230 Field development and operations (2017)

https://www.youtube.com/channel/UCWMfsCe1NQMgx4UZWrVvFg

Life cycle of an oil/gas offshore field



- produce efficiently
- increase uptime

Nr operational days in year

- trouble shooting
- deal with deficiencies and exploit advantages

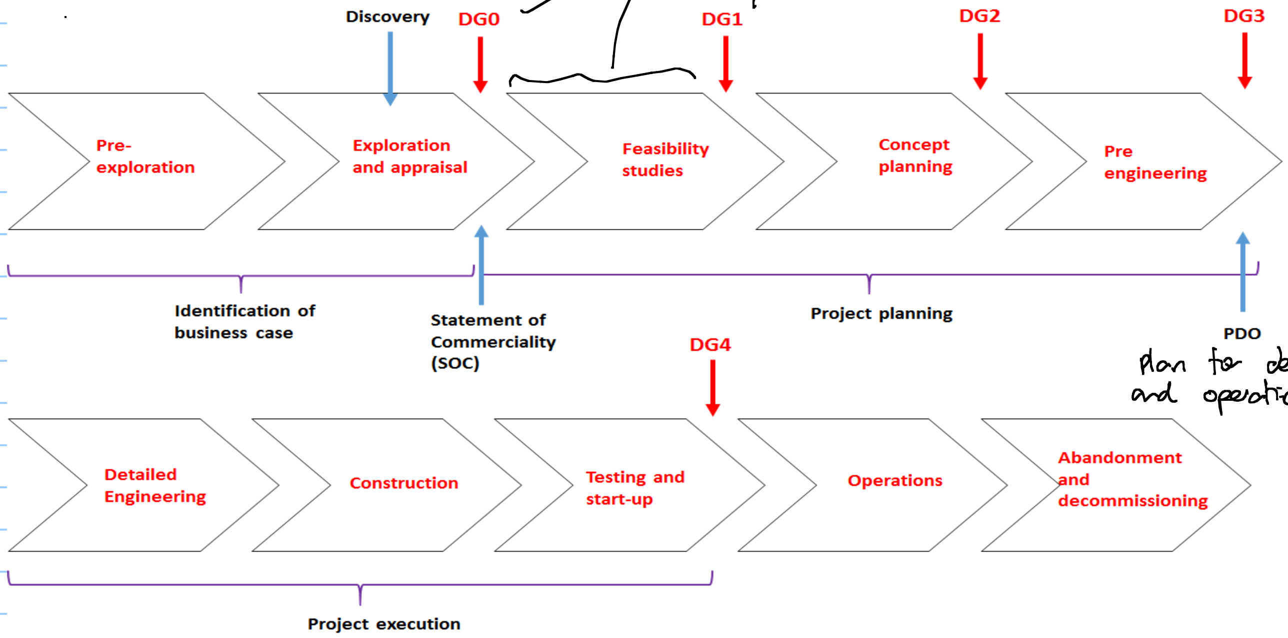
IOR improved oil recovery

field development workflow:

DG Decision gate → economics of field → profitability

find at least 1 way to develop the field

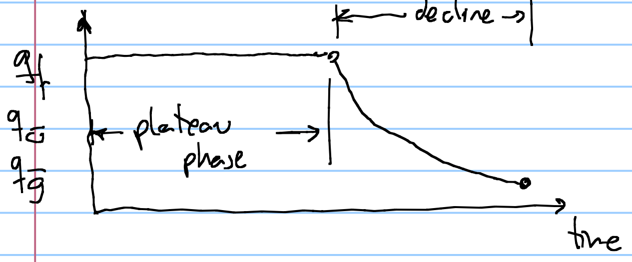
select one and proceed further



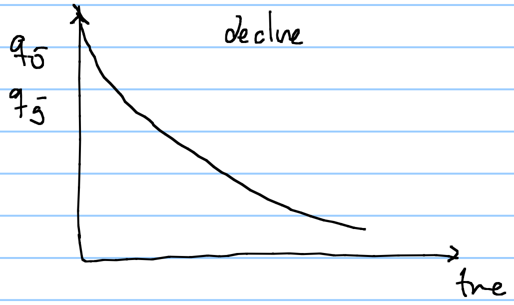
Plan for development and operations

- Production scheduling: defining how much oil/gas will be produced with time from field

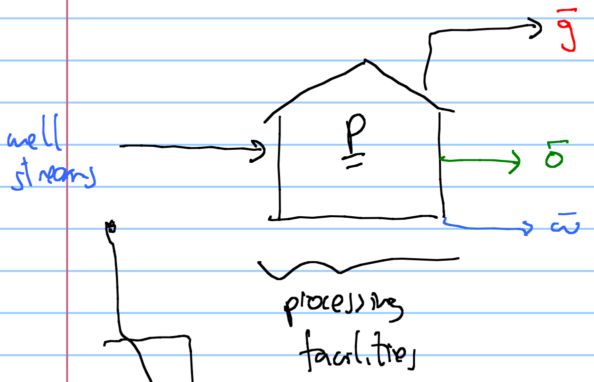
Production mode A (plateau)



Production mode B (potential)

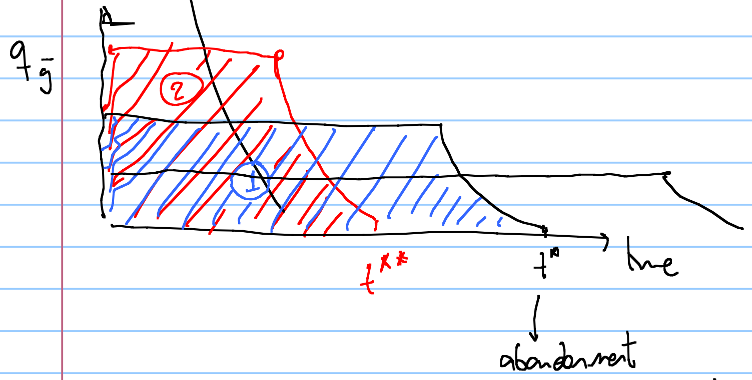


$\bar o$ at standard conditions



cumulative production

$$G_p = \int_0^{t^*} q_{\bar g}\, dt$$



according to SPE

Society of Petroleum engineers

initial oil in place (OOIP) — N oil surface volume

G gas

Q oil/gas

as abandonment $G_p \rightarrow G_{pu}$

ultimate

Mode A

- typically used for new standalone developments
- for medium-large recoverable size $\binom{M}{G}$
- find a balance between revenue $(q_{\bar{g}} \cdot P_{\bar{g}})$ and cost !

if ↑ $q_{\bar{g}}$ → more revenues (early revenue)

↑ $q_{\bar{g}}$ → more expensive facilities

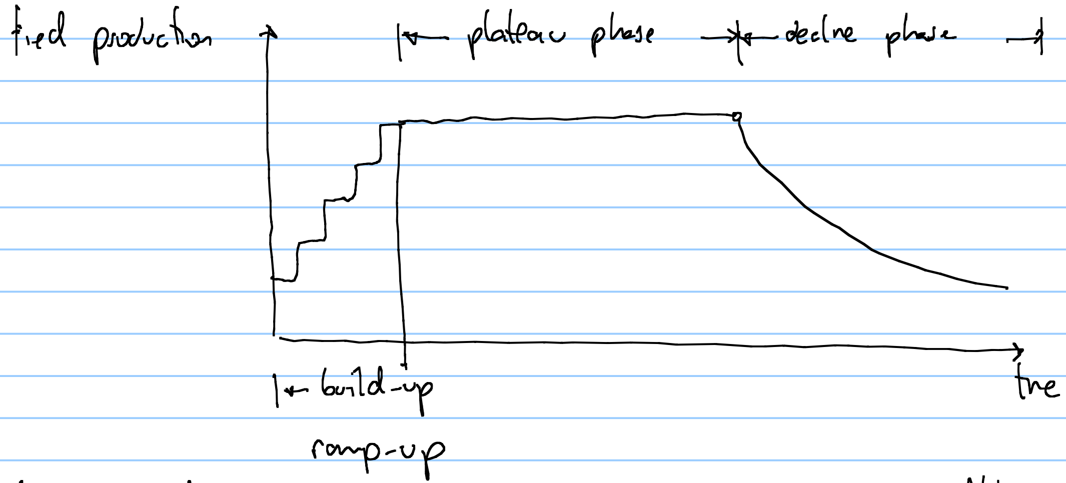
- contracts for oil it is sold on market

  for gas it is typical to have

  contract { amount →
  { period of time

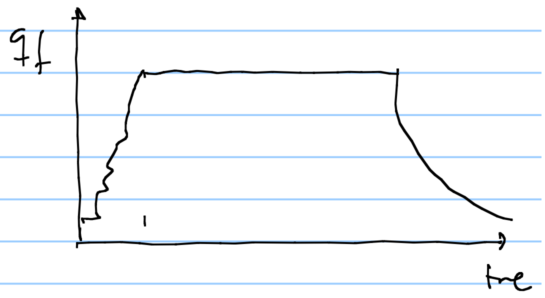
Mode B

- typically used for small-medium (marginal) size reservoirs that have an existing facility close by with spare capacity
- to produce as much as possible as quick as possible

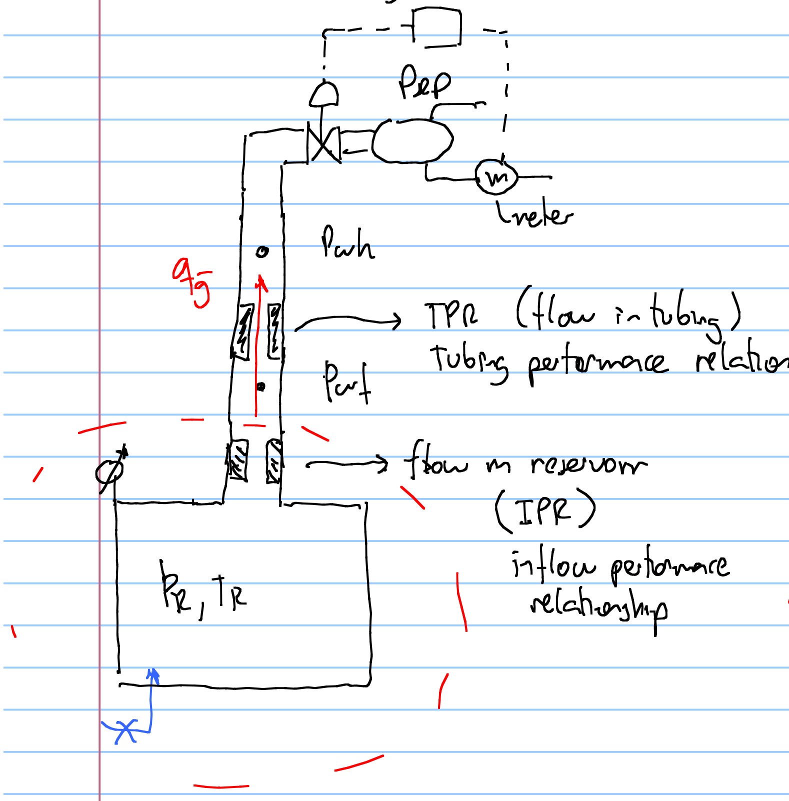


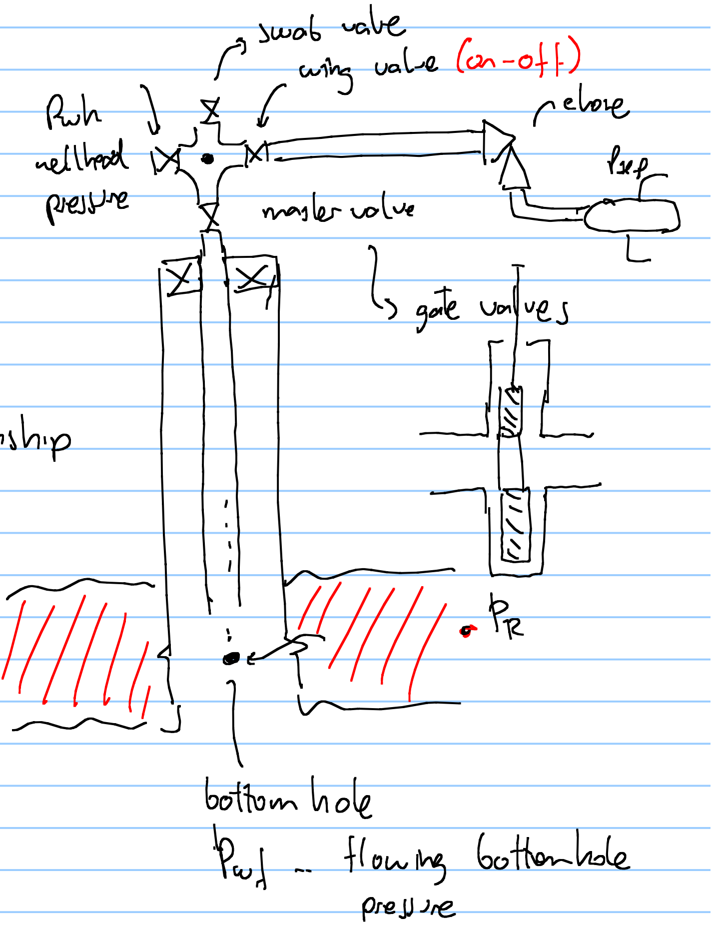
land-based field

offshore fields



Mechanical analog of a field



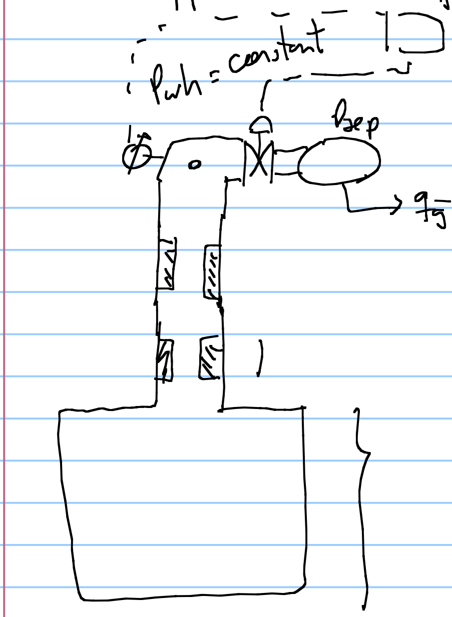


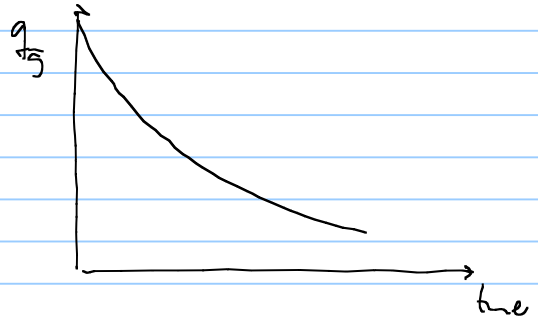
$$q_g = f(P_R, P_{sep}, \text{choke opening})$$

with time $P_R - P_{sep}$ goes down ↓

if $P_R - P_{sep}$ is high q_g ↑, therefore, i need to choke!

what happens in case of node B (potential)





Rule of thumb to decide on plateau height (first estimate)

for oil fields 10% yearly outtake of TRR (total recoverable reserves)

$$q_{plateau} = \frac{0.1 \cdot N_{pu}}{\underbrace{N_{days}/year}_{uptime}} =$$

N_{pu}

uptime ⤷ $\frac{N_{day}}{365}$

Goliat oil field $N_{pu} = 180\ E6$ stb

$q_{plateau}$?

$$q_{plateau} = \frac{0.1 \cdot 180 E6\ stb}{328.5} \approx 55000\ stb/d$$

90% uptime = $N_{day} = 0.9 \cdot 365 = 328.5$

for gas field

annual offtake 2-5% of TRR

$$q_{\bar{g}\_plateau} = \frac{G_{pu} \cdot (0.02 - 0.05)}{N_{day}/year}$$

↳ operational

for Block 2 offshore Tanzania

$G = 311\ E9\ Sm^3$

$RF = 0.7$ $G_{pu} = 217.7\ E9\ Sm^3$

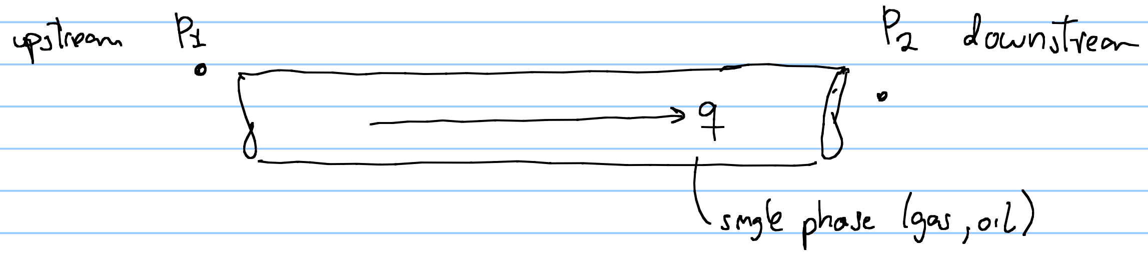
recovery factor $RF = \frac{G_{pu}}{G}$

$$q_{\bar{g}}\ plateau = \frac{217.7\ E9 \cdot (0.025)}{328.5}$$

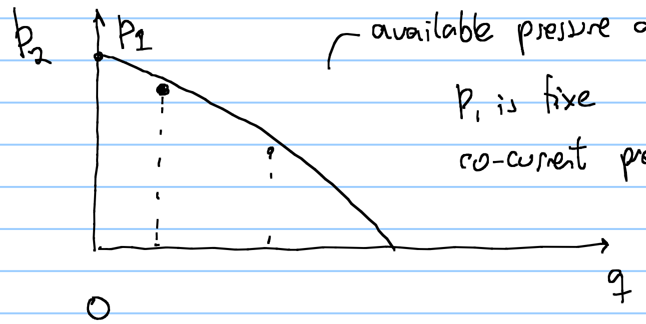
$$q_{\bar{g}}\ plateau = 16.6\ E6\ Sm^3/d$$

flow equilibrium (Nodal analysis, inflow-outflow analysis)

- Horizontal pipe



- keep p_1 fixed, change q, what happens with p_2?

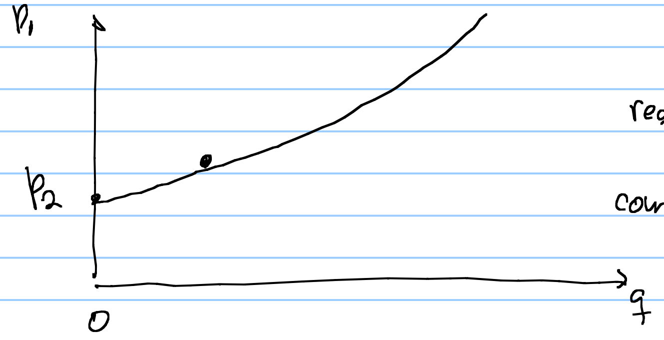


available pressure at pipe outlet

p_1 is fixe

co-curent pressure calculation

- keep p_2 fixed, change q, what happens with p_1

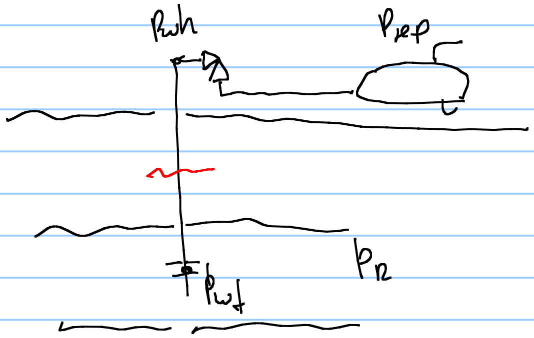


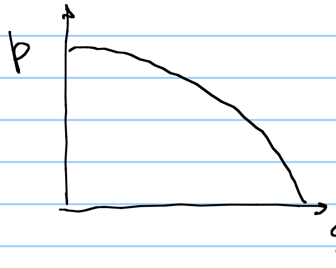
p_2 = fixed

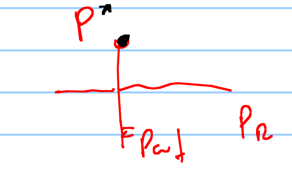
required pressure at pipe inlet

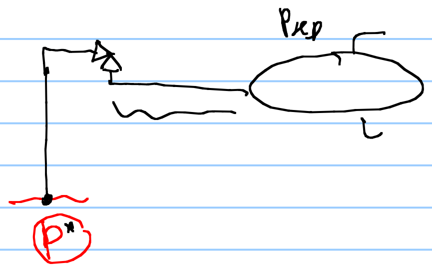
counter-curent pressure calculation

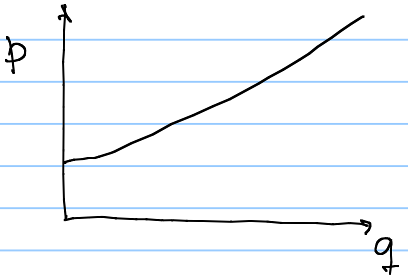
- provide p_1, p_2, calculate q

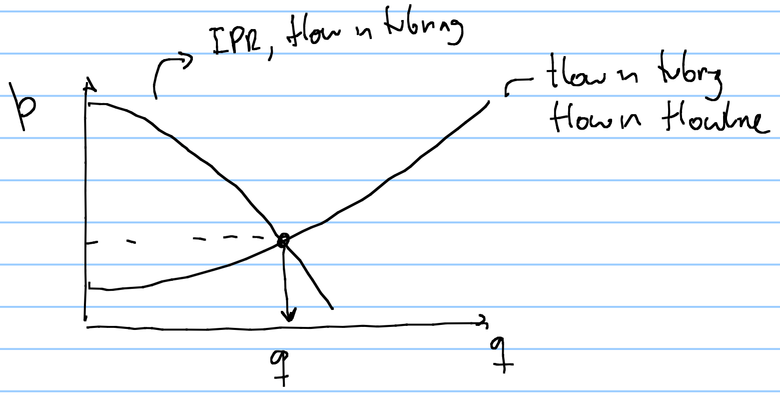




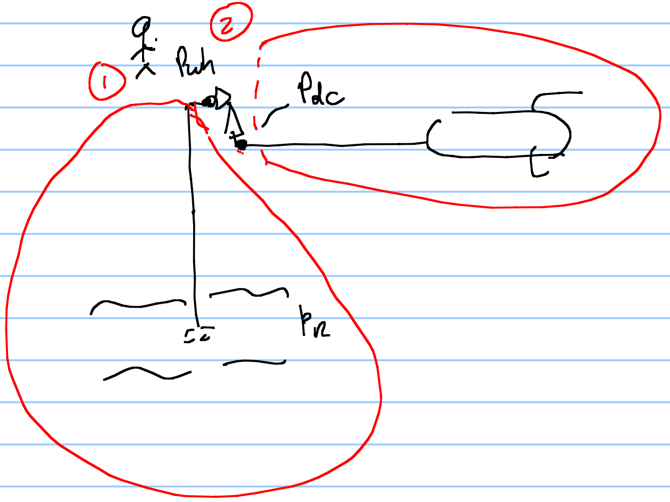


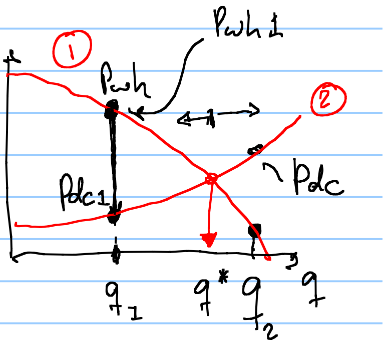


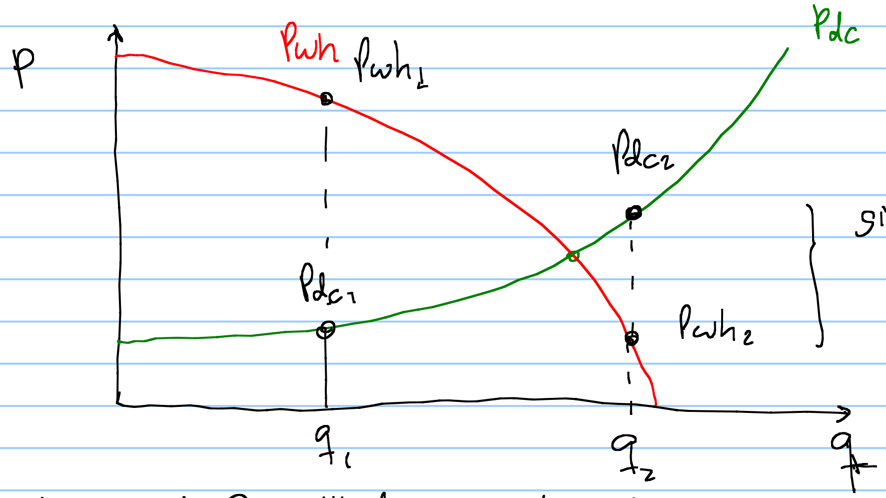




changing equilibrium point @ wellhead







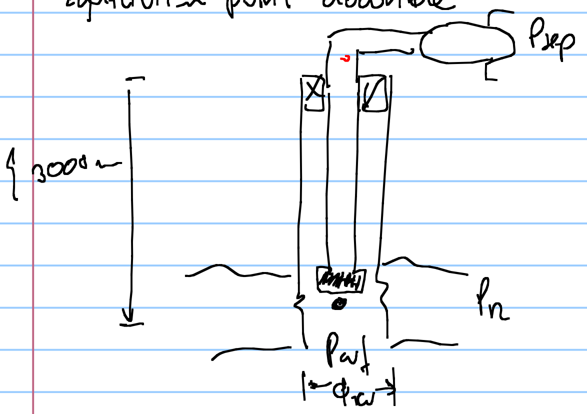
give energy to fluid

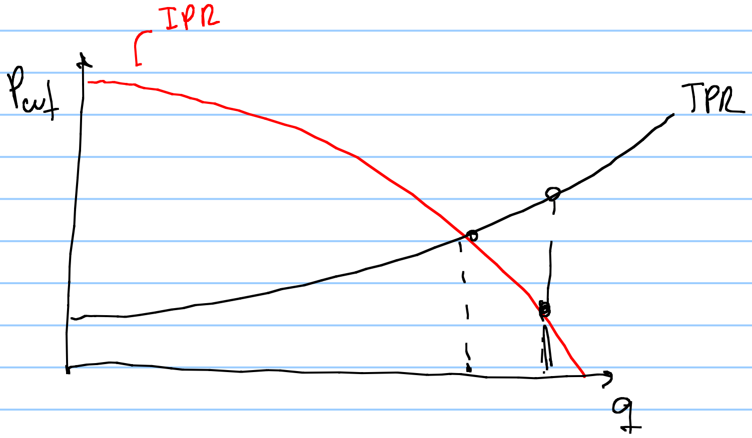
(liquid → pump
gas → compressor)

equilibrium point @ wellhead → choke design

→ topside / surface compression

equilibrium point downhole

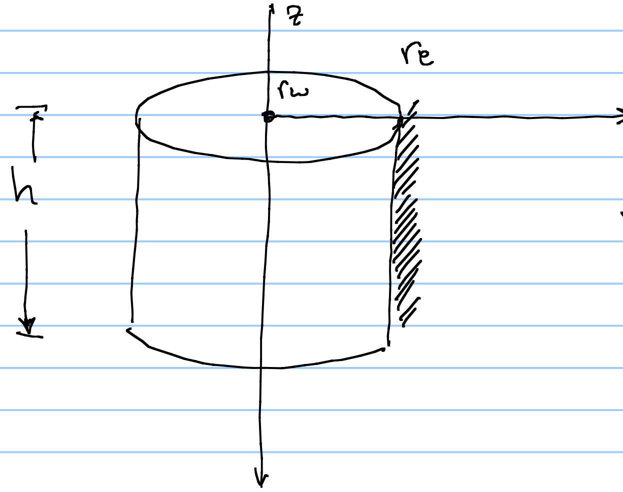


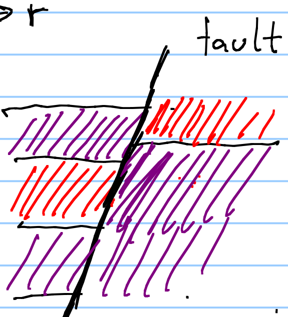


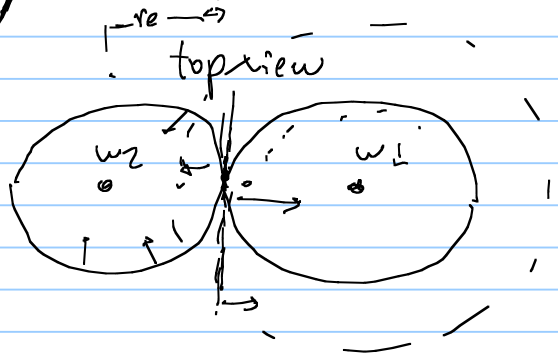
- downhole pump (ESP electric submersible pump)
- downhole choke (not very common)

- flow in formation (Inflow performance relationship)

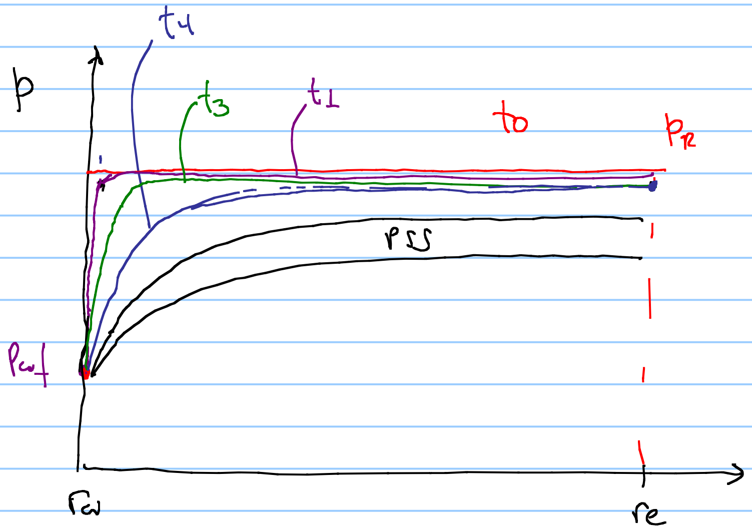
re external reservoir radius
rw wellbore radius







assume initially no production, p_R, t_0



@ t_4, pressure change reaches the boundary r_e

flow regimes in wellbore

$t_0 \rightarrow t_4$ infinite acting (transient) from t_y and forward → steady state (if P_e is kept constant) SS

pseudo steady state (PSS) if P_e changes with time
if no flow at boundary

for wells with medium to high permeability md → 1 darcy

transient is short → hrs → days

$$V = \frac{\textcircled{K}}{\mu A}\left(\frac{\Delta p}{\Delta x}\right)$$

in that case most of production happens at PSS o SS

then we use IPR for PSS, SS

$$\underline{IPR} = f(\underline{P_R}, P_{wf}, \text{reservoir properties})$$

$$IPR \neq \underset{\sim}{f(t)}$$

if significant part of production happen when is transient then

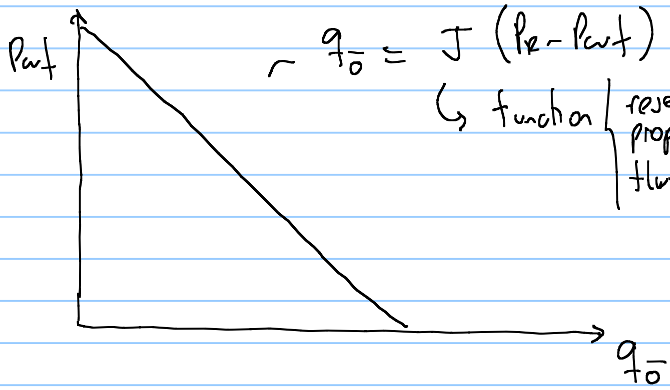
$$IPR = f(t)$$

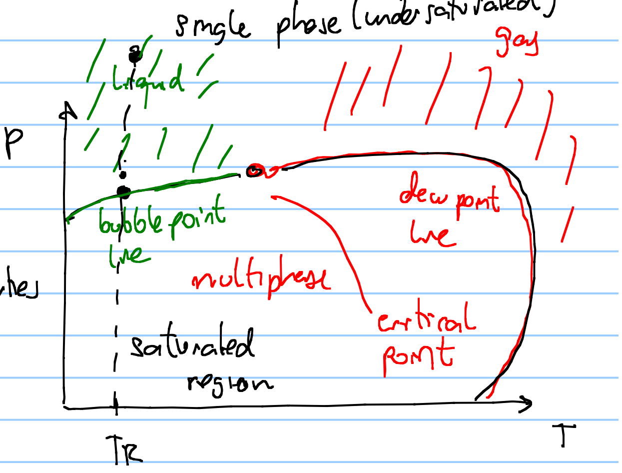
In this course we will assume PSS

IPR equations

$$q_o = J(P_R - P_{wf})$$

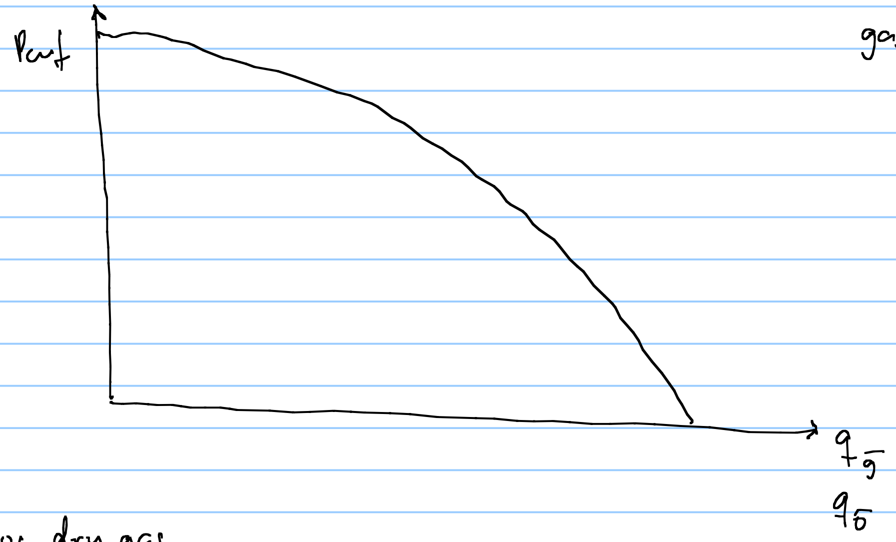
↳ function | reservoir properties, fluid properties





only oil (undersaturated oil) $P_{wf} \geq P_b(T_R)$

gas / saturated oil



for dry gas → Back pressure equation

$$q_g = \underbrace{C_R}_{\text{backpressure coefficient}} \left(P_R^2 - P_{wf}^2\right)^{n}$$

n ← backpressure exponent

empirical equation

$0.5 \le n \le 1$

0.5 → turbulent flow

1 → Darcy flow (laminar flow)

- for saturated oil $P_{wf} < P_b(T_R)$

Vogel

$$\frac{q_o}{q_{o\,max}} = 1 - 0.2\,\frac{P_{wf}}{P_R} - \frac{P_{wf}^2}{P_R^2}$$

flow in tubing (A.K.A. the tubing equation for dry gas)

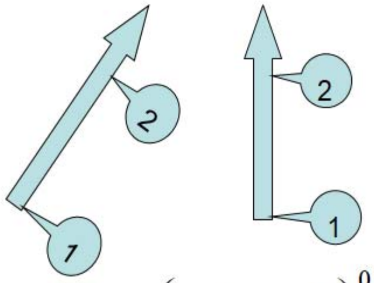
$PV = RT$ $\qquad R = \frac{R_u}{MW}$

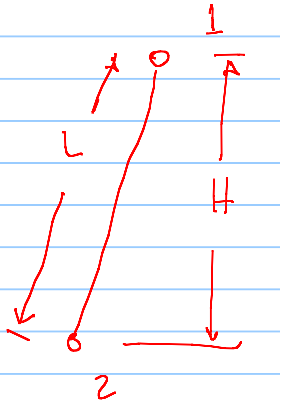
Tubing flow Equation-Dry gas

$$\boxed{q_{sc} = \left(\frac{\pi}{4}\right)\left(\frac{R}{M_{air}}\right)^{0.5}\left(\frac{T_{SC}}{P_{SC}}\right)\left[\frac{D^5}{\gamma_g f_M Z_{av} T_{av} \underline{L}}\right]^{0.5}\left(\frac{s e^S}{e^S - 1}\right)^{0.5}\left(\frac{p_1^2}{\underline{e^S}} - p_2^2\right)^{0.5}}$$

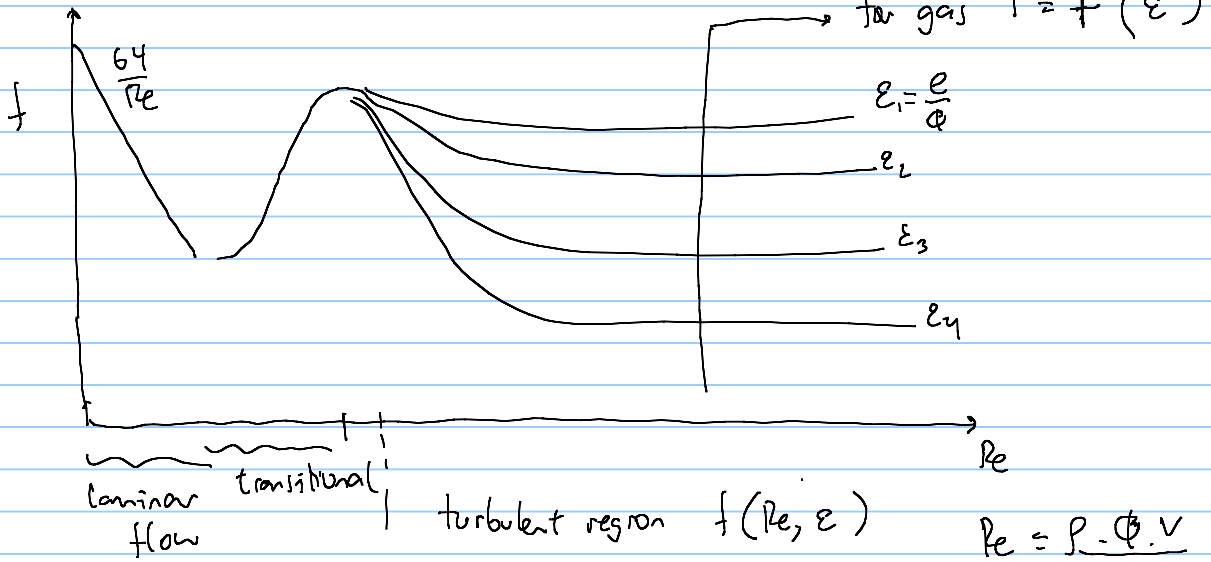
$$\boxed{\frac{s}{2} = \frac{M_g g}{Z_{av} R T_{av}} H = \frac{(28.97)\gamma_g g}{Z_{av} R T_{av}} H}$$

$$q_{gsc} = C_T\left(\frac{p_1^2}{e^s} - p_2^2\right)^{0.5}$$





$$p_{\text{inlet}} = p_1 = e^{s/2}\left(p_2^2 + \frac{q_g^2}{C_T^2}\right)^{0.5} \qquad p_{wh} = p_2 = \left(\frac{p_1^2}{e^s} - \frac{q_g^2}{C_T^2}\right)^{0.5}$$



$Re = \frac{\rho \cdot \Phi \cdot V}{\mu}$

$$f_M = \frac{0.01748}{D^{0.224}\left[|1m|\left|\frac{39.37inch}{1m}\right|\right]^{0.224}} = \frac{0.0077}{D^{0.224}}$$

Smith (1950)

$\underline{\tilde{e}}$ depend mainly on Φ

$f = F(\Phi)$

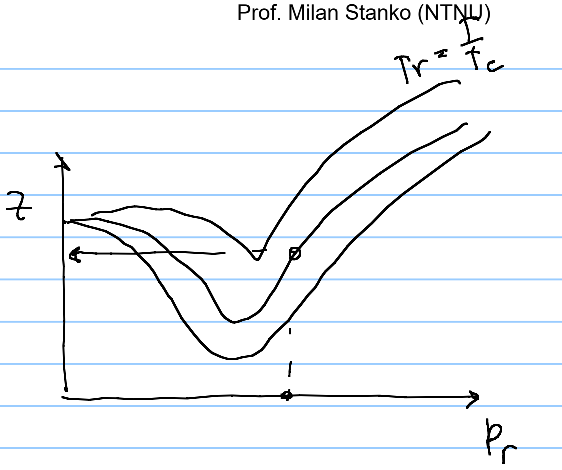
$q_g = C_T \cdot \left(\frac{p_1^2}{e^s} - p_2^2\right)^{0.5}$

$p_1 = 200$ bara $P_2 = 80$ bara

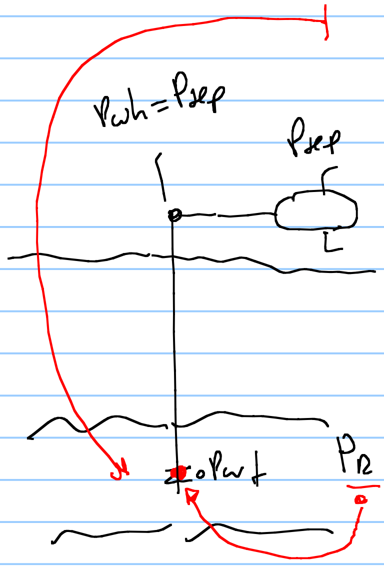
flow equlibrium of single dry gas well

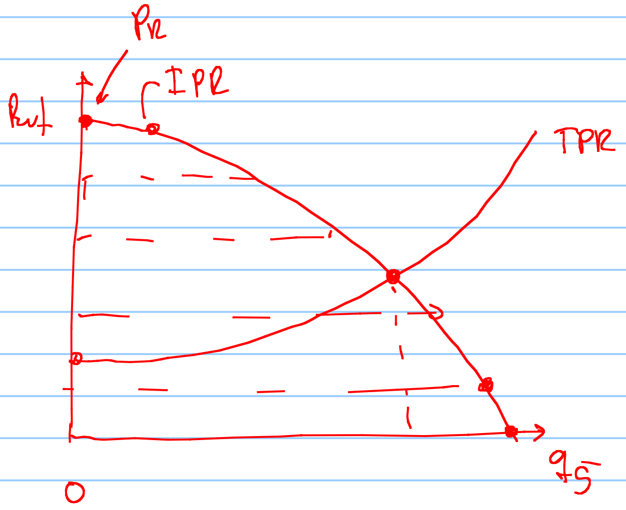
Z

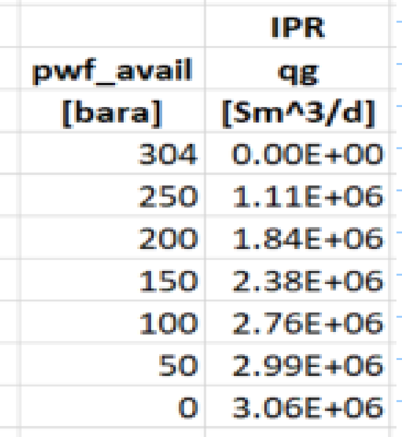
$pV = ZRT$



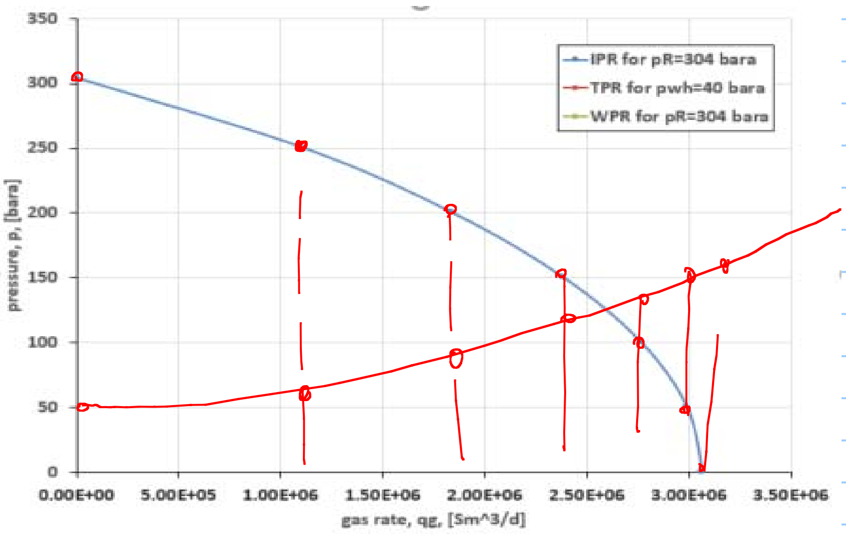
$p_r = \frac{p}{p_c}$





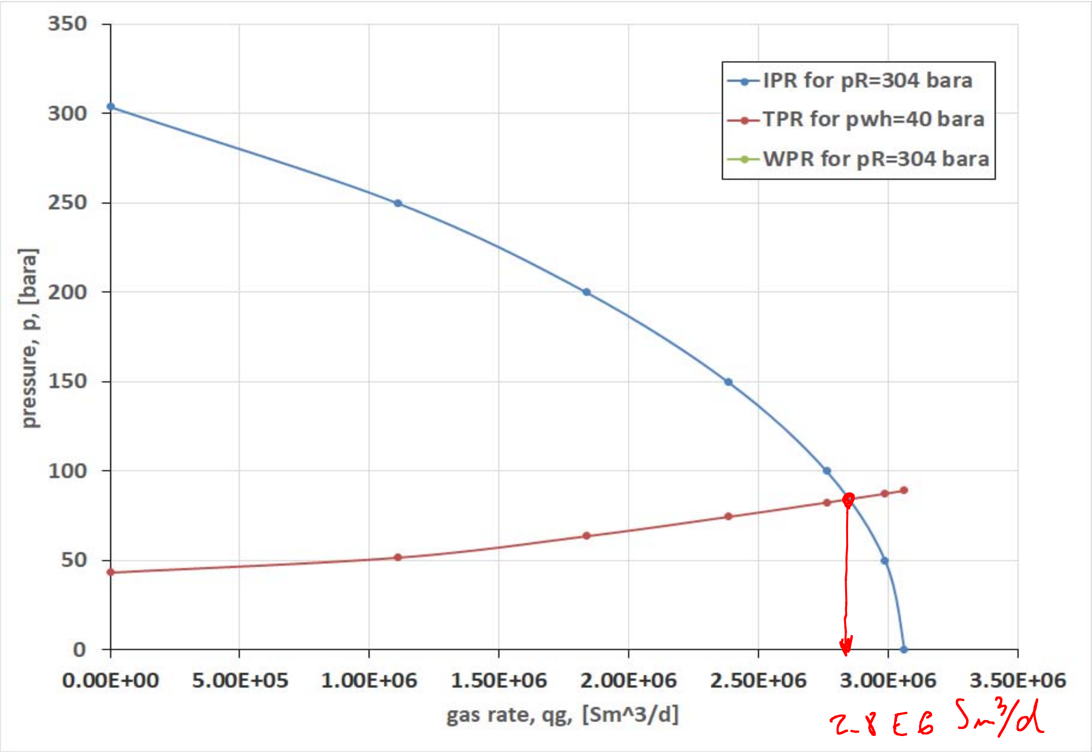


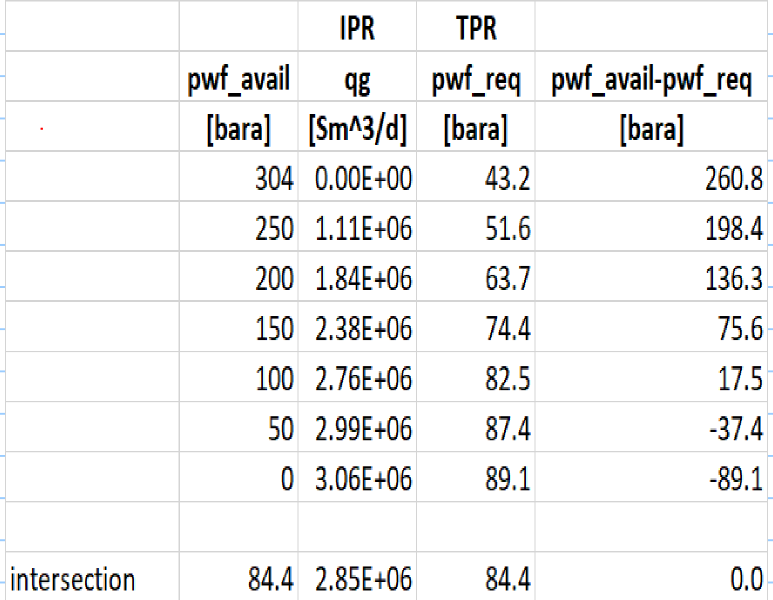
	IPR
pwf_avail	qg
[bara]	[Sm^3/d]
304	0.00E+00
250	1.11E+06
200	1.84E+06
150	2.38E+06
100	2.76E+06
50	2.99E+06
0	3.06E+06



$$q_g = \underset{\sim}{C_T} \cdot \left(\frac{p_1^2}{e^s} - p_2^2\right)^{0.5}$$

$$\overset{?}{q_g} = C_T \left(\frac{\overset{?}{p_{wf}^2}}{e^s} - \overset{✓}{p_{wh}^2}\right)^{0.5}$$





		IPR	TPR	
	pwf_avail	qg	pwf_req	pwf_avail-pwf_req
	[bara]	[Sm^3/d]	[bara]	[bara]
	304	0.00E+00	43.2	260.8
	250	1.11E+06	51.6	198.4
	200	1.84E+06	63.7	136.3
	150	2.38E+06	74.4	75.6
	100	2.76E+06	82.5	17.5
	50	2.99E+06	87.4	-37.4
	0	3.06E+06	89.1	-89.1
intersection	84.4	2.85E+06	84.4	0.0

to get a better approximation of C_T, S assuming $P_{wf} = P_R$

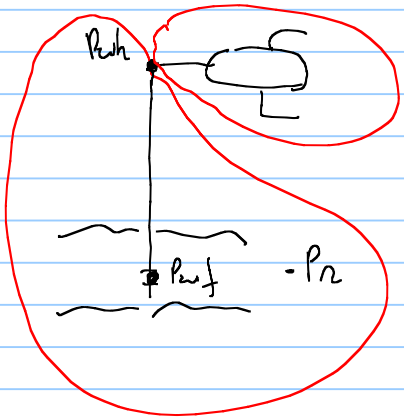
↳ C_T, S

↳ execute flow equilibrium

↓

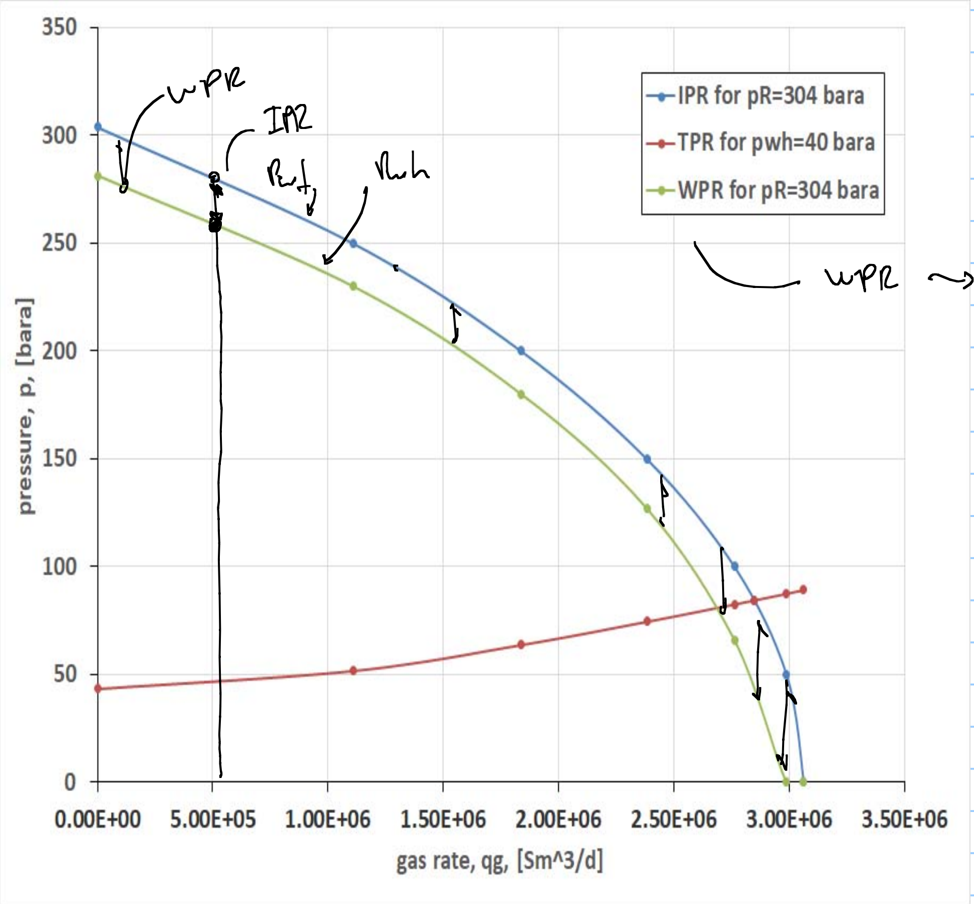
P_{wf}

flow equilibrium at well head

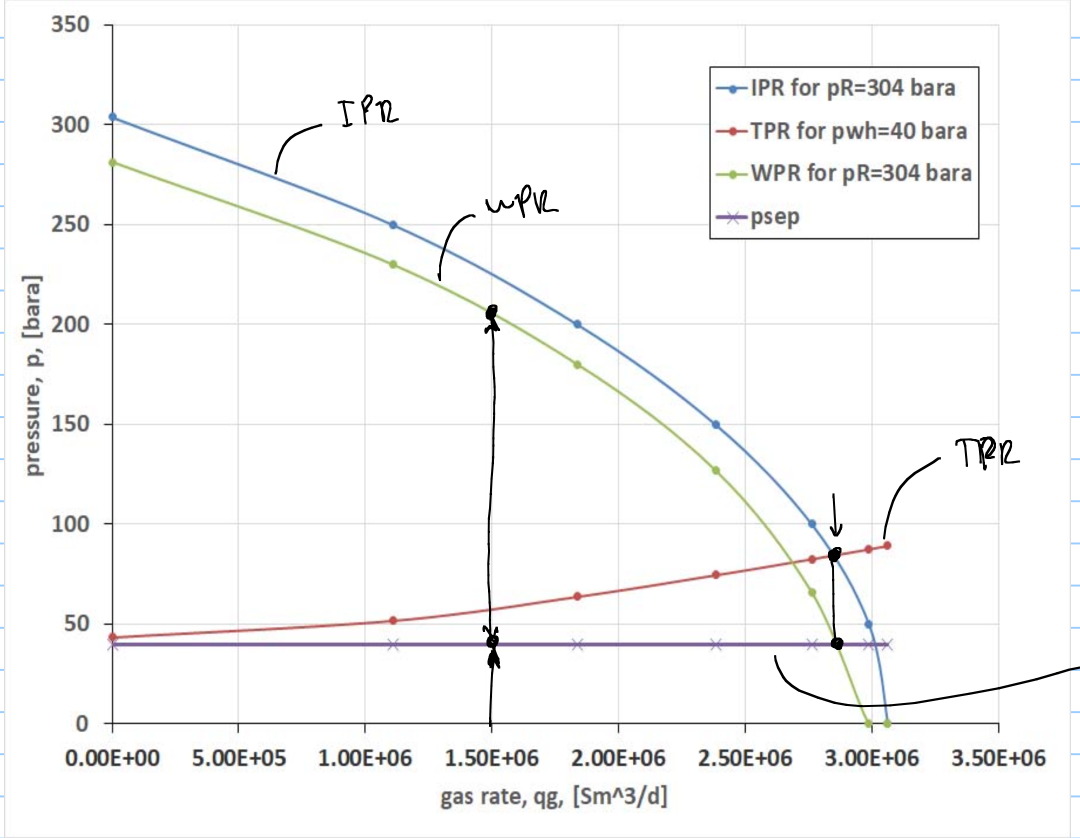


$$q_g = \overset{\checkmark}{C_T}\left(\frac{\overset{\checkmark}{P_{wf}^2}}{e^S} - \overset{?}{P_{wh}^2}\right)^{0.5}$$

$$P_{wh} = \left(\underbrace{\frac{P_{wf}^2}{e^S}} - \underbrace{\left(\frac{q_s}{C_T}\right)^2}\right)^{0.5}$$



WPR ⇝ well head performance relationship

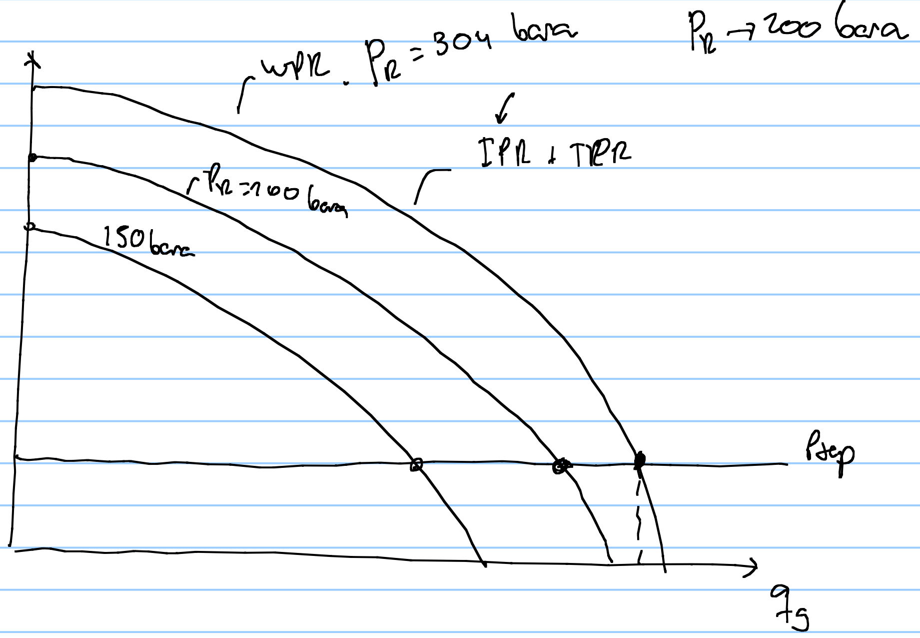


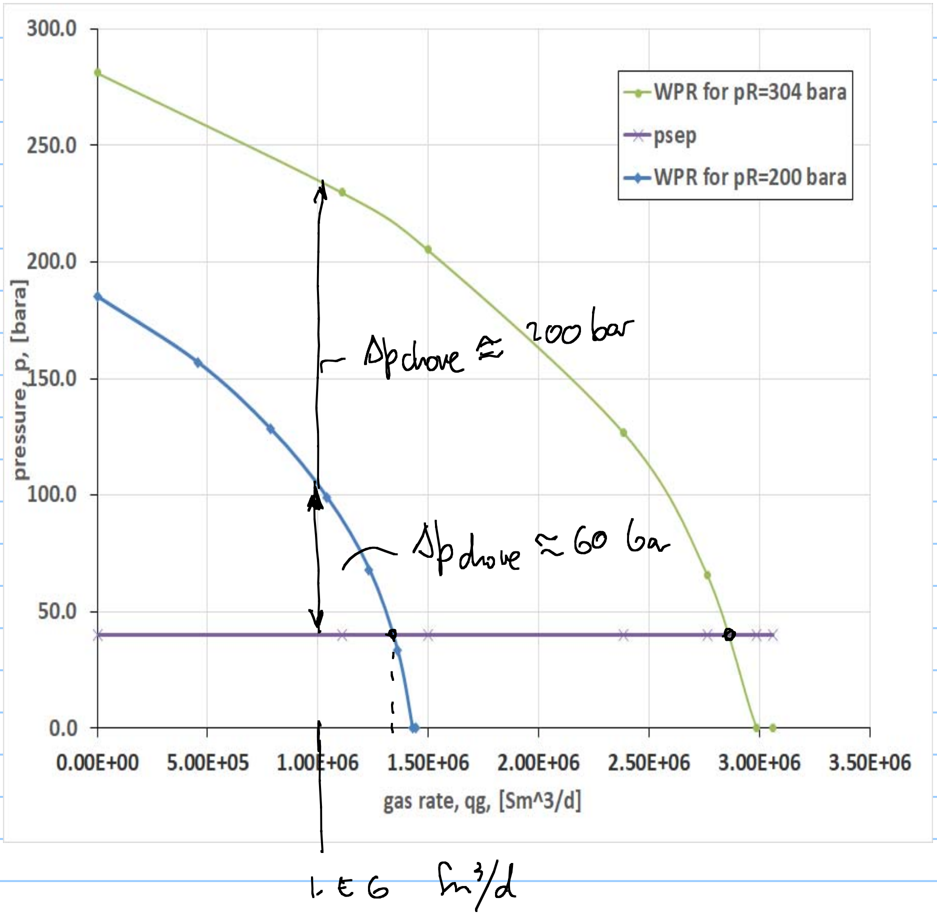
IPR + TPR
downhole equilibrium

P_{sep} + WPR
wellhead equilibrium

to deliver a rate of 1.5 E6 Sm^3/d I need to apply choking at wellhead for 165.2 bar Δp

- effect of depletion P_R ↓





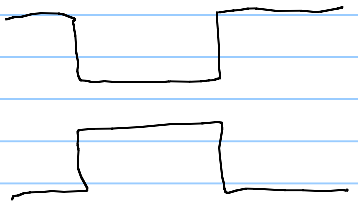
@ $P_R = 304$ bara

$q_g = 2.85$ E6 Sm³/d

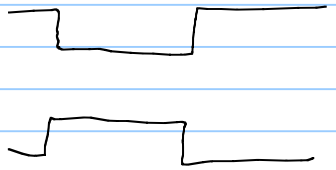
@ $P_R = 200$ bara

$q_g = 1.35$ E6 Sm³/d

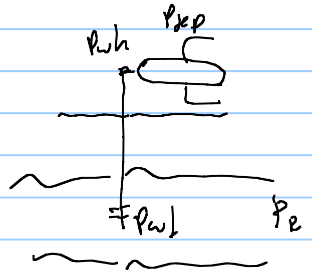
when $P_R = 304$ bara



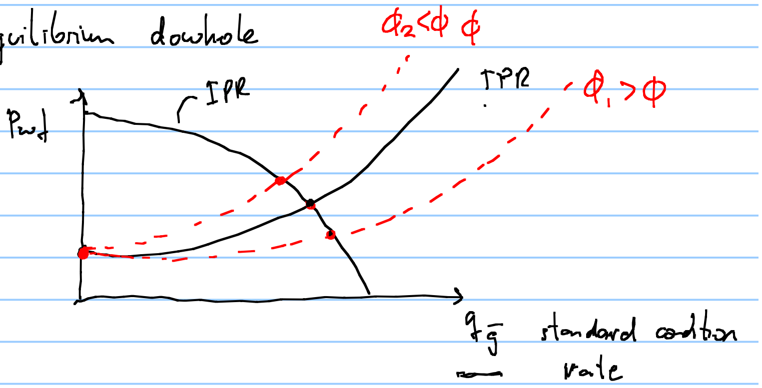
when $P_R = 200$ bara

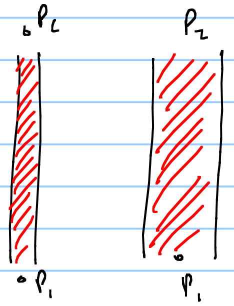


Day 2



flow equilibrium downhole

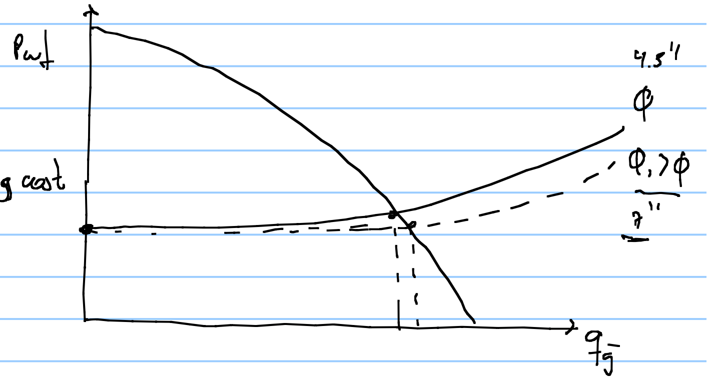




variation of tubing size "ϕ"

How to chose ϕ tubing

- minimize tubing Δp → max rate

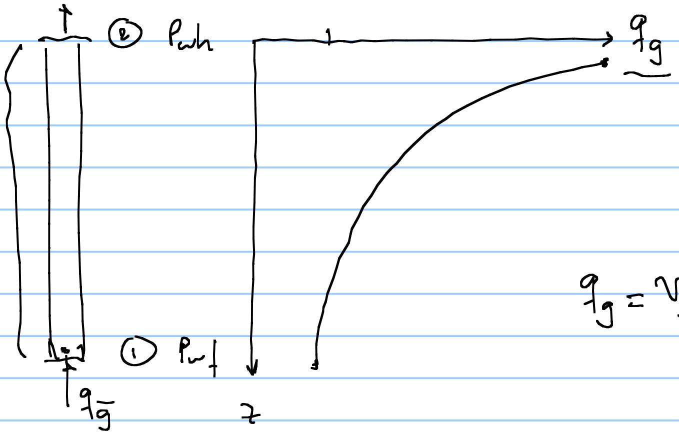


- minimize tubing cost

- avoid erosion

$$\dot m = \rho_{wh} \cdot q_{g2}$$

$$\dot m = \rho_{wf} \cdot q_{g1}$$

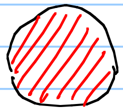


$$p\tilde V = ZRT$$

$$p\frac{1}{\rho} = ZRT$$

$$\frac{p}{ZRT} = \rho$$

$$q_g = v_g \cdot A$$



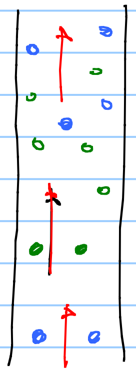
$$\rho_{wf} > \rho_{wh} \rightsquigarrow q_{g1} < q_{g2}$$

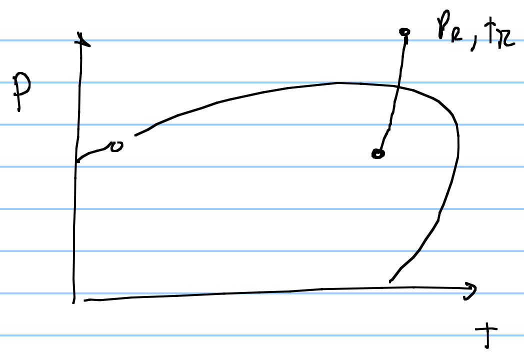
- Select ϕ such that we don't get erosion in tubing

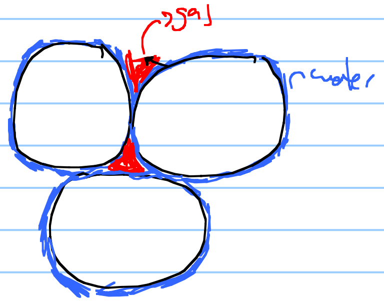
$v_g @wh < V_{erosional}$ → API 14E

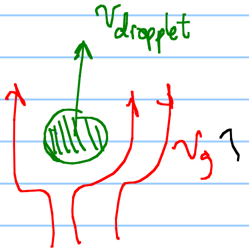
American petroleum Institute

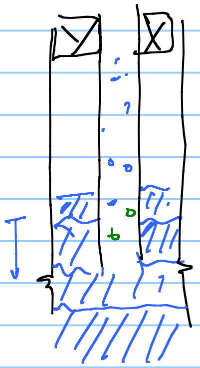
- liquid loading → condensate
  ↘ water in solution dissolved in the gas





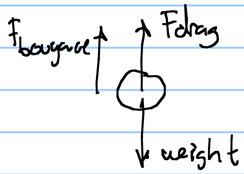






liquid loading → accumulation of liquid in wellbore
↳ additional backpressure against formation which brings q_g ↓

Select Φ of tubing such that v_g is high enough to lift droplets of liquid ↘ Turner

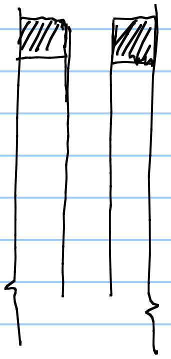


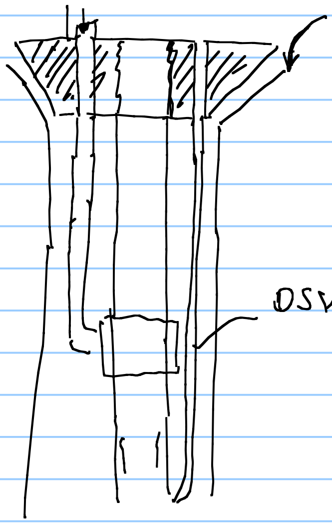
$\sim \underset{\sim}{v_{gc}} < v_g$

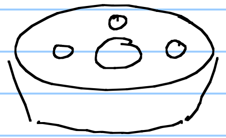
- tubing hanger

→ chemical injection (scale inhibitor)
downhole pressure gauge
power cable

landing shoulders

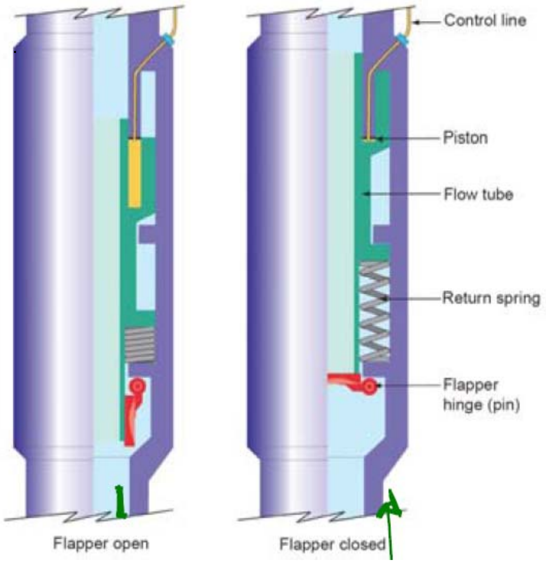




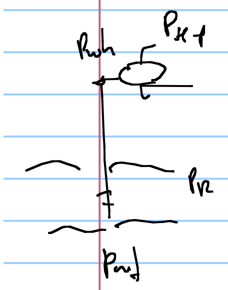


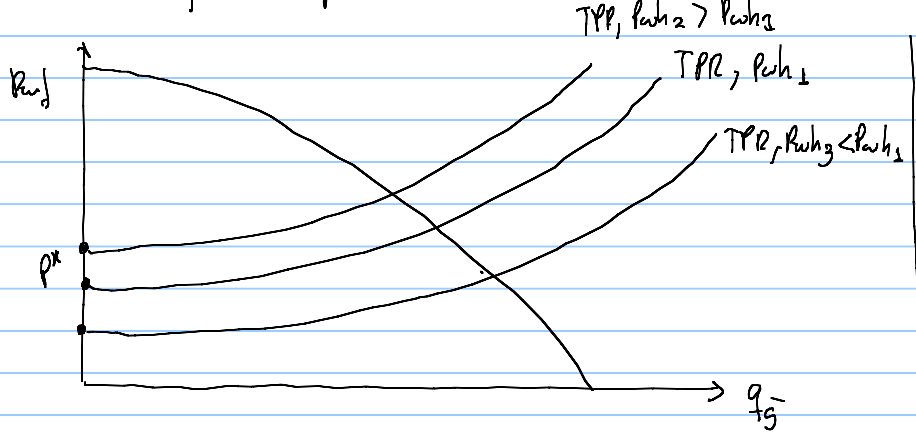
DSV downhole safety valve 100 m - 200 m below wellhead

Φ of the tubing has to be small enough to allow tubing hanger integrity

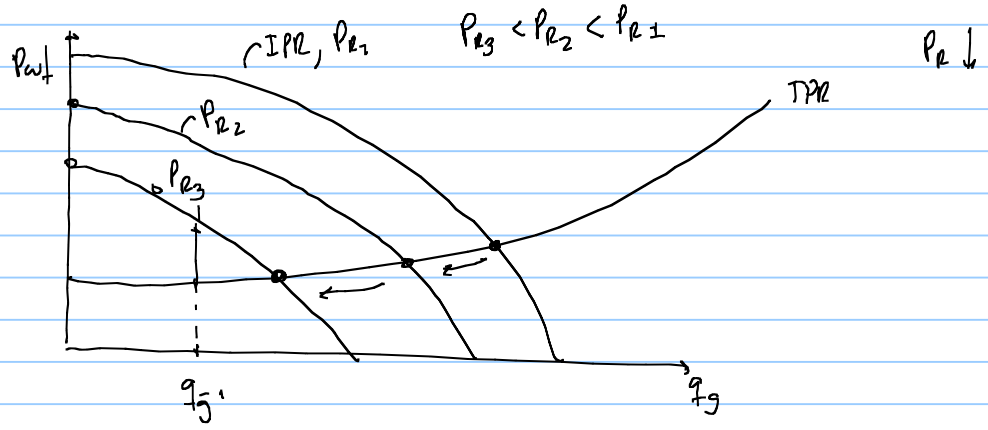


- Effect of pwh on equilibrium point



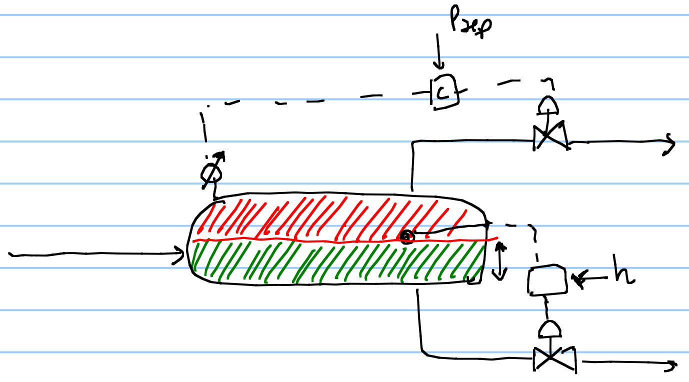


- effect of depletion on flow equilibrium



Short

Separator



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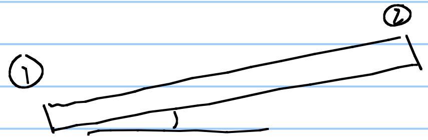
flowline

$$q_{\bar{g}} = C_T\left(\frac{P_1^2}{e^s} - P_2^2\right)^{0.5}$$



$$\underbrace{q_{\bar{g}} = C_{F2}\left(\frac{P_{in}^2}{e^s} - P_{out}^2\right)^{0.5}}$$

if pe is horizontal s = 0

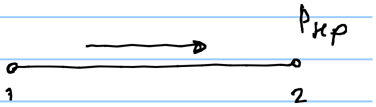
$$\left(P_{in}^2 - P_{out}^2\right)^{0.3} \qquad C_T ?$$

$$\underbrace{C_{F2}} = \underbrace{const} \cdot \underbrace{\left(\frac{s\,e^s}{e^s - 1}\right)} \qquad s = 0 \qquad \frac{0 \cdot 1}{1 - 1} = \frac{0}{0} \quad \text{undefined !}$$

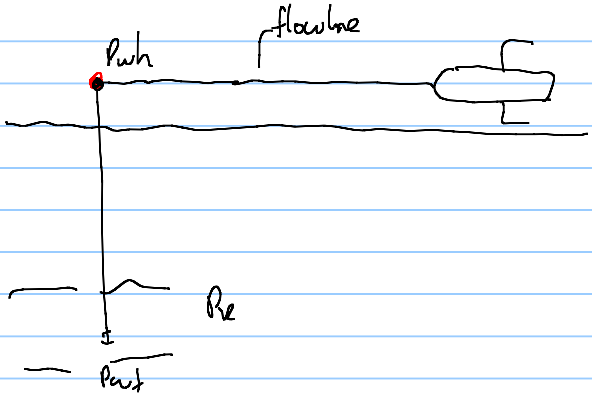
L'Hopital $\lim_{x\to 0} f(x) \Rightarrow$ undefined $\quad \lim_{x\to 0}\frac{f(x)}{g(x)} \to \lim_{x\to 0}\frac{f'(x)}{g'(x)}$ -

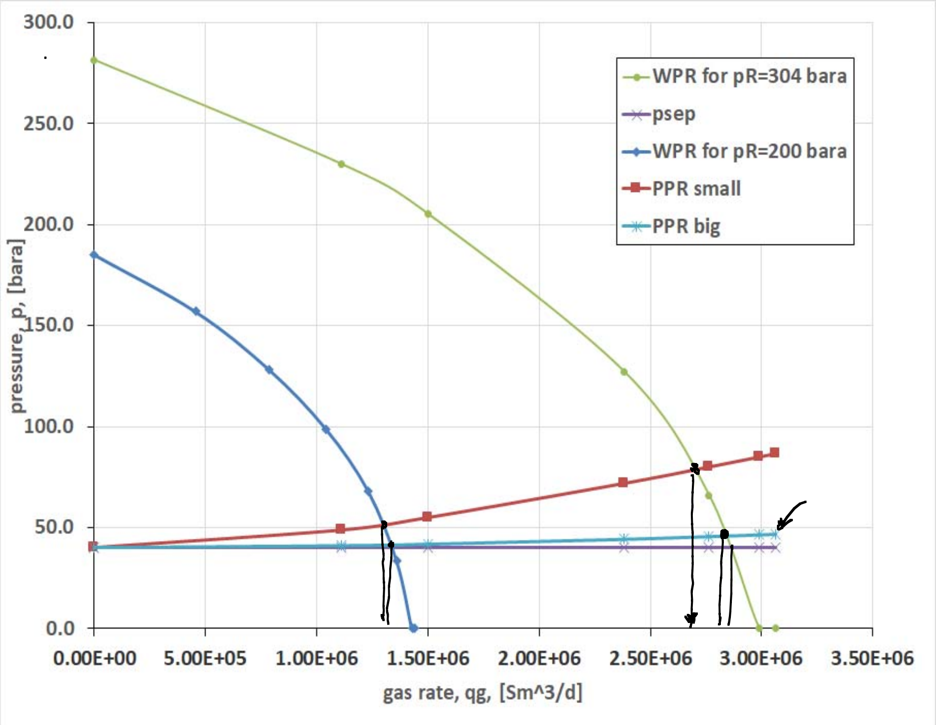
$$\frac{\frac{d}{ds}\left(s\,e^s\right)}{\frac{d}{ds}\left(e^s - 1\right)} = \frac{s \cdot e^s + e^s}{e^s} = \frac{1}{1} = 1$$

$$q_{\bar{g}} = C_{F2}\left(P_{in}^2 - P_{out}^2\right)^{0.5}$$



Exercise





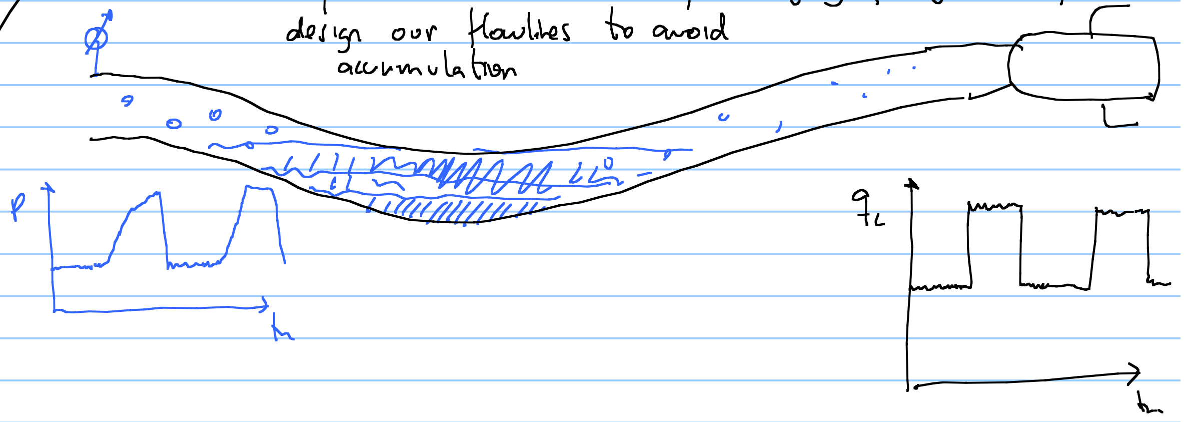
- pipeline sizing → minimize Δp, maximize rate q_g

→ cost !

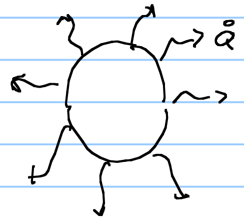
→ erosion

→ liquid accumulation → liquid slugging (intermittent flow of gas and liquid)

design our flowlines to avoid accumulation



→ big Ø leads to more cooling → more oil/water condensation, more liquid accumulation



corrosion

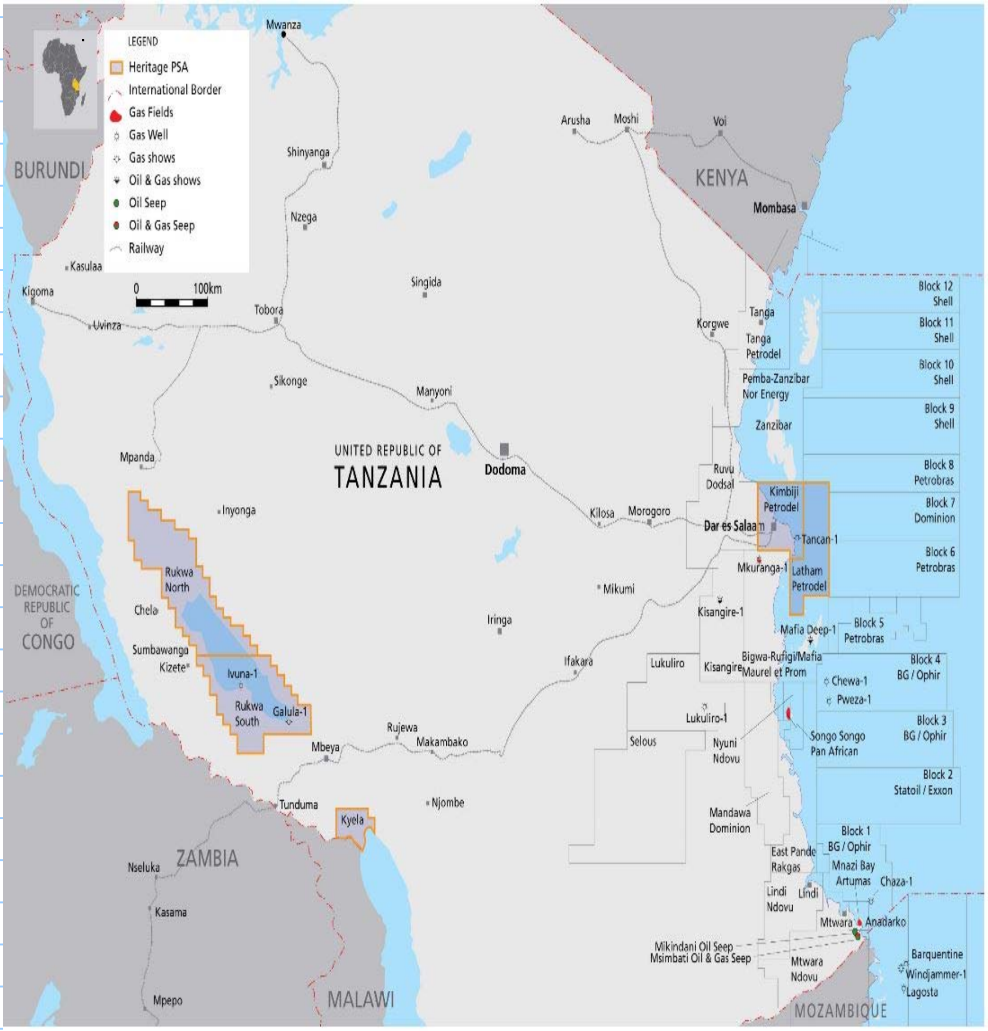
corrosion TOL top of line

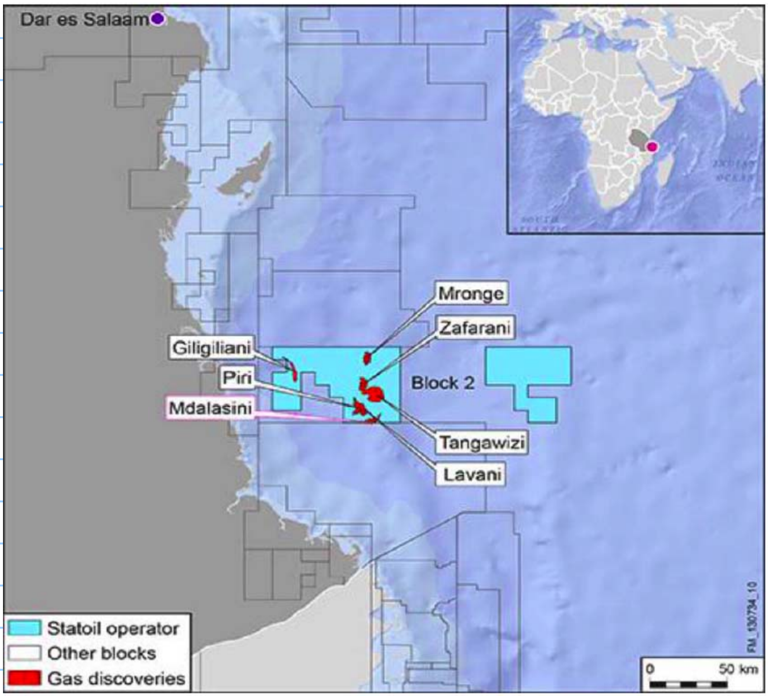
→ Hydrates if T is low

→ oil flowlines wax, $\mu\uparrow$ $\Delta p\uparrow$

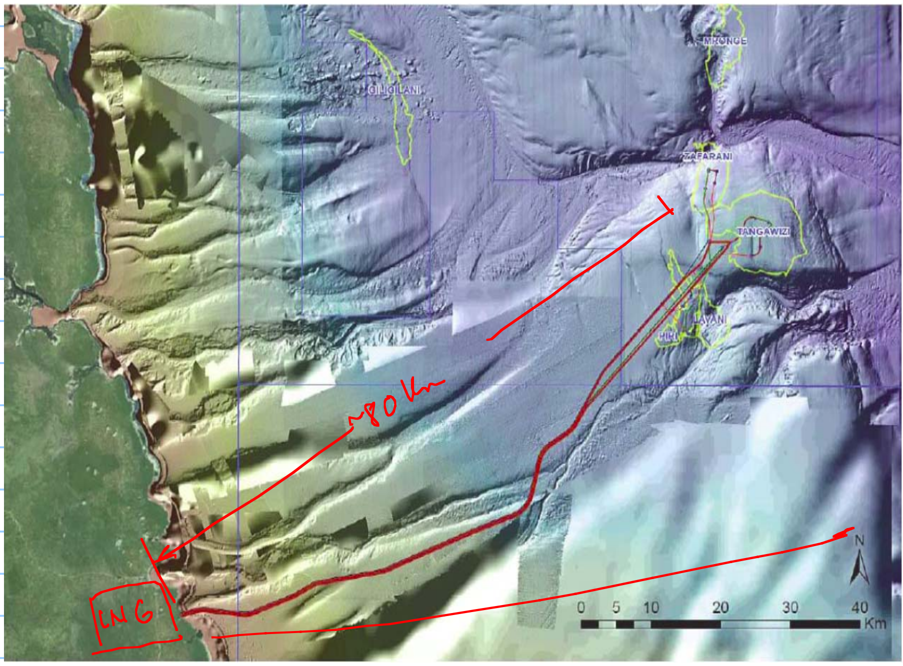
field production scheduling → define, calculate/estimate the field production profile with time

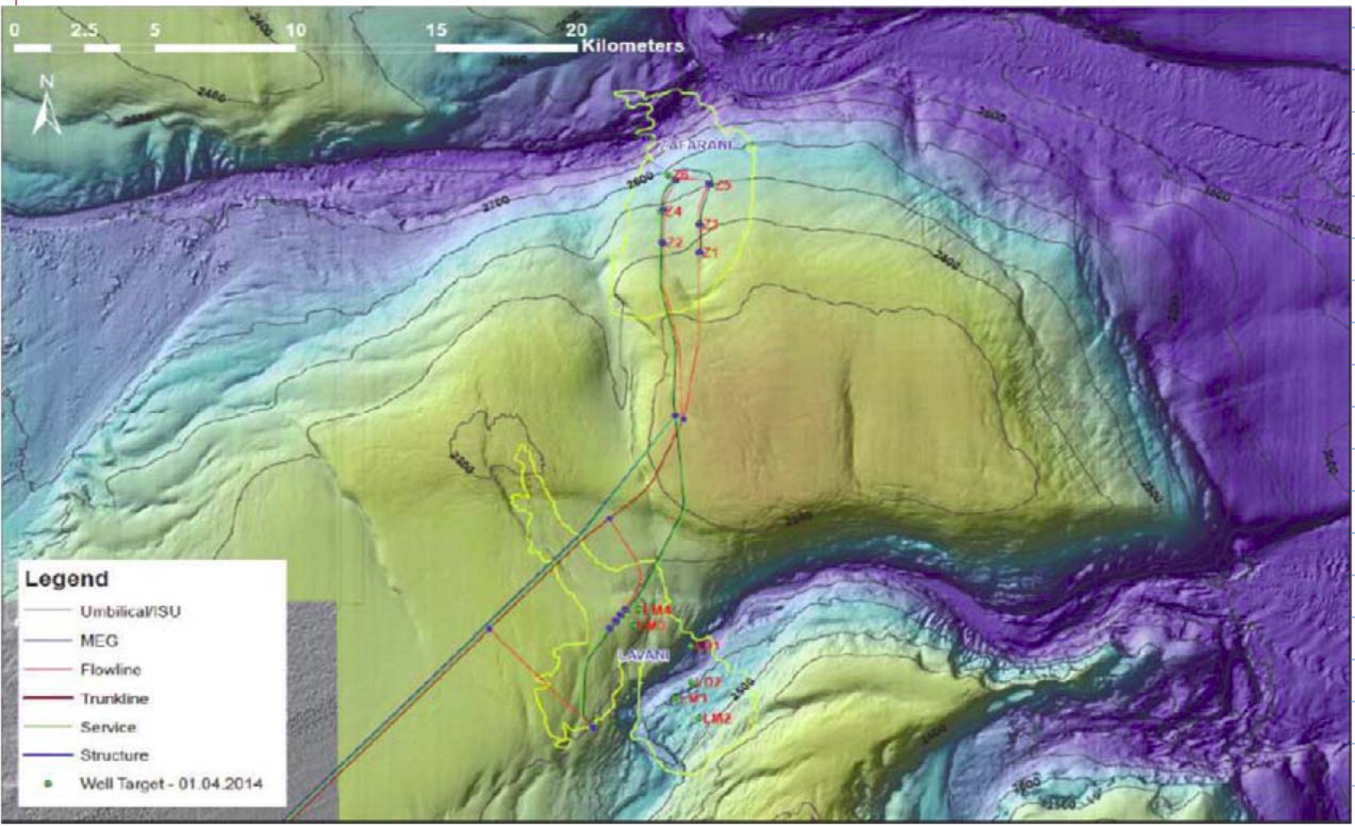
Block 2 offshore Tanzania





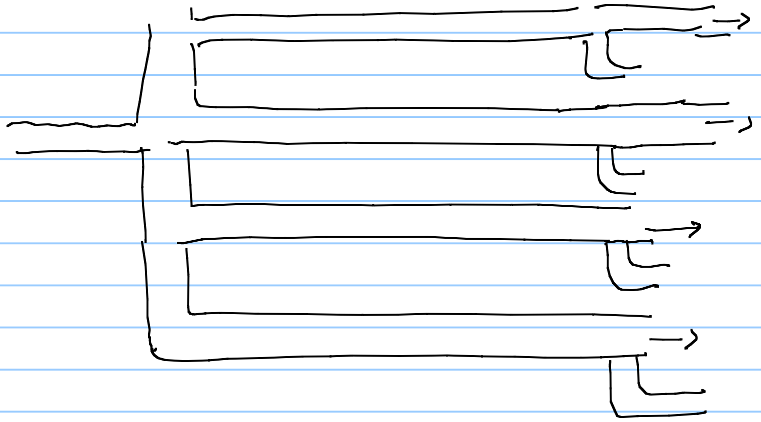
water depth 2200 – 2600 m

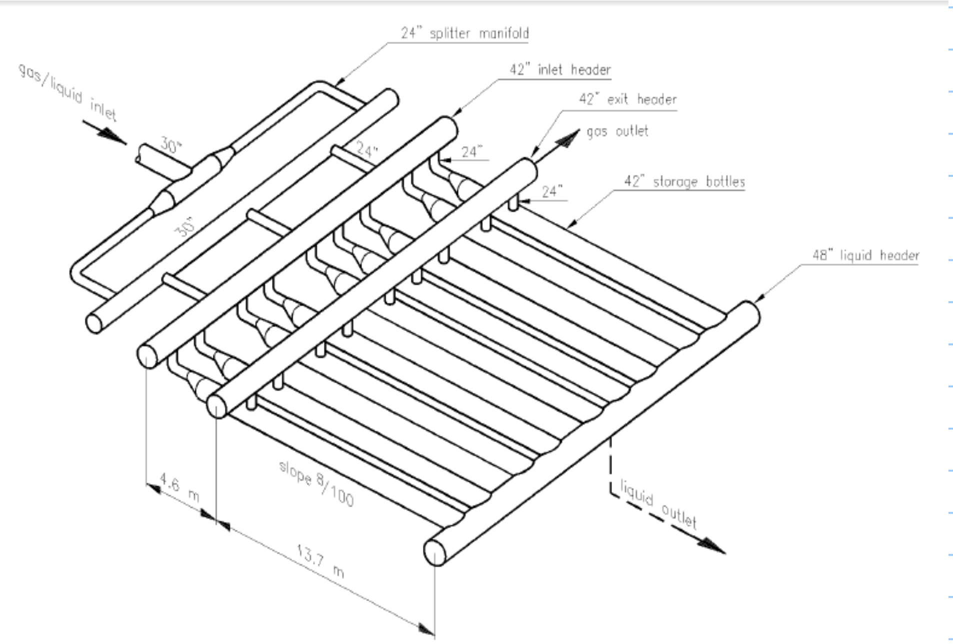




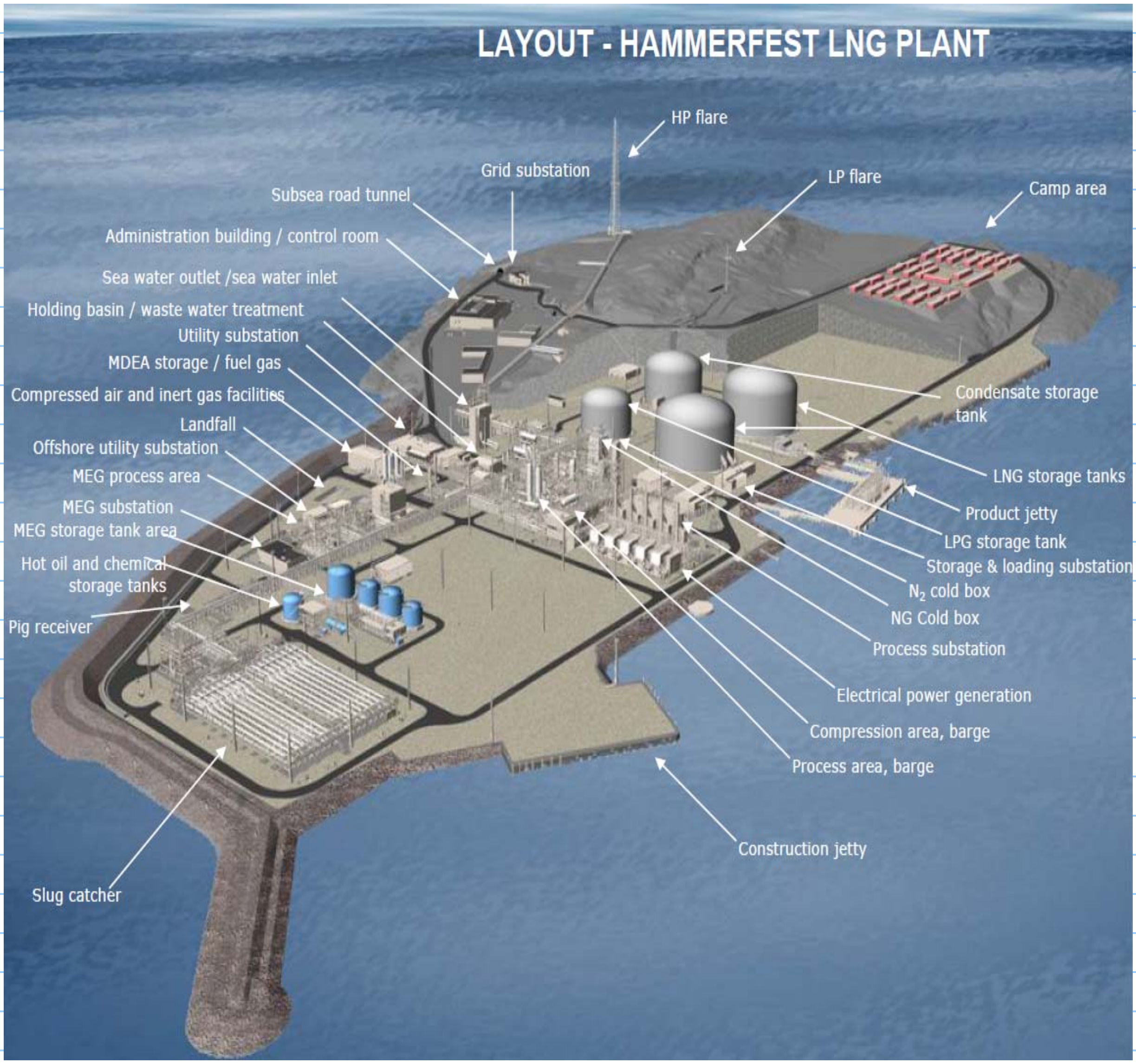
Snowhite (Snøhvit) Subsea to beach

onshore facilities ; slugcatcher





LNG Plant



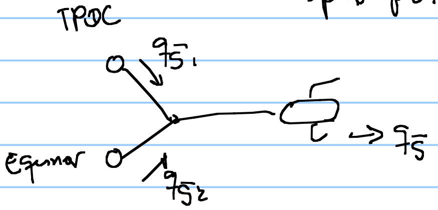
- contract for a' fixed amount of gas 18 E6 Sm³/d
  - ↳ plateau length ~> choking mode A
  - ↳ post plateau production profile ~> open choke (mode B)

- Subsea layout/architecture

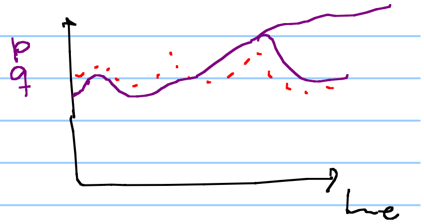
Pr

Production manifold

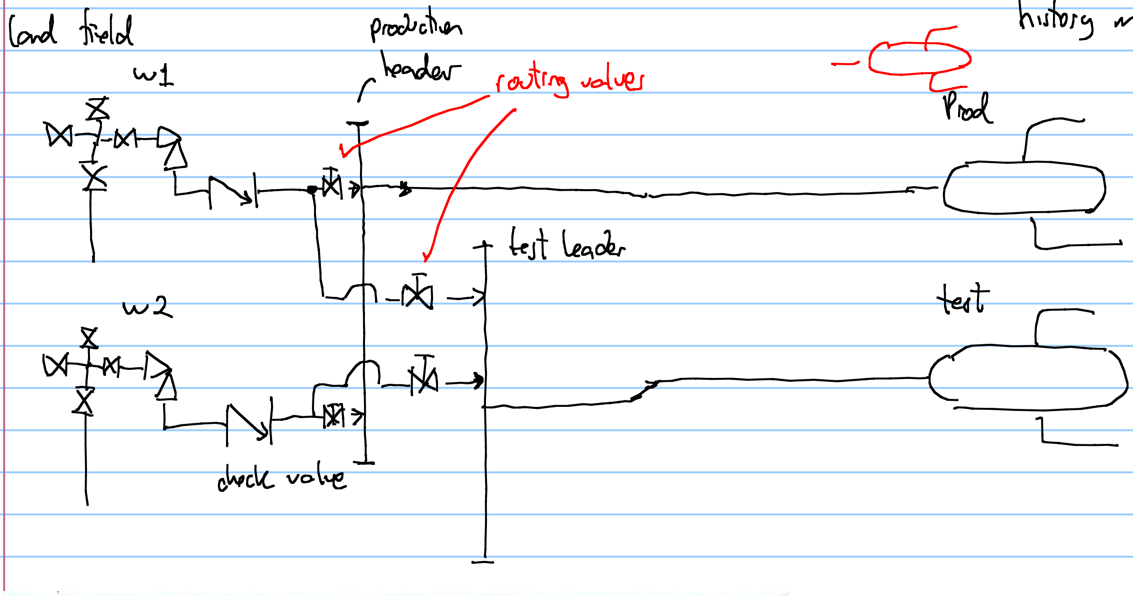
- route the production of wells
- test wells → allocation determine source of gas/oil
  ↓
  - split profit !
  - to improve reservoir models



compare model vs. data



history matching

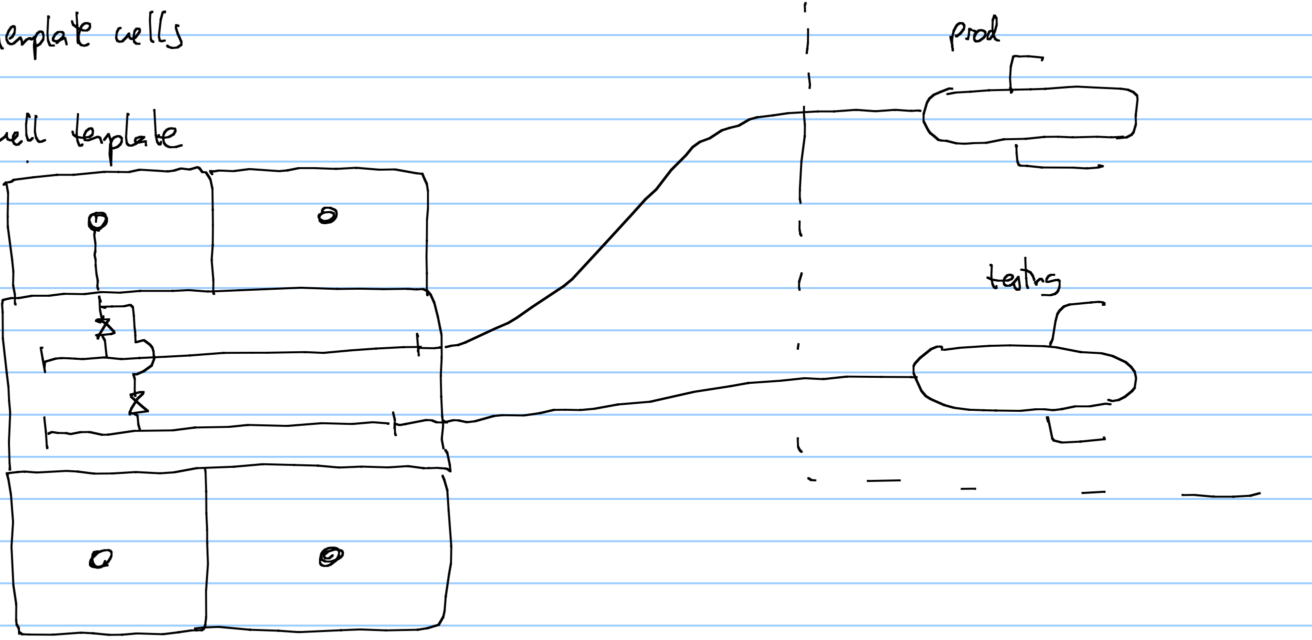


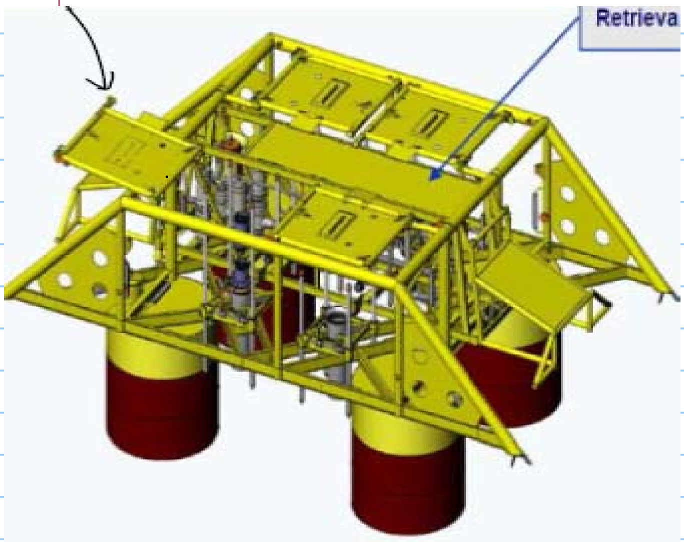
floating, production, storage offloading vessel

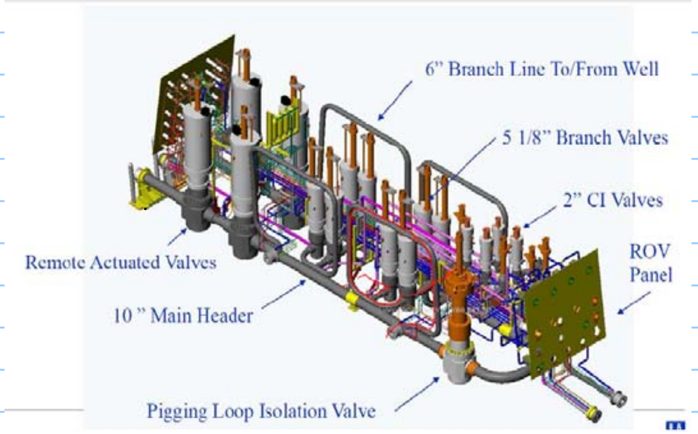
Subsea systems

template wells

4-well template

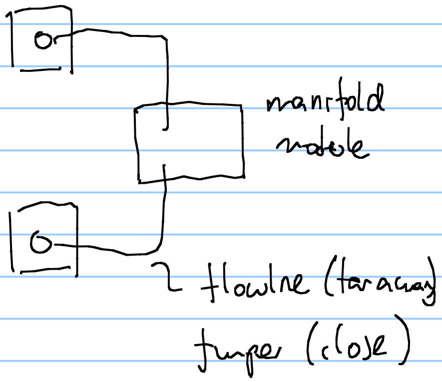


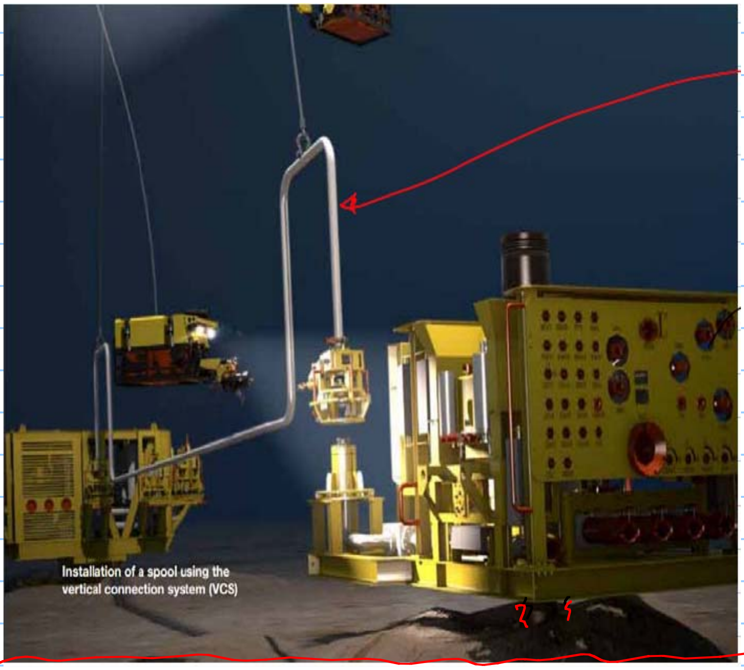


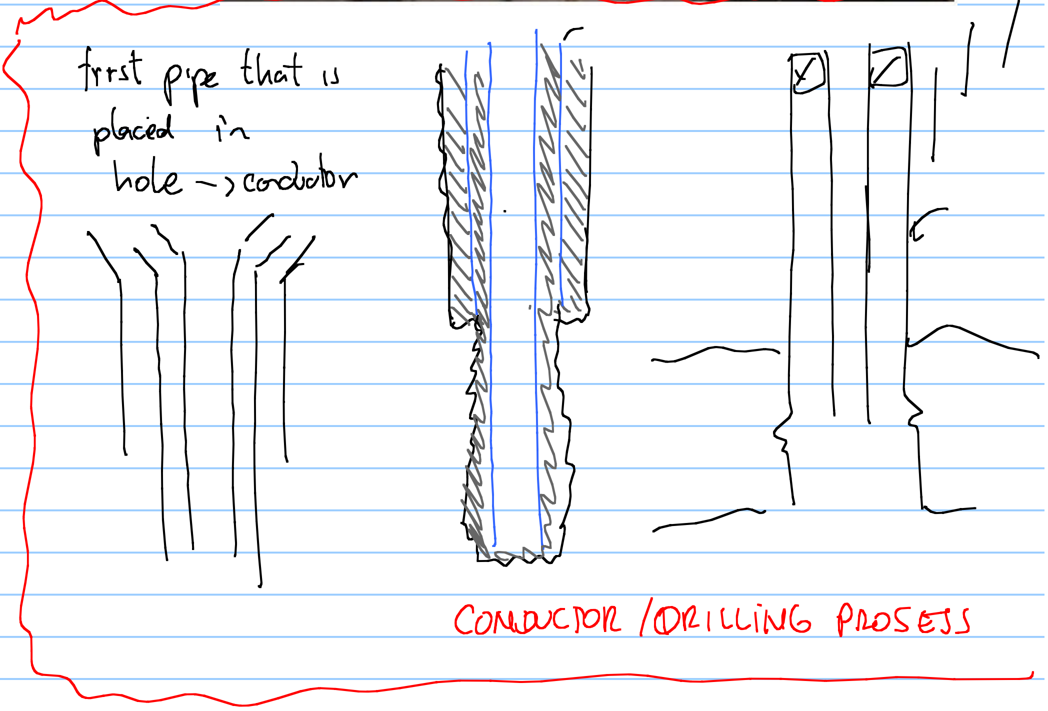


two types of subsea wells

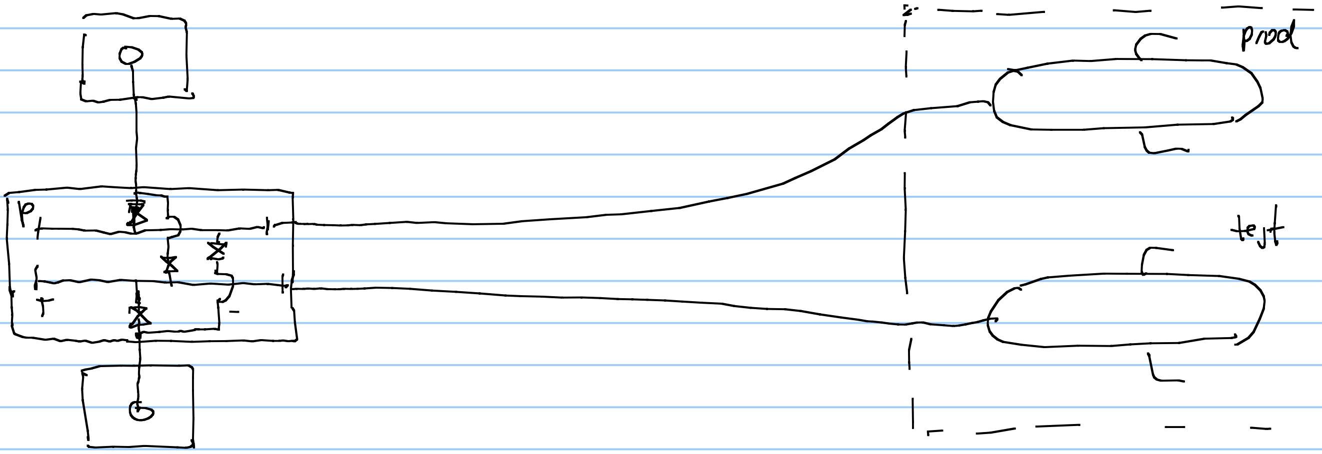
Satellite wells

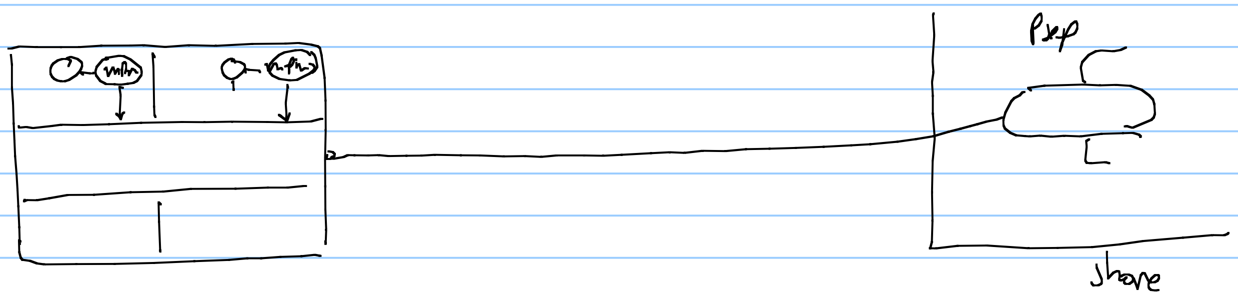



Installation of a spool using the vertical connection system (VCS)

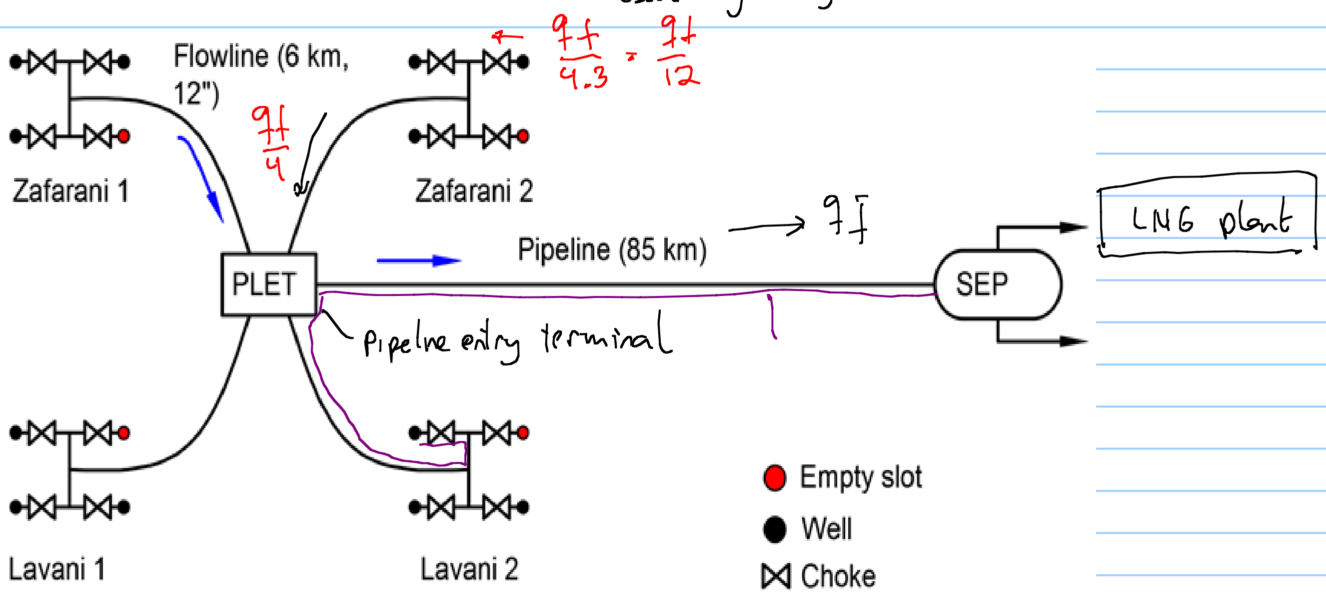

first pipe that is placed in hole -> conductor

CONDUCTOR / DRILLING PROSESS





subsea gathering network



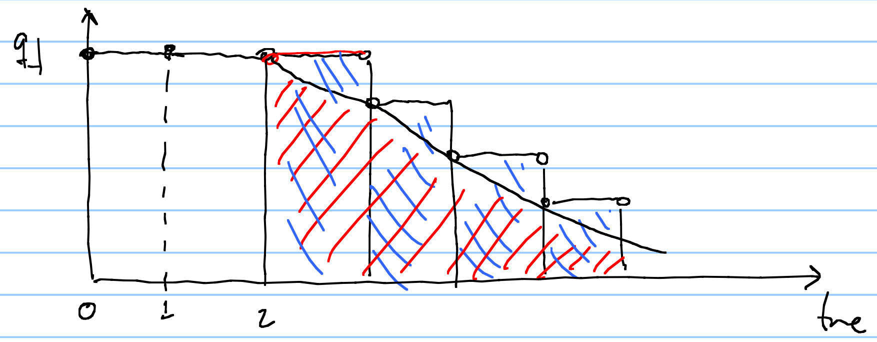
same P_{art}, P_{wh}

all well are identical

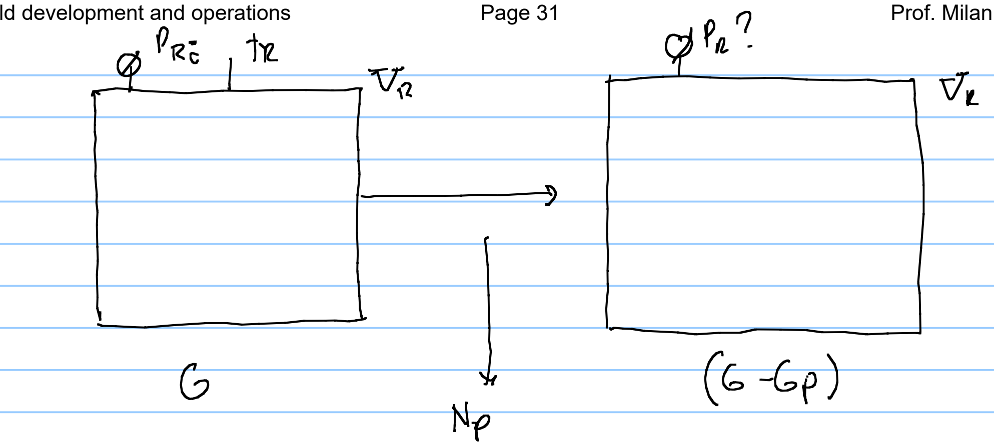
all flowlines are identical

all well drain from the same reservoir

How to calculate $P_R = f(t)$?



Dry gas material Balance



$$pV = RZT_R$$

$$p\frac{V}{m} = RZT_R$$

$$m_i = \frac{P_{Ri} V_R}{R Z_i T_R} \qquad m^* = \frac{P_R V_R}{R Z_R T_R}$$

Sm^3 kg

$$G_p \approx f(m_i - m^*)$$

final equation

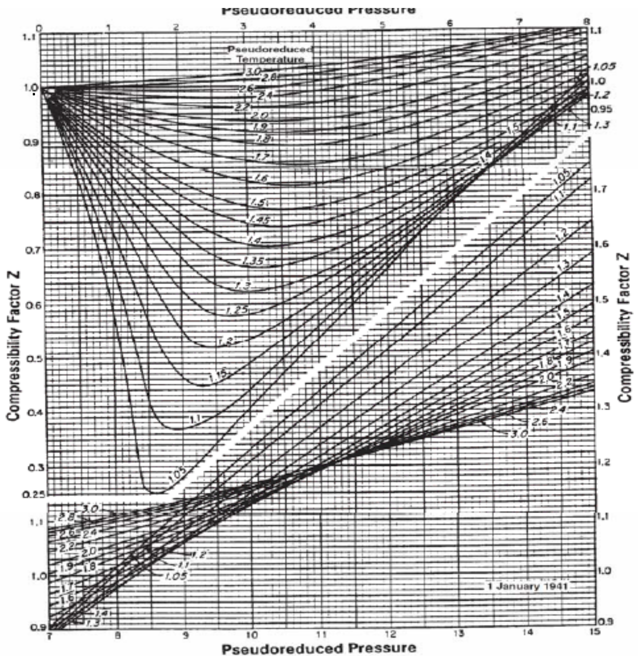
$$P_R = P_i \frac{Z_R}{Z_i}\left(1 - \underbrace{\frac{G_p}{G}}_{\text{Recovery factor}}\right)$$

neglecting rock compressibility

$$\overset{?}{P_R} = \overset{✓}{P_i}\, \frac{\overset{?}{Z_R}}{\underset{✓}{Z_i}}\left(1 - \overset{✓}{RF}\right)$$

0 q field

1 q field



$Z_R = f(T_R, P_R)$

assume $P_{R\,assumed}$

↓

calculate Z_R

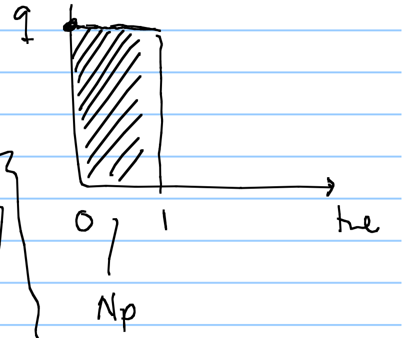
↓

equation calcula P_R

↓

is $P_{R\,assumed} = P_{R\,calc}$?

↳ yes



time	p_R
t_1	p_{R_1}
t_2	p_{R_2}
t_3	p_{R_3}
⋮	

$p_{R_1} \to p_{R_2}$ slow changing

Z_{R_2} with $(p_{R_1}$

Z_{R_i} with $p_{R_{i-1}}$

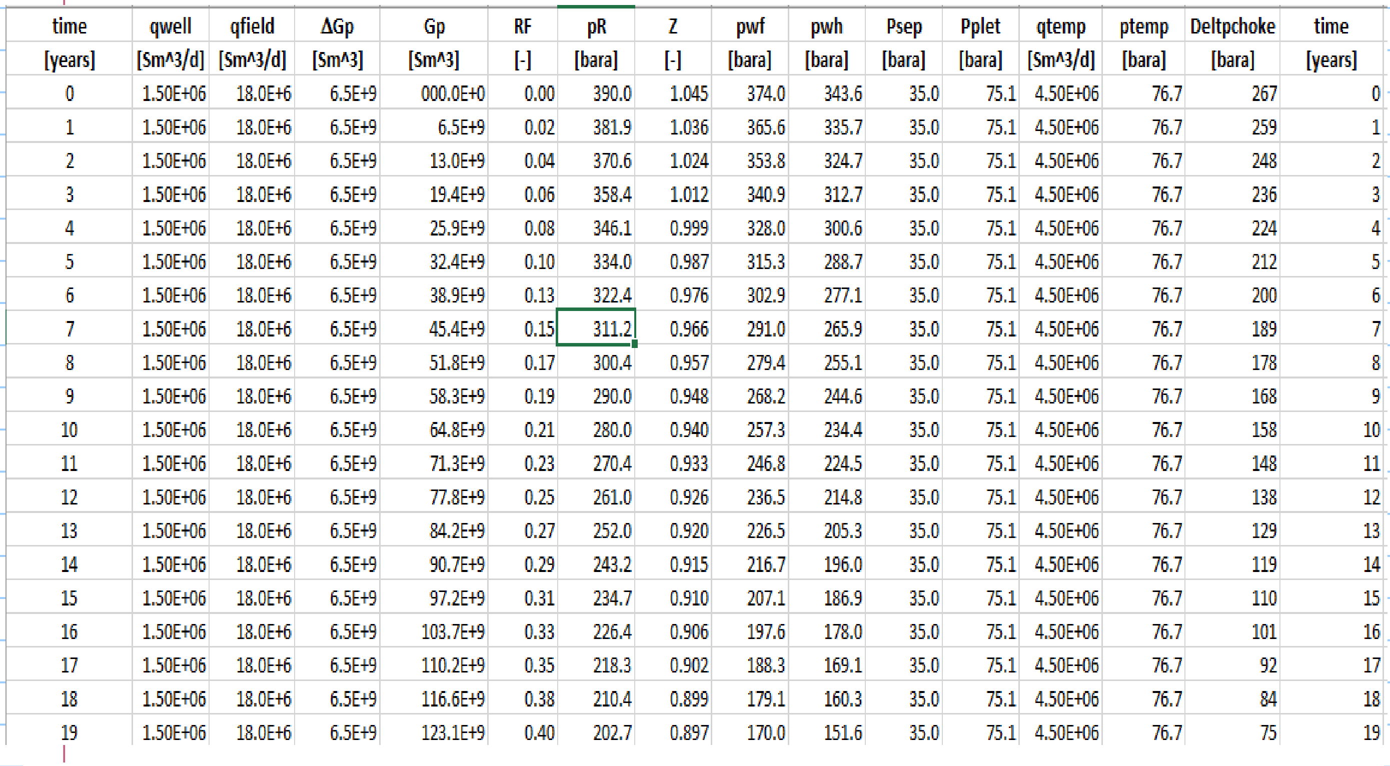
Sm³/d

years

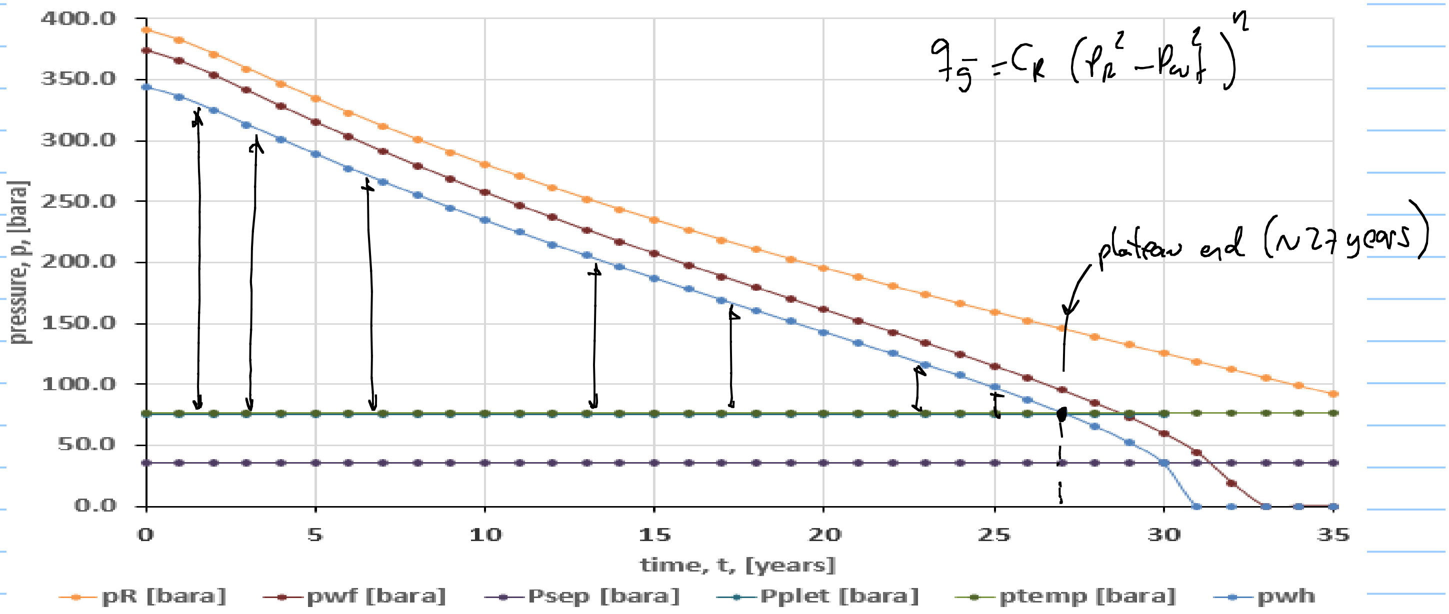
$t_i - t_{i-1}$

$\frac{\text{Ndays}}{\text{year}}$ ~ uptime

$\Delta G_p = q_{year} (1 - 0) \cdot uptime$

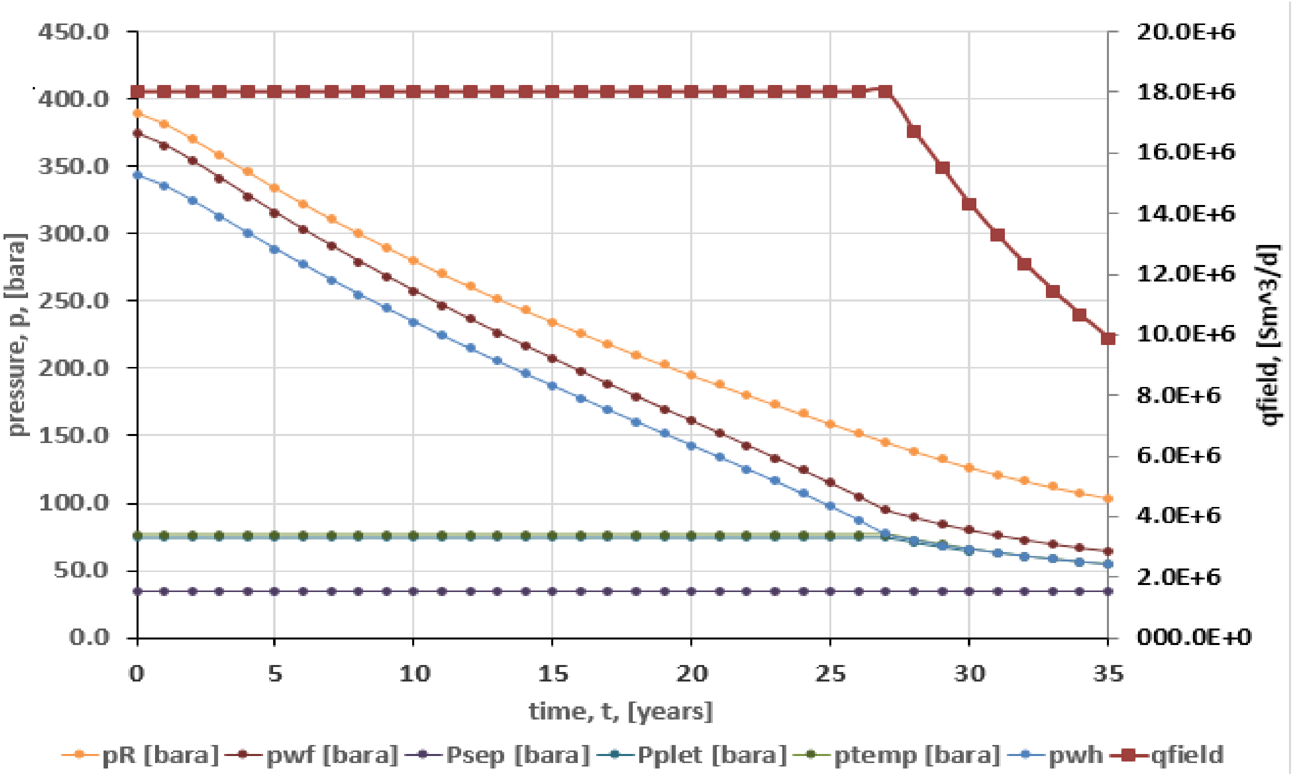


time	qwell	qfield	ΔGp	Gp	RF	pR	Z	pwf	pwh	Psep	Pplet	qtemp	ptemp	Deltpchoke	time
[years]	[Sm^3/d]	[Sm^3/d]	[Sm^3]	[Sm^3]	[-]	[bara]	[-]	[bara]	[bara]	[bara]	[bara]	[Sm^3/d]	[bara]	[bara]	[years]
0	1.50E+06	18.0E+6	6.5E+9	000.0E+0	0.00	390.0	1.045	374.0	343.6	35.0	75.1	4.50E+06	76.7	267	0
1	1.50E+06	18.0E+6	6.5E+9	6.5E+9	0.02	381.9	1.036	365.6	335.7	35.0	75.1	4.50E+06	76.7	259	1
2	1.50E+06	18.0E+6	6.5E+9	13.0E+9	0.04	370.6	1.024	353.8	324.7	35.0	75.1	4.50E+06	76.7	248	2
3	1.50E+06	18.0E+6	6.5E+9	19.4E+9	0.06	358.4	1.012	340.9	312.7	35.0	75.1	4.50E+06	76.7	236	3
4	1.50E+06	18.0E+6	6.5E+9	25.9E+9	0.08	346.1	0.999	328.0	300.6	35.0	75.1	4.50E+06	76.7	224	4
5	1.50E+06	18.0E+6	6.5E+9	32.4E+9	0.10	334.0	0.987	315.3	288.7	35.0	75.1	4.50E+06	76.7	212	5
6	1.50E+06	18.0E+6	6.5E+9	38.9E+9	0.13	322.4	0.976	302.9	277.1	35.0	75.1	4.50E+06	76.7	200	6
7	1.50E+06	18.0E+6	6.5E+9	45.4E+9	0.15	311.2	0.966	291.0	265.9	35.0	75.1	4.50E+06	76.7	189	7
8	1.50E+06	18.0E+6	6.5E+9	51.8E+9	0.17	300.4	0.957	279.4	255.1	35.0	75.1	4.50E+06	76.7	178	8
9	1.50E+06	18.0E+6	6.5E+9	58.3E+9	0.19	290.0	0.948	268.2	244.6	35.0	75.1	4.50E+06	76.7	168	9
10	1.50E+06	18.0E+6	6.5E+9	64.8E+9	0.21	280.0	0.940	257.3	234.4	35.0	75.1	4.50E+06	76.7	158	10
11	1.50E+06	18.0E+6	6.5E+9	71.3E+9	0.23	270.4	0.933	246.8	224.5	35.0	75.1	4.50E+06	76.7	148	11
12	1.50E+06	18.0E+6	6.5E+9	77.8E+9	0.25	261.0	0.926	236.5	214.8	35.0	75.1	4.50E+06	76.7	138	12
13	1.50E+06	18.0E+6	6.5E+9	84.2E+9	0.27	252.0	0.920	226.5	205.3	35.0	75.1	4.50E+06	76.7	129	13
14	1.50E+06	18.0E+6	6.5E+9	90.7E+9	0.29	243.2	0.915	216.7	196.0	35.0	75.1	4.50E+06	76.7	119	14
15	1.50E+06	18.0E+6	6.5E+9	97.2E+9	0.31	234.7	0.910	207.1	186.9	35.0	75.1	4.50E+06	76.7	110	15
16	1.50E+06	18.0E+6	6.5E+9	103.7E+9	0.33	226.4	0.906	197.6	178.0	35.0	75.1	4.50E+06	76.7	101	16
17	1.50E+06	18.0E+6	6.5E+9	110.2E+9	0.35	218.3	0.902	188.3	169.1	35.0	75.1	4.50E+06	76.7	92	17
18	1.50E+06	18.0E+6	6.5E+9	116.6E+9	0.38	210.4	0.899	179.1	160.3	35.0	75.1	4.50E+06	76.7	84	18
19	1.50E+06	18.0E+6	6.5E+9	123.1E+9	0.40	202.7	0.897	170.0	151.6	35.0	75.1	4.50E+06	76.7	75	19

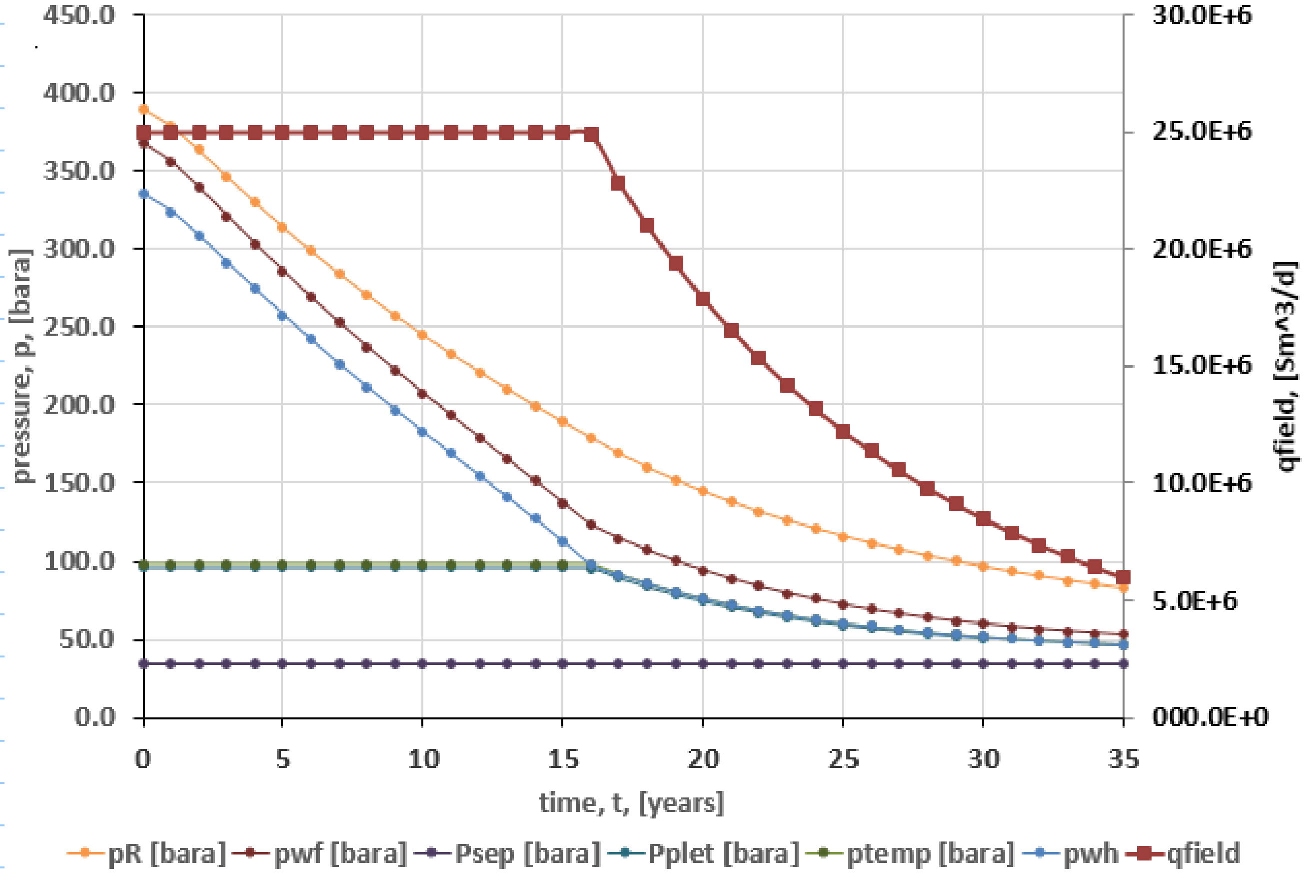


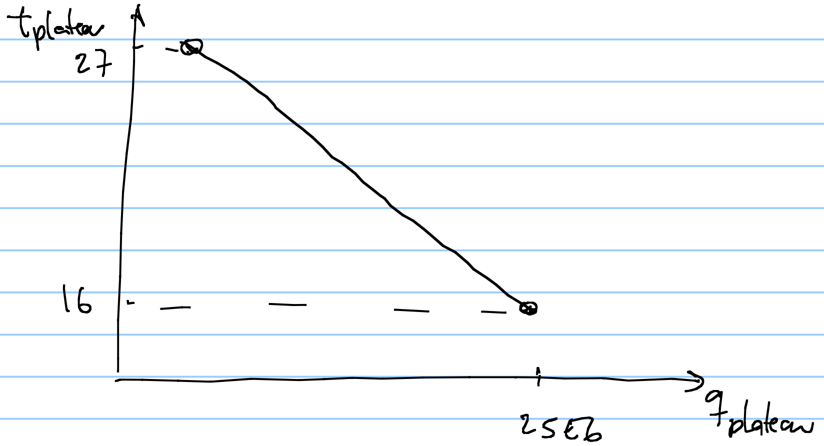
$q_g = C_R (p_R^2 - p_{wf}^2)^n$

plateau end (~27 years)



for higher plateau 25E6 Sm^3/d





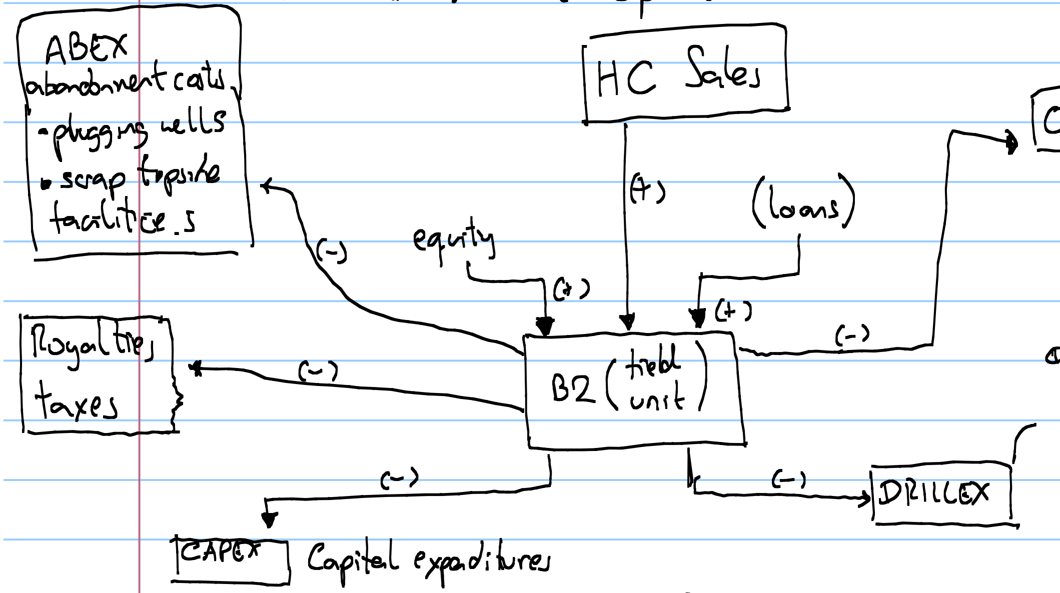
cost (CAPEX + OPEX)

capital expeditures operational expeditures

NPV calculations Net present value ← Revenue

year	ΔG_p	Revenue	P_g
	☐	$\Delta G_p \cdot P_g$	☐
		$\Delta G_p P_g$	

- Cash flow in field development

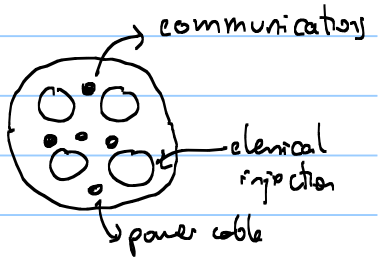


operational expenditures
- well intervention
- Salaries
- insurance
- energy consumption
- transportation
- maintenance
- chemical

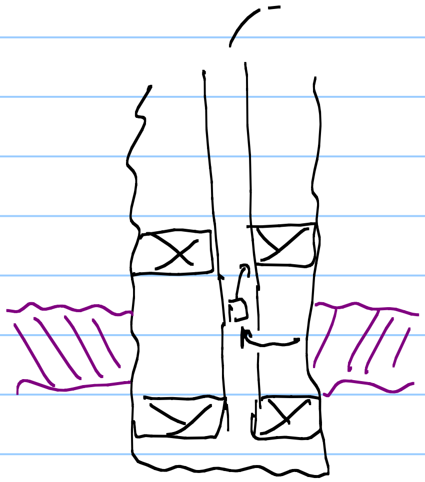
drilling expenditures
- rig rental rate 1.000.000 usd/d
- completion equipment
- test (logging, flow test)
  fluid

CAPEX Capital expenditures

- engineering studies (salaries, contractors)
- Processing facilities (separation, compression, water injection, LNG water treatment, oil treatment, gas processing)
- offshore structure (FPSO, platform, TLP, GBS → Gravity based structure)
  TLP: tension leg platform
  - living quarters
  - auxiliary equipment
- subsea system
  - templates, flowline, pipeline, umbilical
  - subsea processing

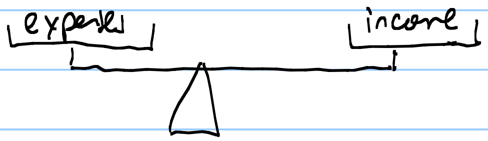


- Export transport vessel



How do we deal with expenses and income?

compare



- Cash flow calculations

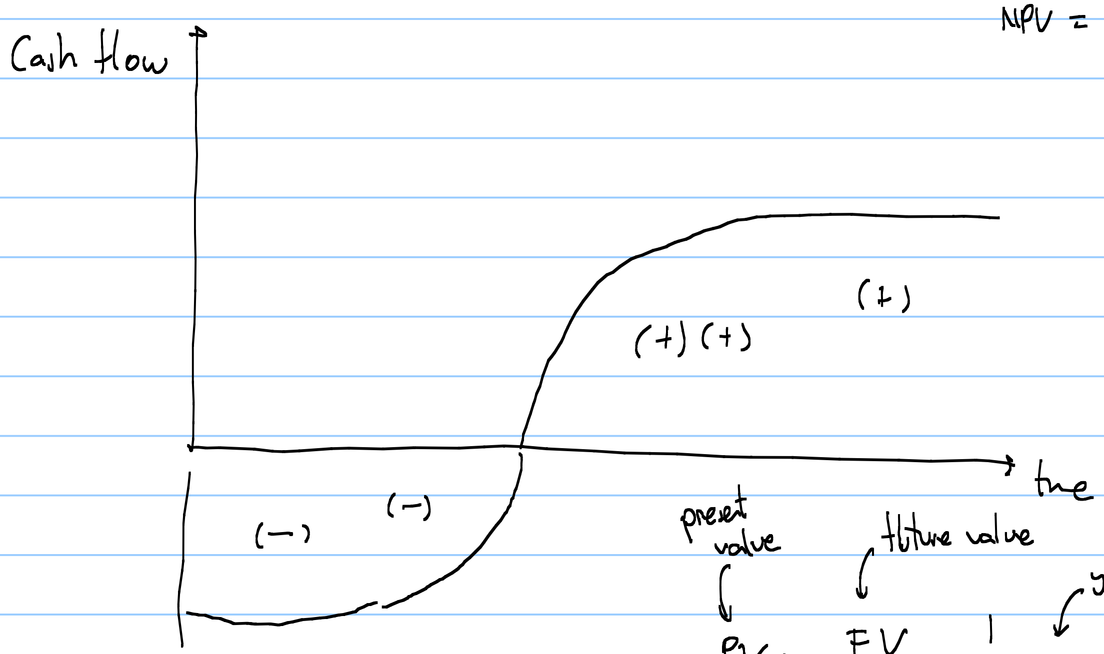
Revenue - tax - royalty

Discounted cash flow

0

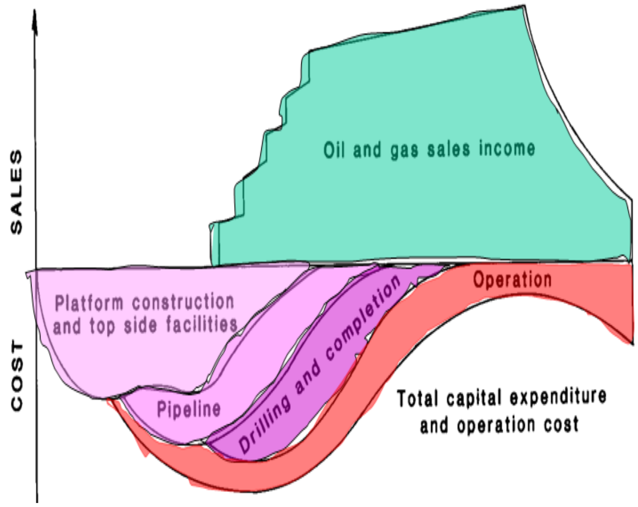
t	Revenue	CAPEX	DRILLEX	OPEX	Net income	Cash flow	DCF
year 1	0	(−)	(−)	0	0	(income − expenditure)	$\frac{CF}{(1+i)^n}$
year 2	0	(−)	(−)	0	0	(−)	−
year 3	0	(−)	(−)	0	0	(−)	−
	0	(−)	(−)	0	0	(−)	−
start of production →	(+)	0	0	(−)	(+)	(+)	−
	(+)	0	0	(−)	(+)	(+)	−
	(+)	0	0	(−)	(+)	(+)	−
	(+)	0	0	(−)	(+)	(+)	−
	(−)	0	0	(−)	(+)	(+)	−

$$NPV = \Sigma (DCF)_n$$



$$\overset{\text{present value}}{PV} = \overset{\text{future value}}{\underbrace{FV}} \cdot \frac{1}{(1+\underset{\text{interest}}{i})^{\overset{\text{year counter}}{n}}}$$

Revenue and Cost Profiles



The Ultimate driver in E&P operations

n years

+ gas price . Gas production(i)

$$NPV = \sum_{i=0}^{N} \frac{\text{OIL PRICE}(i) \times \text{OIL PROD}(i) - \text{CAPEX}(i) - \text{OPEX}(i) - \text{TAX}(i)}{(1+r)^{i}}$$

year counter

discount factor ~6-10%

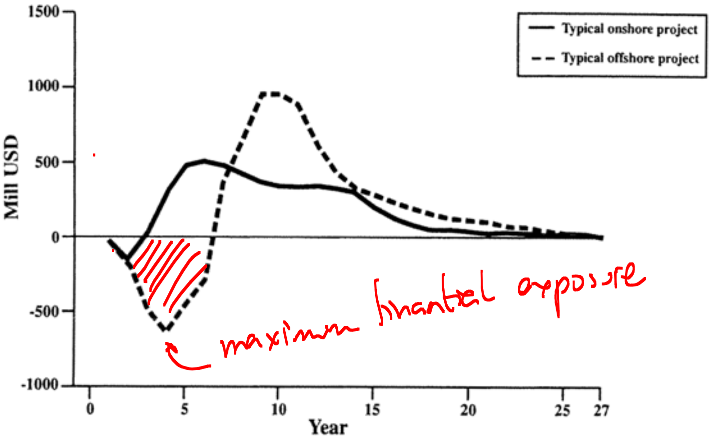
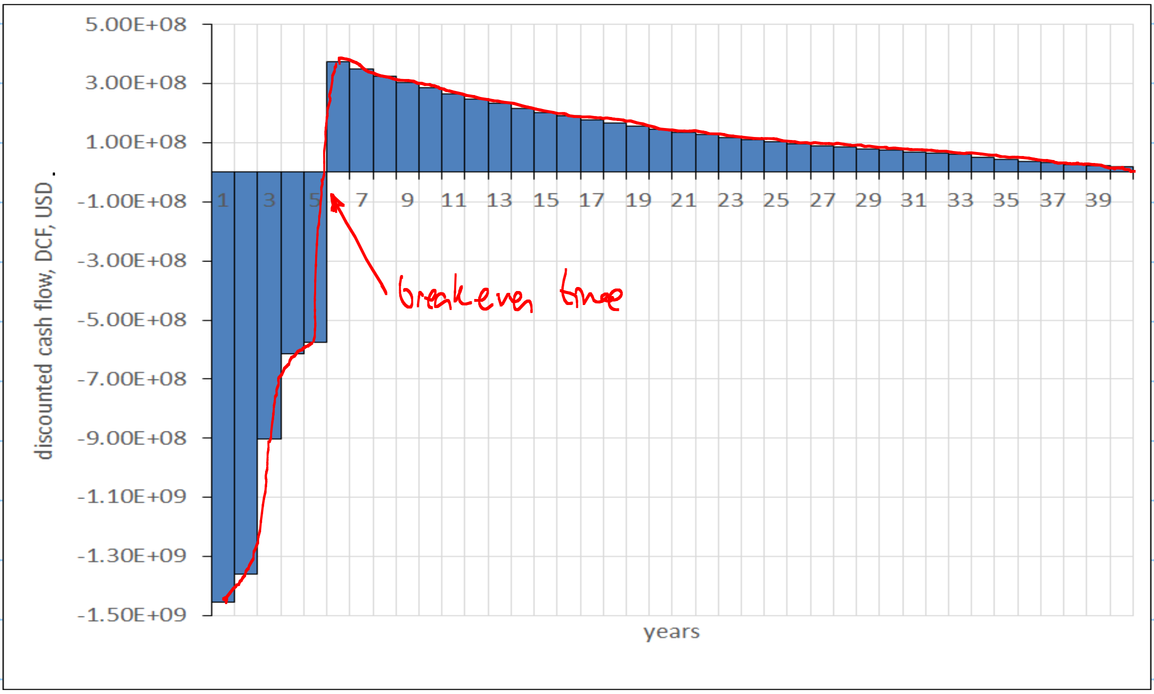
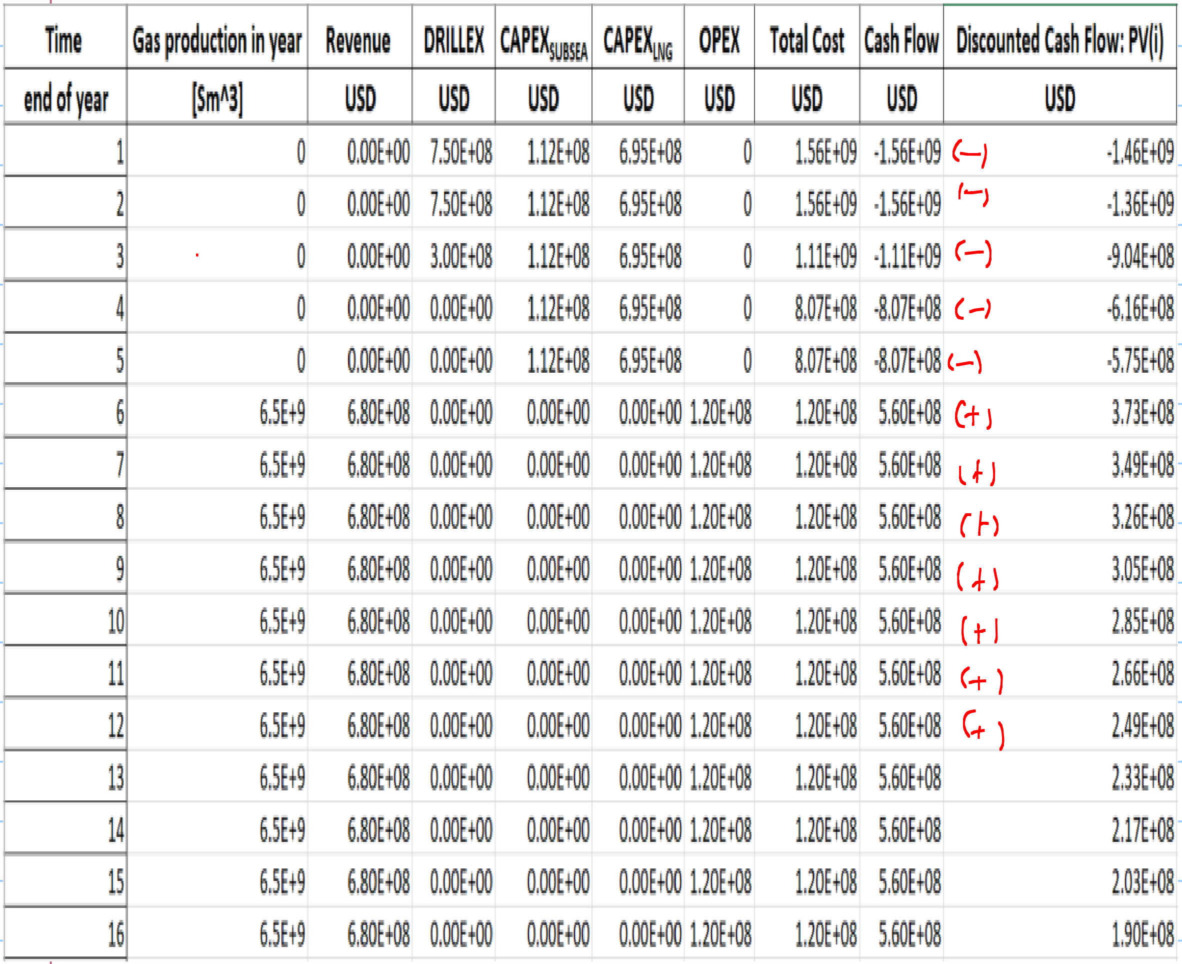


Fig. 9. Typical before tax cash flow profiles for offshore and onshore projects.

Class exercise





Time	Gas production in year	Revenue	DRILLEX	$CAPEX_{SUBSEA}$	$CAPEX_{LNG}$	OPEX	Total Cost	Cash Flow	Discounted Cash Flow: PV(i)
end of year	[Sm^3]	USD	USD	USD	USD	USD	USD	USD	USD
1	0	0.00E+00	7.50E+08	1.12E+08	6.95E+08	0	1.56E+09	-1.56E+09 (−)	-1.46E+09
2	0	0.00E+00	7.50E+08	1.12E+08	6.95E+08	0	1.56E+09	-1.56E+09 (−)	-1.36E+09
3	0	0.00E+00	3.00E+08	1.12E+08	6.95E+08	0	1.11E+09	-1.11E+09 (−)	-9.04E+08
4	0	0.00E+00	0.00E+00	1.12E+08	6.95E+08	0	8.07E+08	-8.07E+08 (−)	-6.16E+08
5	0	0.00E+00	0.00E+00	1.12E+08	6.95E+08	0	8.07E+08	-8.07E+08 (−)	-5.75E+08
6	6.5E+9	6.80E+08	0.00E+00	0.00E+00	0.00E+00	1.20E+08	1.20E+08	5.60E+08 (+)	3.73E+08
7	6.5E+9	6.80E+08	0.00E+00	0.00E+00	0.00E+00	1.20E+08	1.20E+08	5.60E+08 (+)	3.49E+08
8	6.5E+9	6.80E+08	0.00E+00	0.00E+00	0.00E+00	1.20E+08	1.20E+08	5.60E+08 (+)	3.26E+08
9	6.5E+9	6.80E+08	0.00E+00	0.00E+00	0.00E+00	1.20E+08	1.20E+08	5.60E+08 (+)	3.05E+08
10	6.5E+9	6.80E+08	0.00E+00	0.00E+00	0.00E+00	1.20E+08	1.20E+08	5.60E+08 (+)	2.85E+08
11	6.5E+9	6.80E+08	0.00E+00	0.00E+00	0.00E+00	1.20E+08	1.20E+08	5.60E+08 (+)	2.66E+08
12	6.5E+9	6.80E+08	0.00E+00	0.00E+00	0.00E+00	1.20E+08	1.20E+08	5.60E+08 (+)	2.49E+08
13	6.5E+9	6.80E+08	0.00E+00	0.00E+00	0.00E+00	1.20E+08	1.20E+08	5.60E+08	2.33E+08
14	6.5E+9	6.80E+08	0.00E+00	0.00E+00	0.00E+00	1.20E+08	1.20E+08	5.60E+08	2.17E+08
15	6.5E+9	6.80E+08	0.00E+00	0.00E+00	0.00E+00	1.20E+08	1.20E+08	5.60E+08	2.03E+08
16	6.5E+9	6.80E+08	0.00E+00	0.00E+00	0.00E+00	1.20E+08	1.20E+08	5.60E+08	1.90E+08

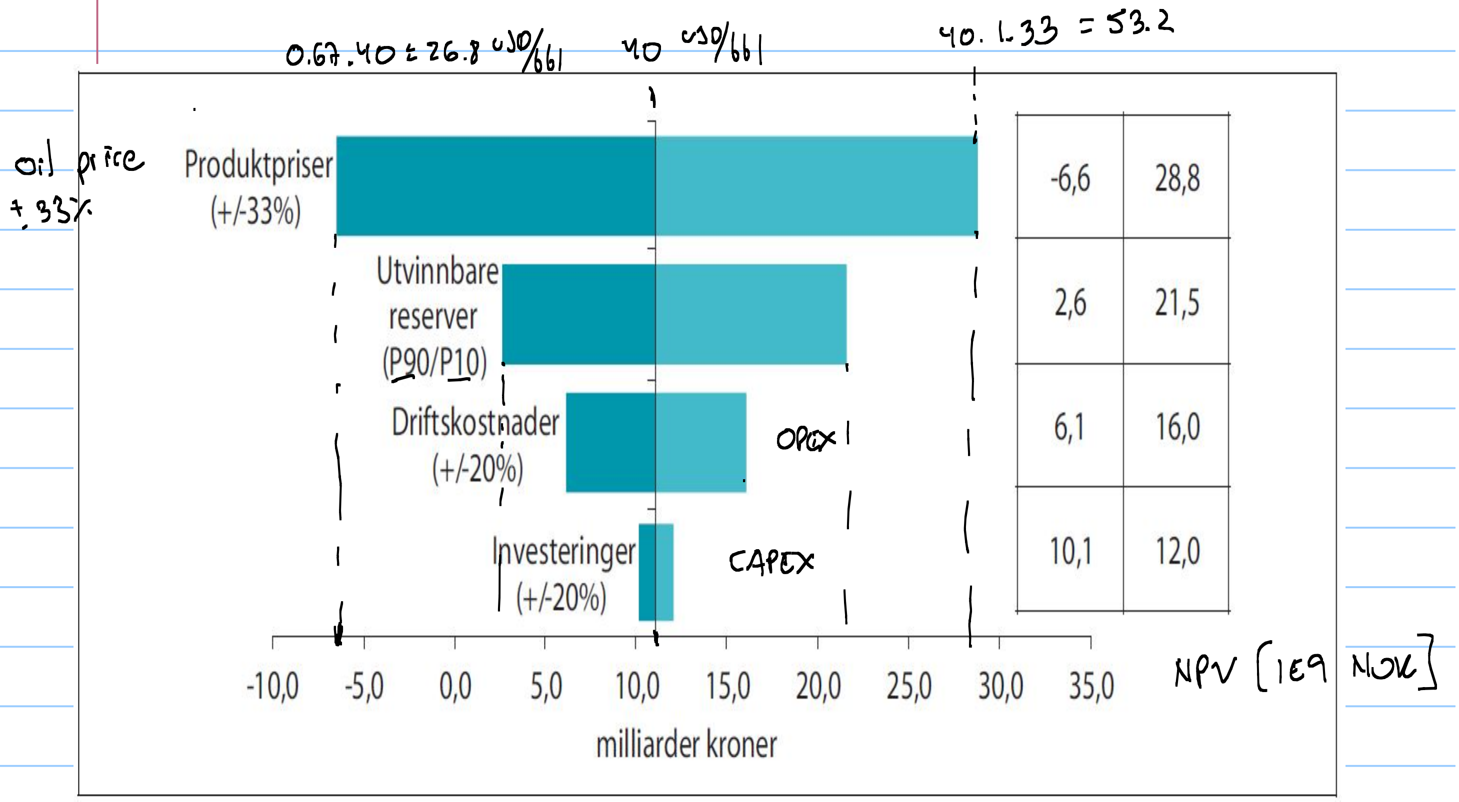
I always have to perform sensitivity analyses on input

Ceteris Paribus "one change all same"

change ⇝ calculate NPV
↓
go back to original.
↓
change
MP
↓

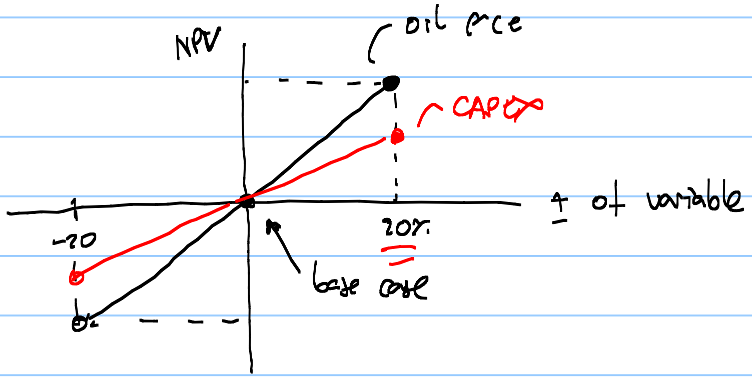
- gas prices / oil prices (HC)
- cost figures ± 40% ± 20% (PDO)
- reserve size
- opex
-
-

- Tornado chart



-6,6	28,8
2,6	21,5
6,1	16,0
10,1	12,0

- Spider plot



NPV base case 170 E6 USD

		-20%	+20
gas price	±20	NPV	NPV
CAPEX	±20%	NPV	NPV
OPEX	±20%		

change variable ✓

↓

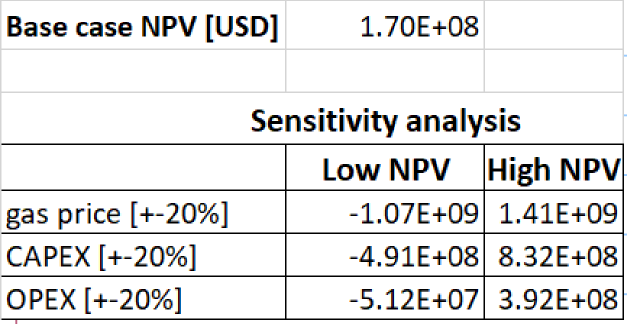
calculate NPV ✓

↓

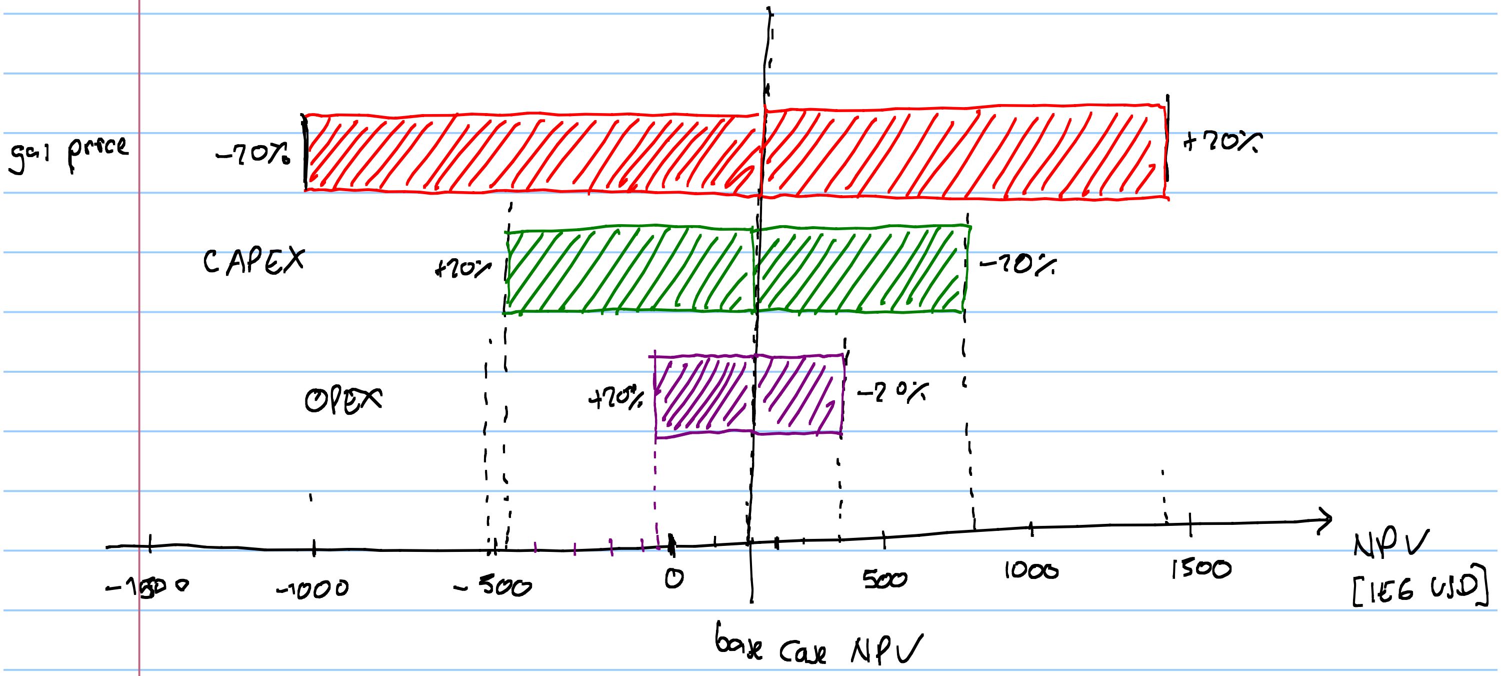
save NPV on table

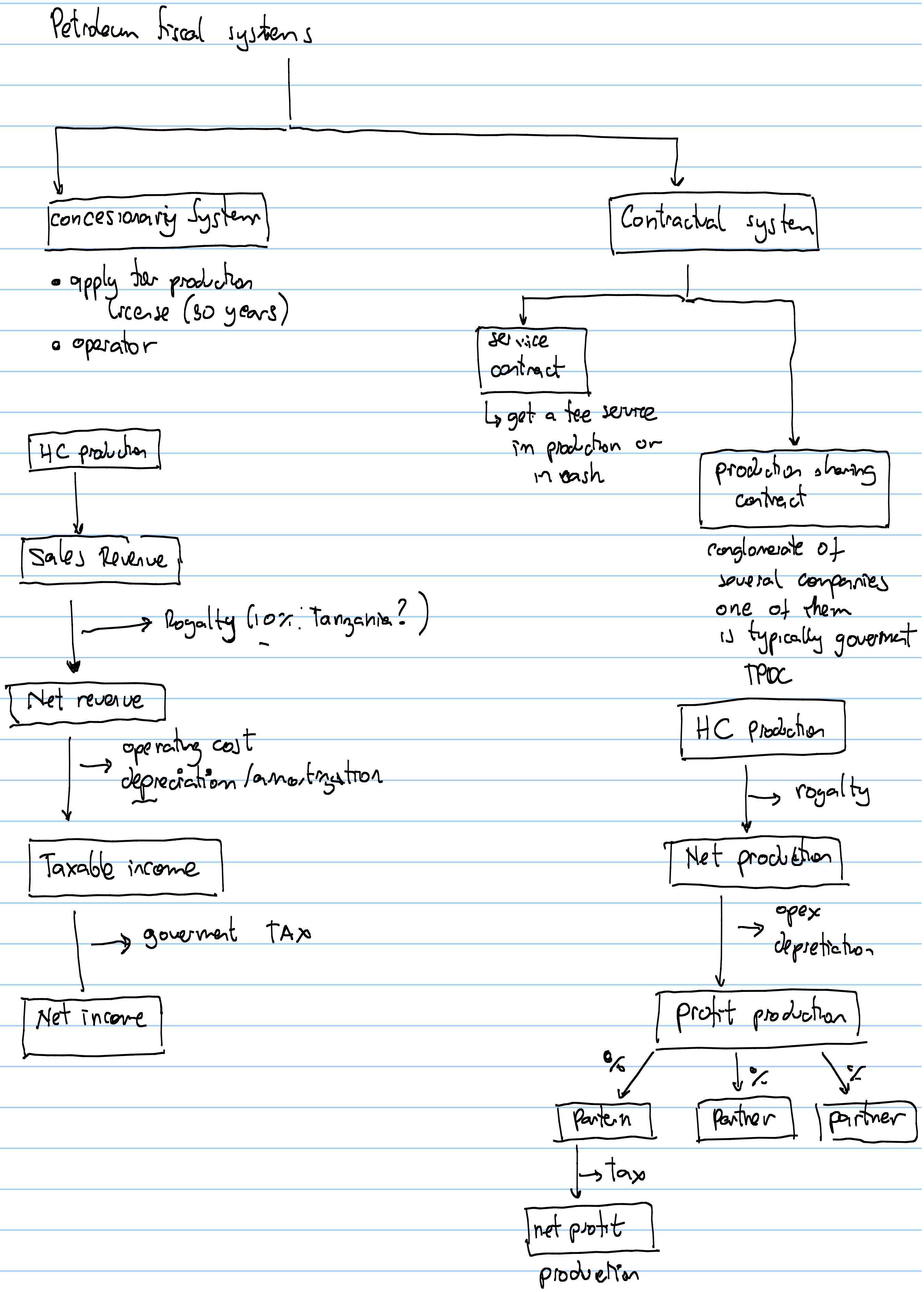
↓

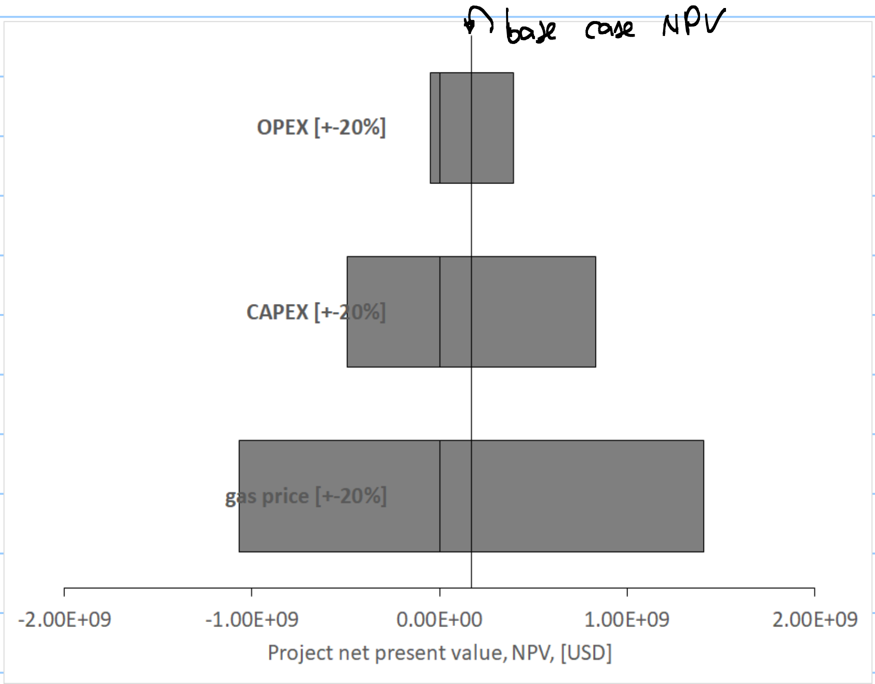
revert back to original



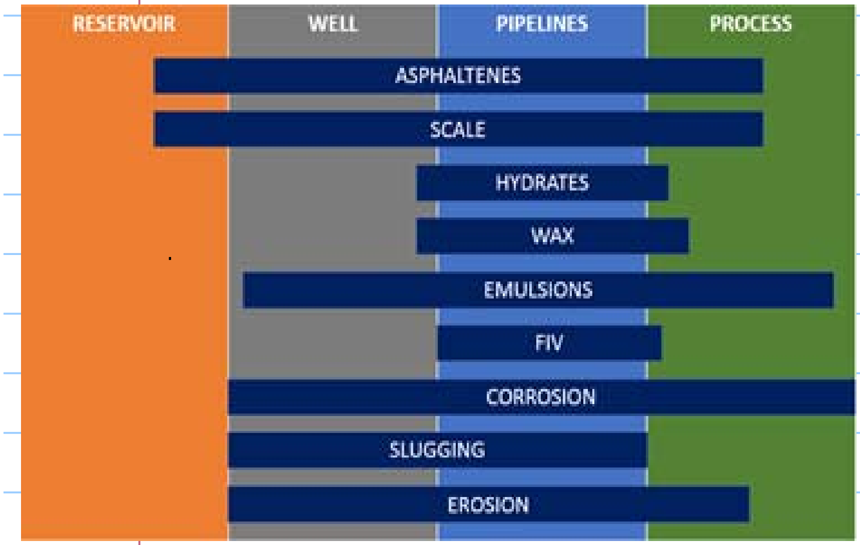
Base case NPV [USD]	1.70E+08	
Sensitivity analysis		
	Low NPV	**High NPV**
gas price [+-20%]	-1.07E+09	1.41E+09
CAPEX [+-20%]	-4.91E+08	8.32E+08
OPEX [+-20%]	-5.12E+07	3.92E+08




Petroleum fiscal systems
concesionary System
• apply for production licence (30 years)
• operator
HC production
Sales Revenue
Royalty (10%: Tanzania?)
Net revenue
operating cost
depreciation/amortization
Taxable income
goverment TAX
Net income
Contractual system
service contract
↳ get a fee service in production or in cash
production sharing contract
conglomerate of several companies one of them is typically goverment
TPDC
HC Production
royalty
Net production
opex
depreciation
Profit production
%
%
%
Partner
Partner
partner
tax
net profit production



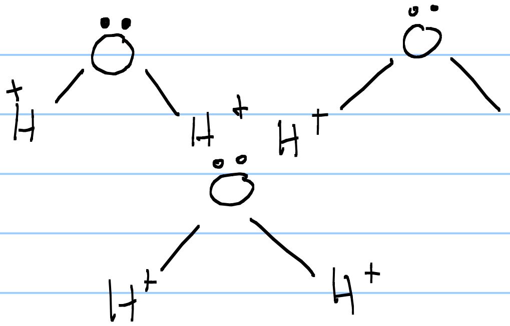
B2 pipeline to shore

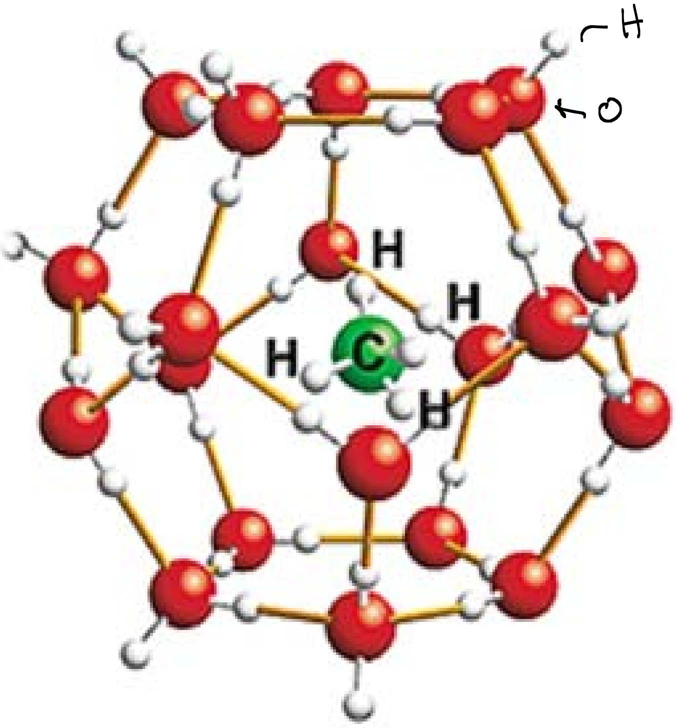


flow assurance: ensuring the uninterrupted flow of hydrocarbons from reservoir to processing facilities

- HYDRATES (gas)
- WAX (oil)
- Scaling (gas + oil)
- slugging
- corrosion
- emulsion
- foaming
- asphaltene precipitation
- erosion

Natural gas Hydrates

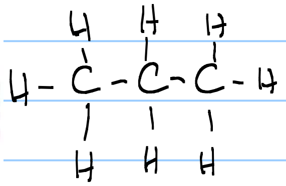




when T

~9 Å 1E-10 m

small molecules go inside the cage → CH_2



$$H-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-H$$

C_2H_6

C_3H_8

CO_2

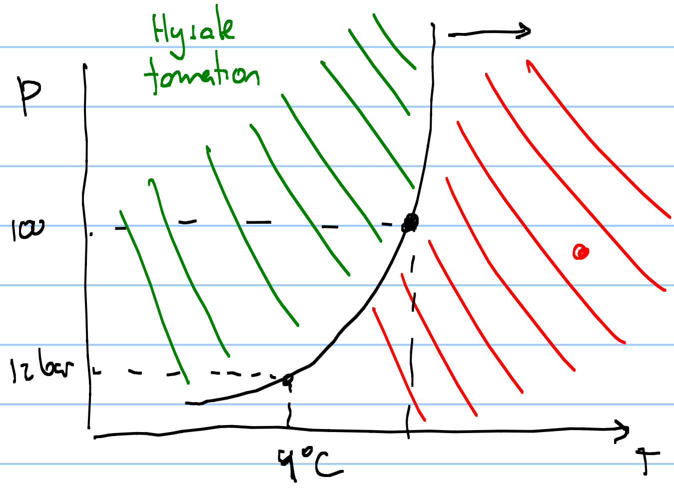
N_2

⋮

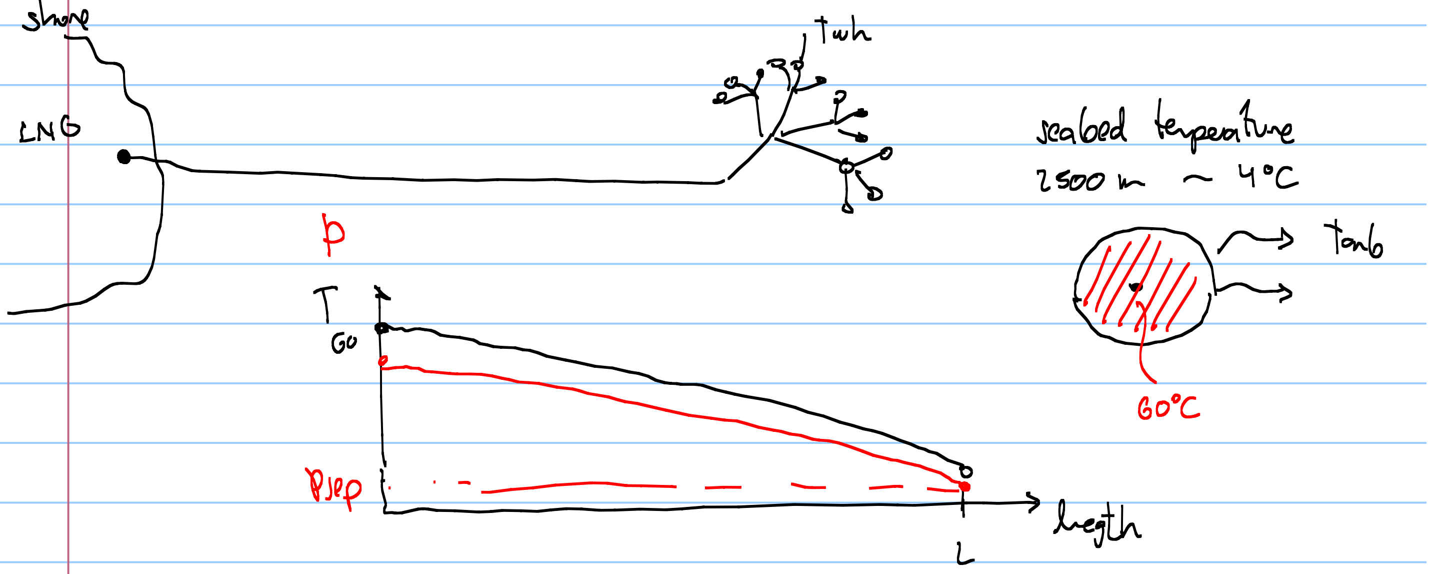
"Ice" like structure

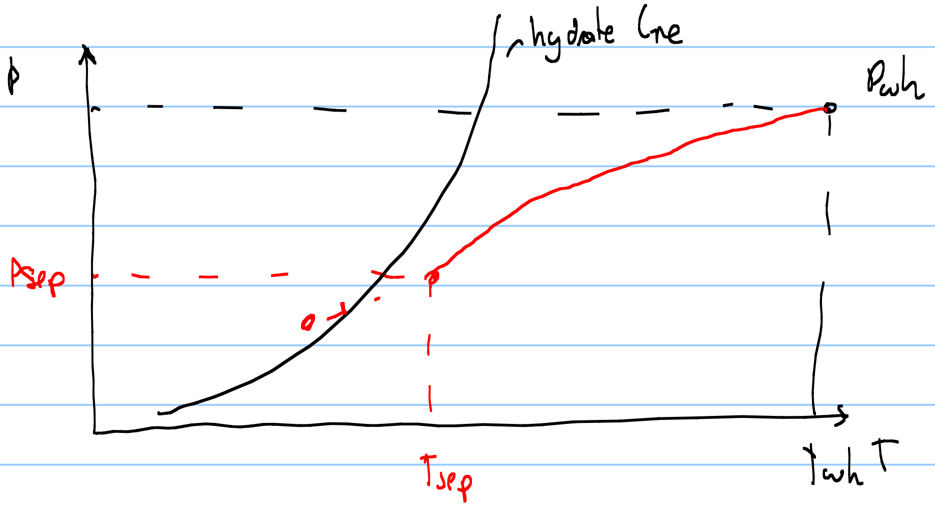
operational problem → pipeline plugging

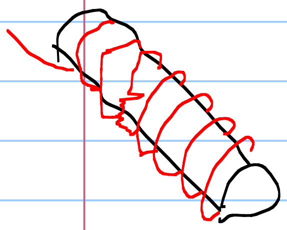
- Hydrate formation conditions
  - Small HC molecules CH_4 C_2H_6
  - free water { from reservoir / water condensed from gas
  - special conditions of P, T



How to operate in "safe" zone → conservative hydrate management
traditional hydrate management



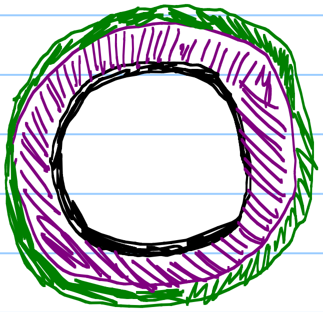




counteracting measures:

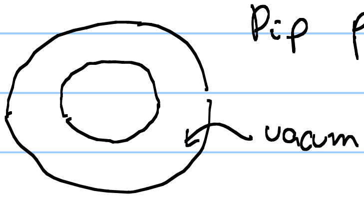
- heating pipe (heat tracing)
  ↳ effective for short distances (<20km)

convection (fluid)
conduction (solid)
radiation (wave)

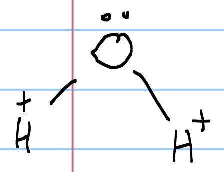


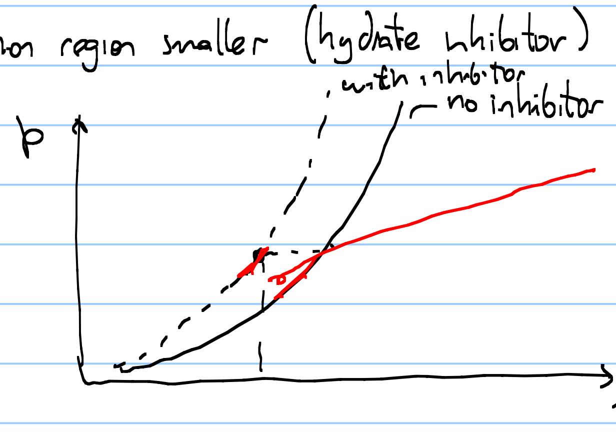
- pipe insulation

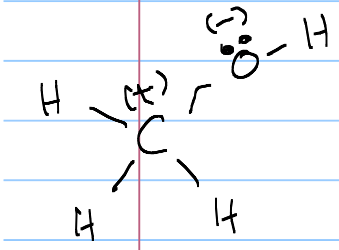
PiP pipe in pipe $



Make hydrate formation region smaller (hydrate inhibitor)

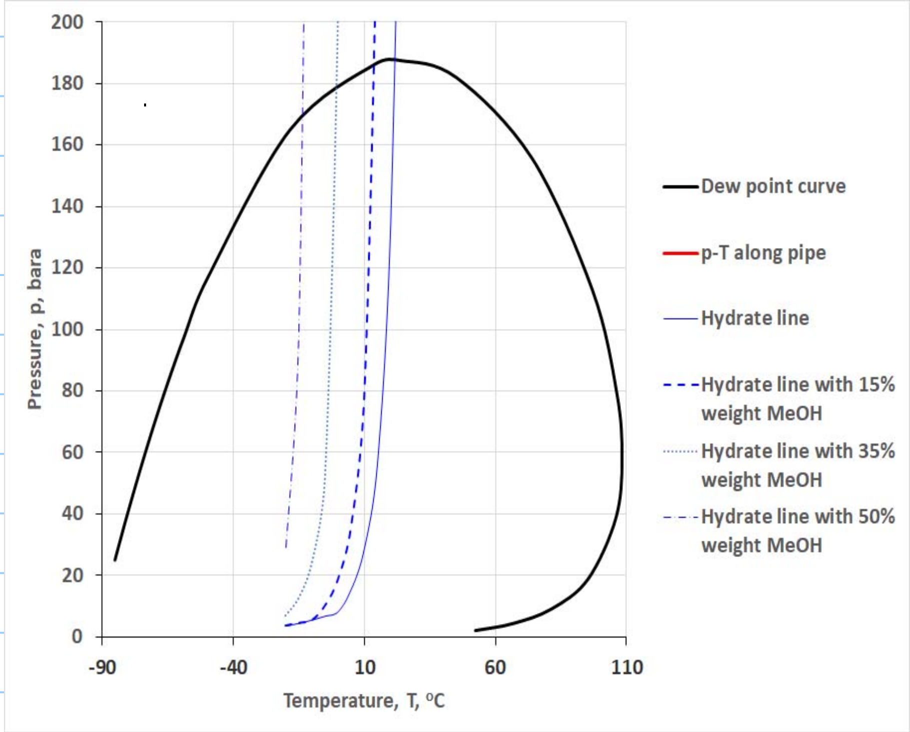


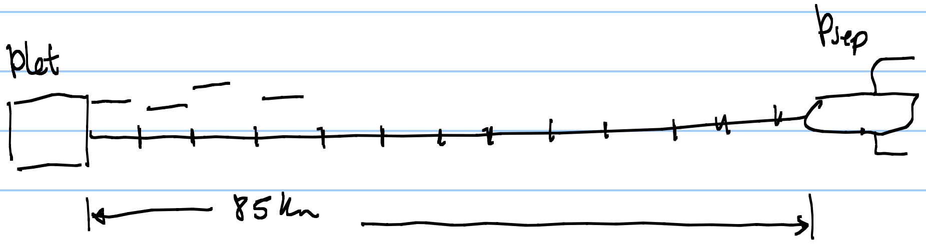




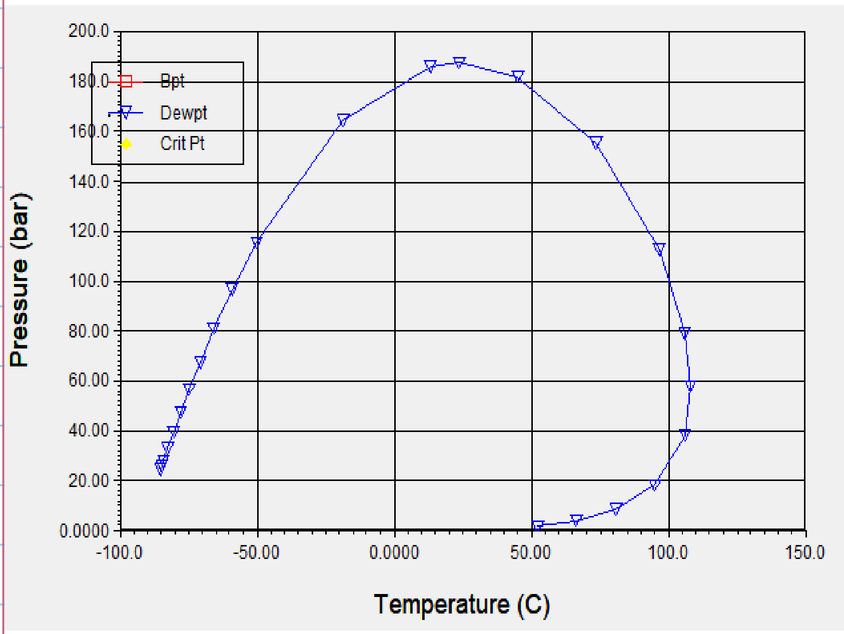
Some hydrate inhibitor : MeOH methanol
: TEG tri-ethylene glycol
: MEG mono-ethylene glycol

$$10\% < \frac{m_{inhibitor}}{m_{water} + m_{inhibitor}} < 60\%$$



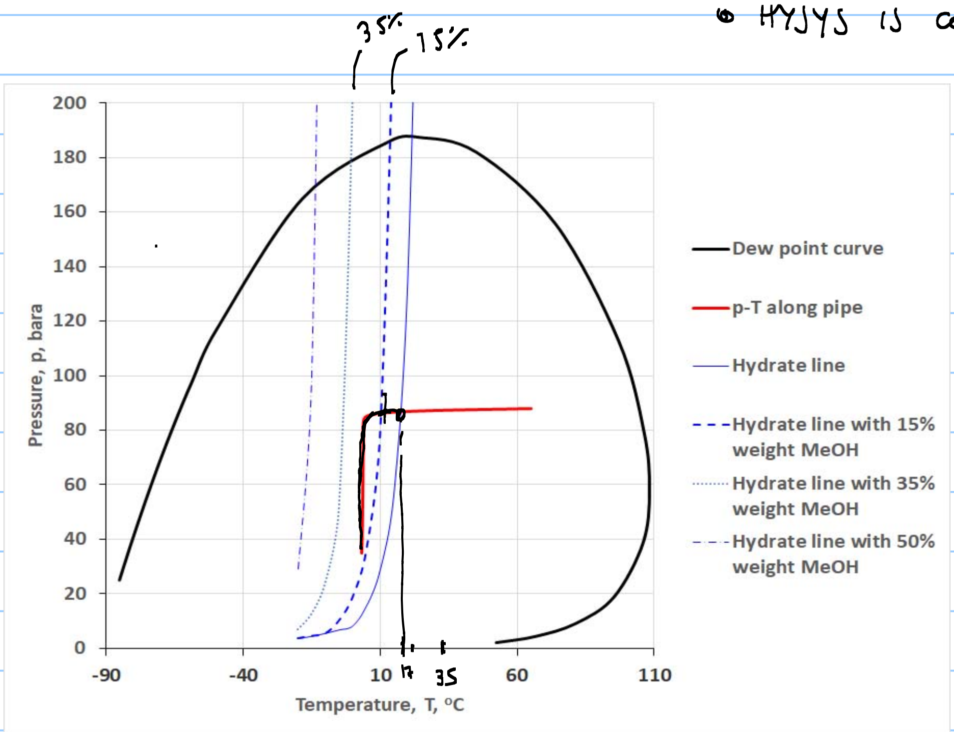


$$\text{vapour mass fraction} = \text{vapour mole fraction} = \frac{\text{moles vapor}}{\text{total moles}}$$



Pipeline Δp with excel ≈ 40 bara
pipeline Δp with HYSY = 53 bara
} 10% difference !

- HYSYS is considering variation of ρ, μ along pipe
- HYSYS is considering liquid !



I need to inject 35% (weight) of inhibitor into the pipeline
MeOH

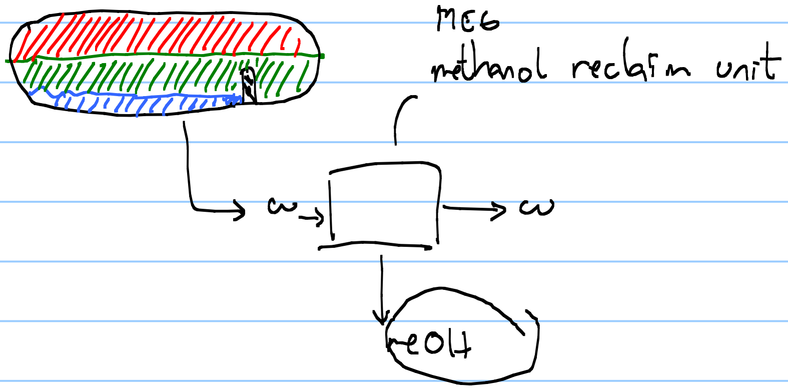
$$\left\{ 0.35 = \frac{\dot{m}_{inhibitor}}{\dot{m}_{inhibitor} + \dot{m}_{water}} \right.$$

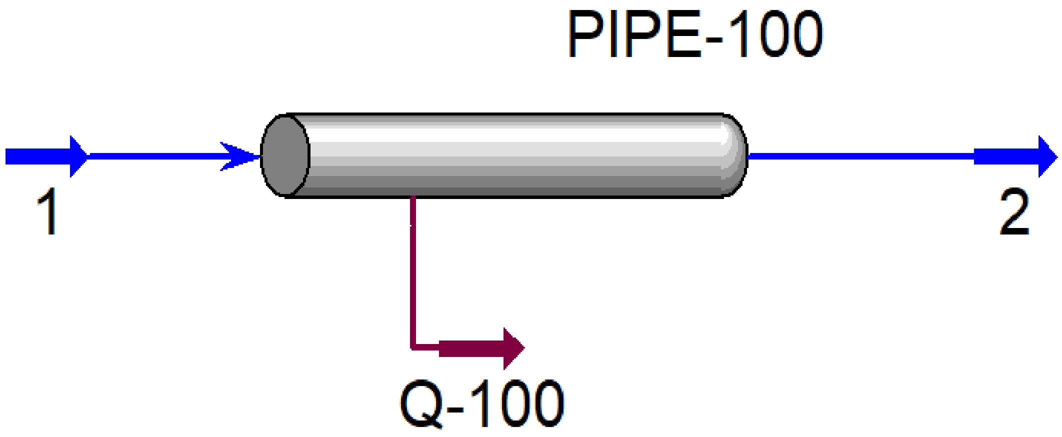
$$\dot{m}_{water} = q_{\bar{w}} \cdot \rho_{\bar{w}} = 69 \frac{S\cancel{m^3}}{d} \, 854 \frac{kg}{\cancel{m^3}} = \left[\frac{kg}{d} \right]$$

$$\dot{m}_{inhibitor}(1-0.35) = 0.35 \, \dot{m}_{water}$$

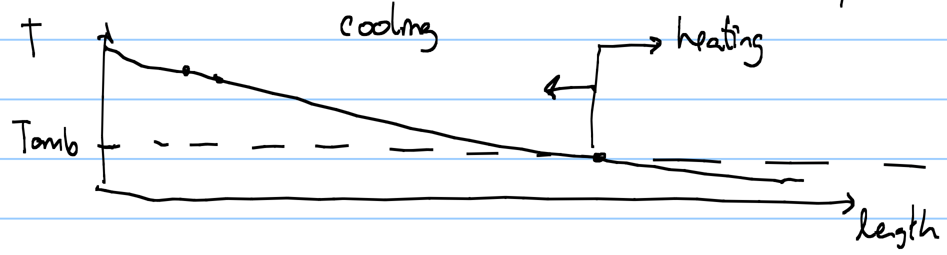
$$\dot{m}_{inhibitor} = \frac{(0.35)}{(1-0.35)} \cdot \dot{m}_{water}$$

$$\dot{m}_{inhibitor} = 0.54 \cdot 59000 \, \frac{kg}{d} = \underline{35000 \, \frac{kg}{d}}$$





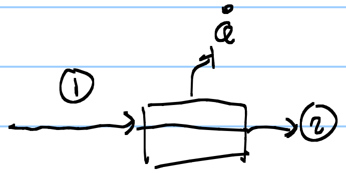
in gas pipelines T can go below ambient temperature



Joule Thompson effect

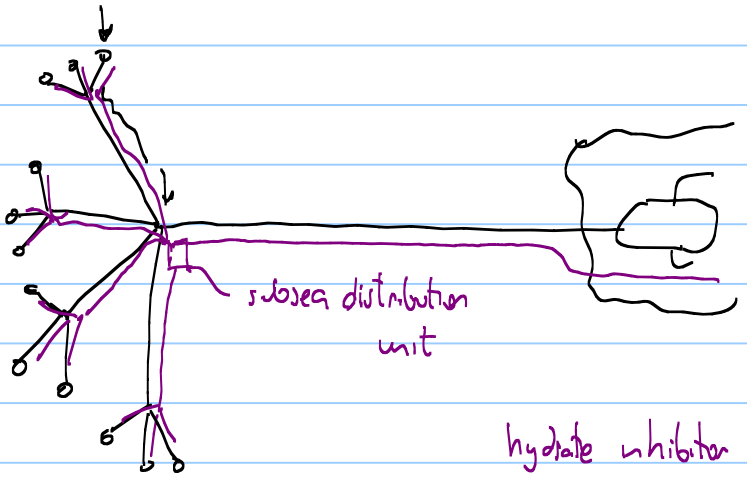
$$\frac{d\overset{\text{enthalpy}}{h}}{dx} = \underbrace{\frac{dT}{dx}\frac{dh}{dT}}_{} + \underbrace{\frac{dP}{dx}\frac{dh}{\underline{dp}}}_{}$$

more relevant in liquid and in gas + lots of liquid

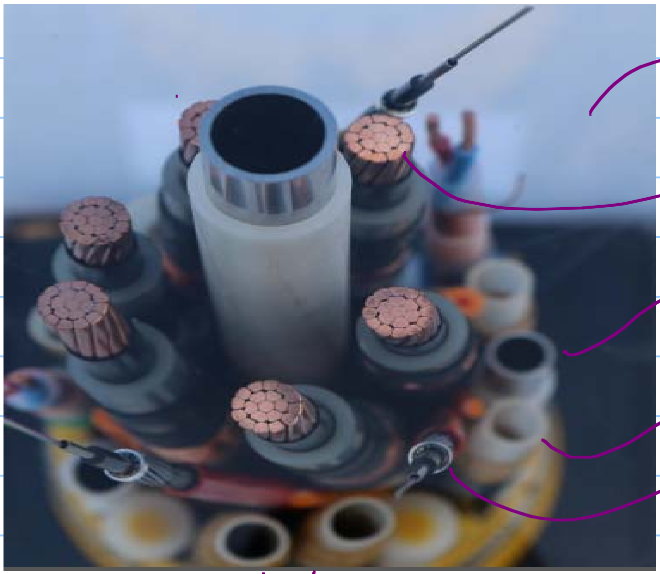


$$\dot{m}(h_2-h_1) = \dot{Q}$$

-



hydrate inhibitor are injected with umbilical



pipe bundle

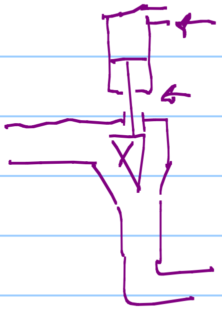
power

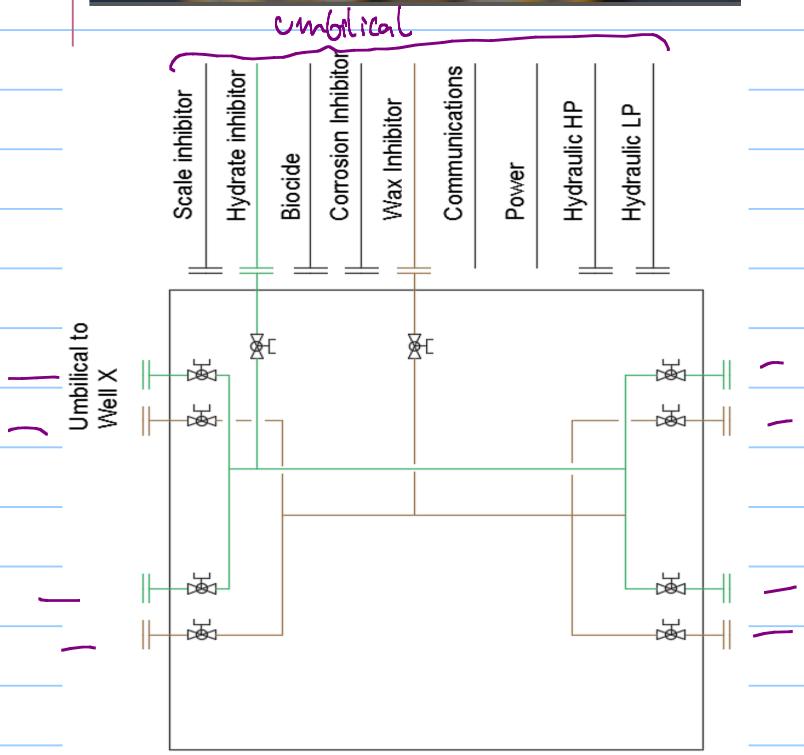
chemical injection

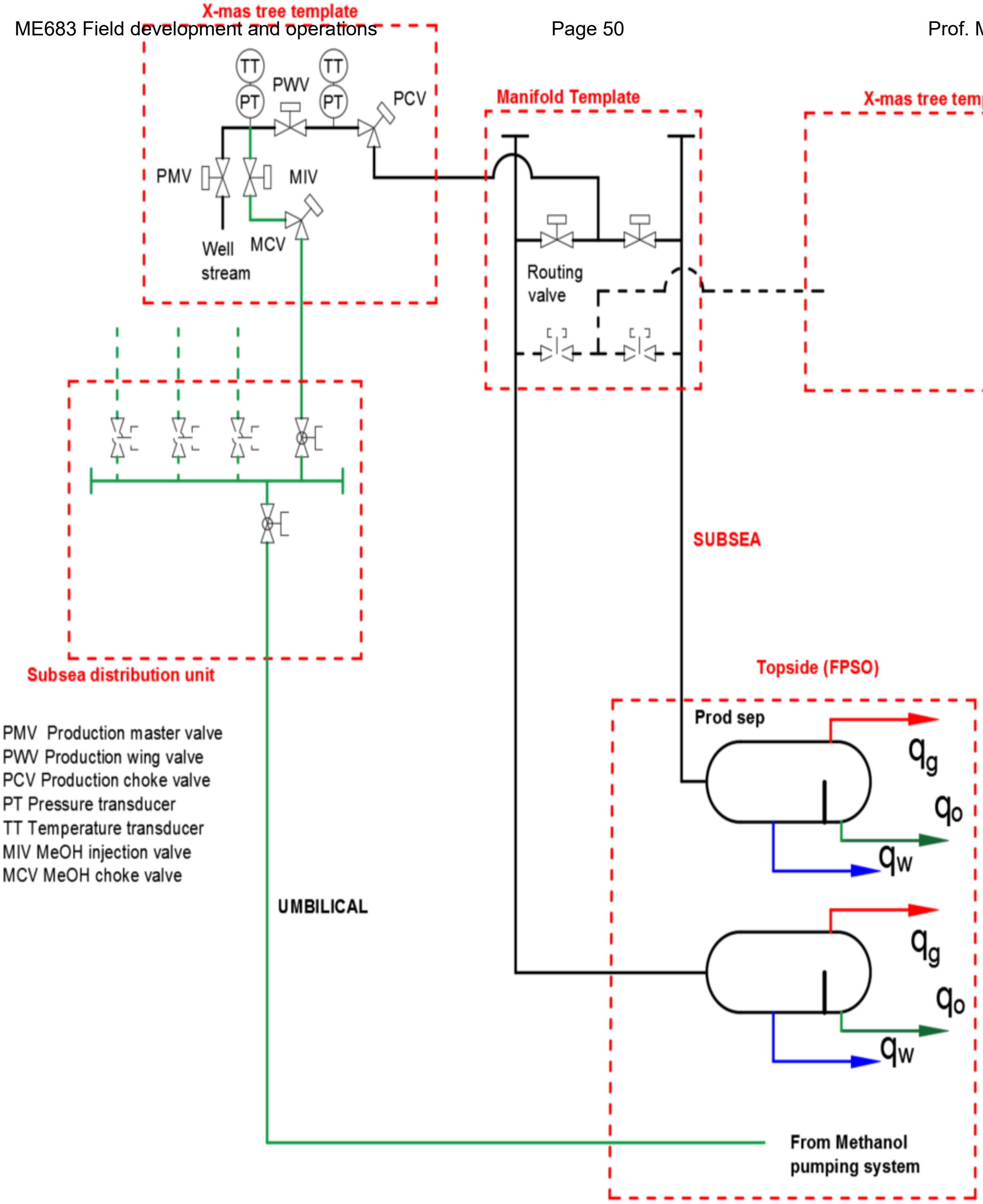
hydraulic line

communication

hydrate inhibitor



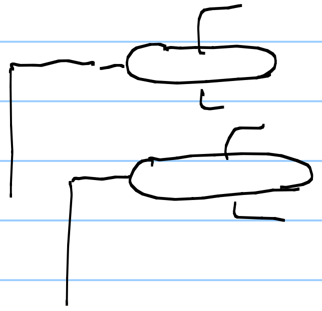



X-mas tree template
TT
PT
PWV
TT
PT
PCV
PMV
MIV
Well stream
MCV
Manifold Template
Routing valve
X-mas tree template
SUBSEA
Subsea distribution unit
Topside (FPSO)
Prod sep
q_g
q_o
q_w
q_g
q_o
q_w
PMV Production master valve
PWV Production wing valve
PCV Production choke valve
PT Pressure transducer
TT Temperature transducer
MIV MeOH injection valve
MCV MeOH choke valve
UMBILICAL
From Methanol pumping system

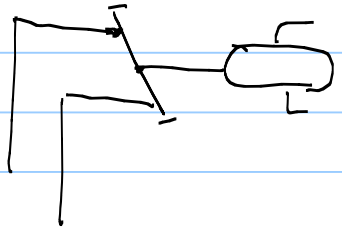
Day 4

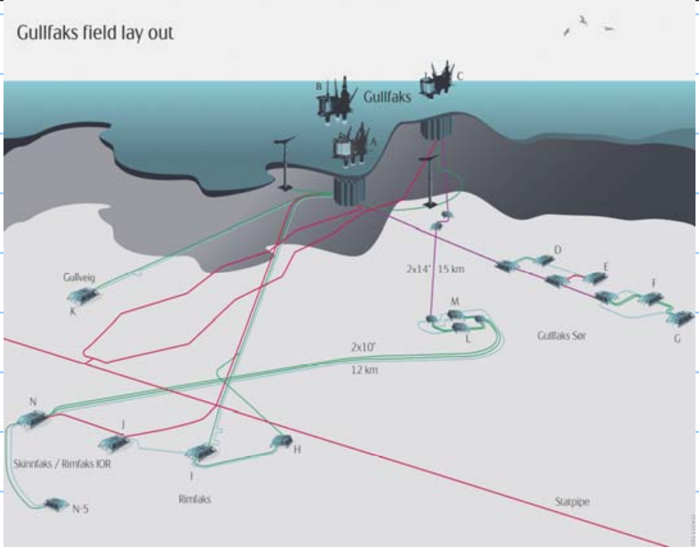
Gathering system / comingling system

Networks → collection/system of pipes, flowlines and pipelines that take production from wells to processing facilities.

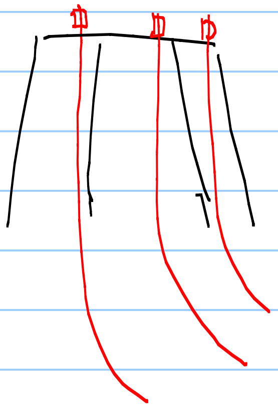


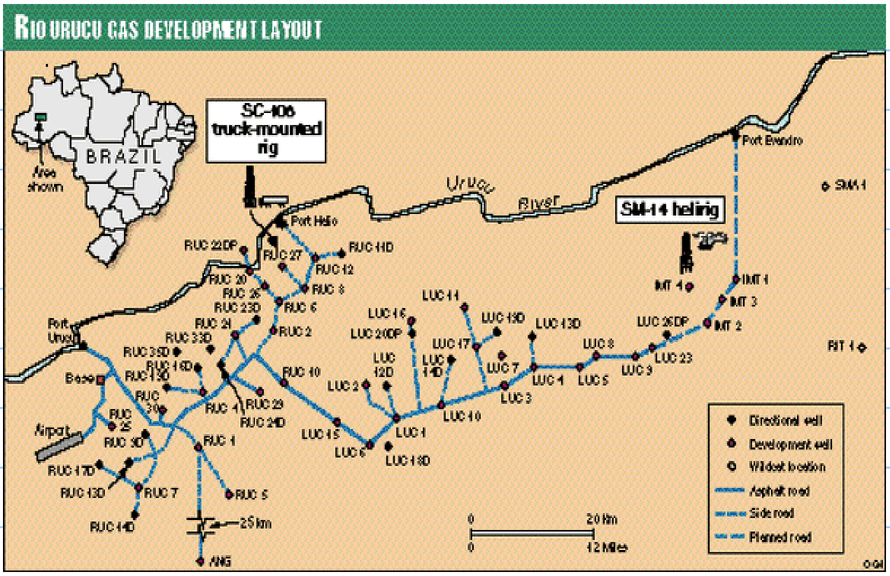
standalone wells

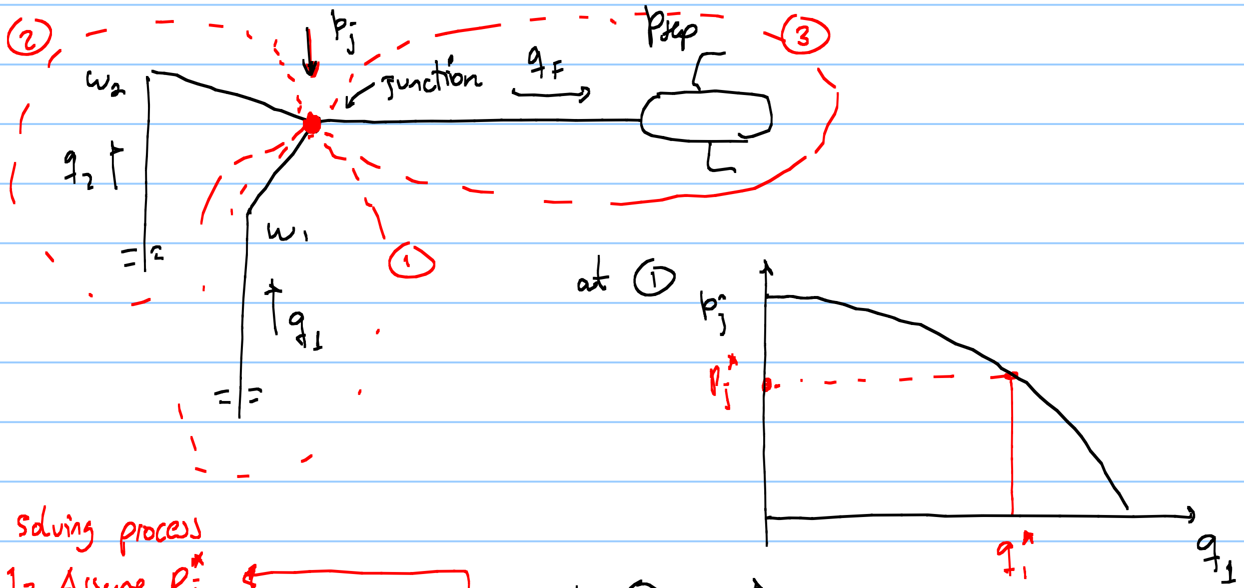




subsea systems







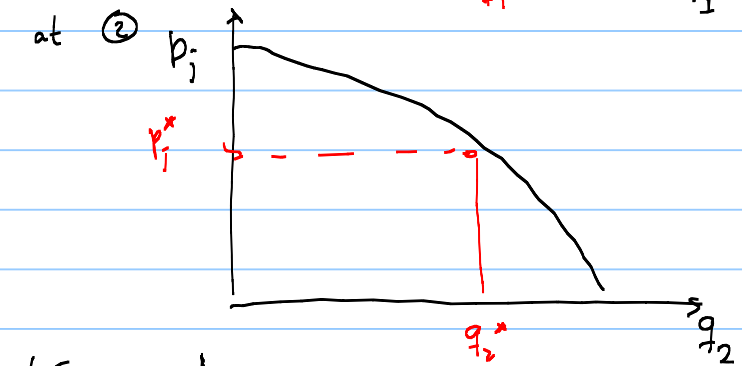
solving process

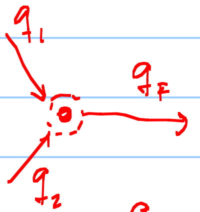
1_ Assume p_j^*

in curve ① read q_1^*

In curve ① read q_2^*

in curve ③ read q_F^*



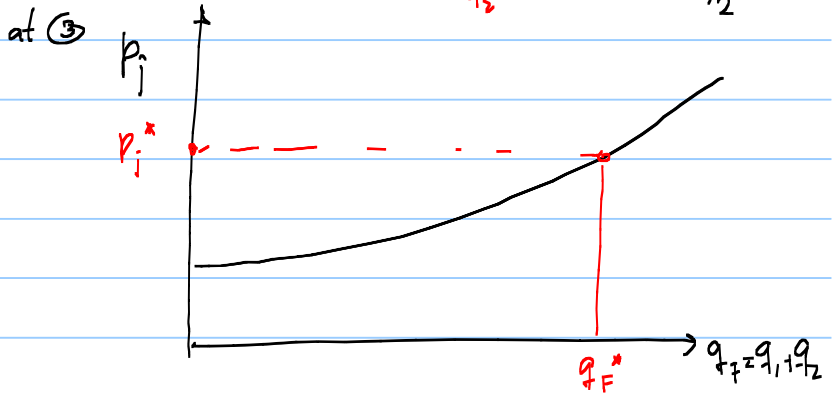


$q_F = q_1 + q_2$

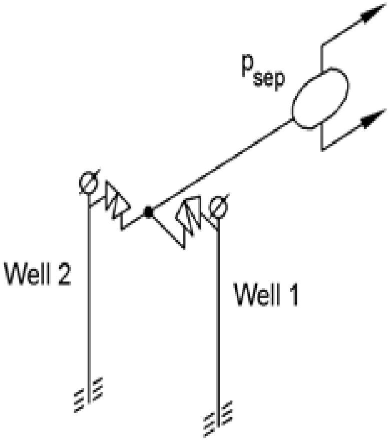
verify $q_F^* = q_1^* + q_2^*$ → not → 1_ Assume p_j^*

↓

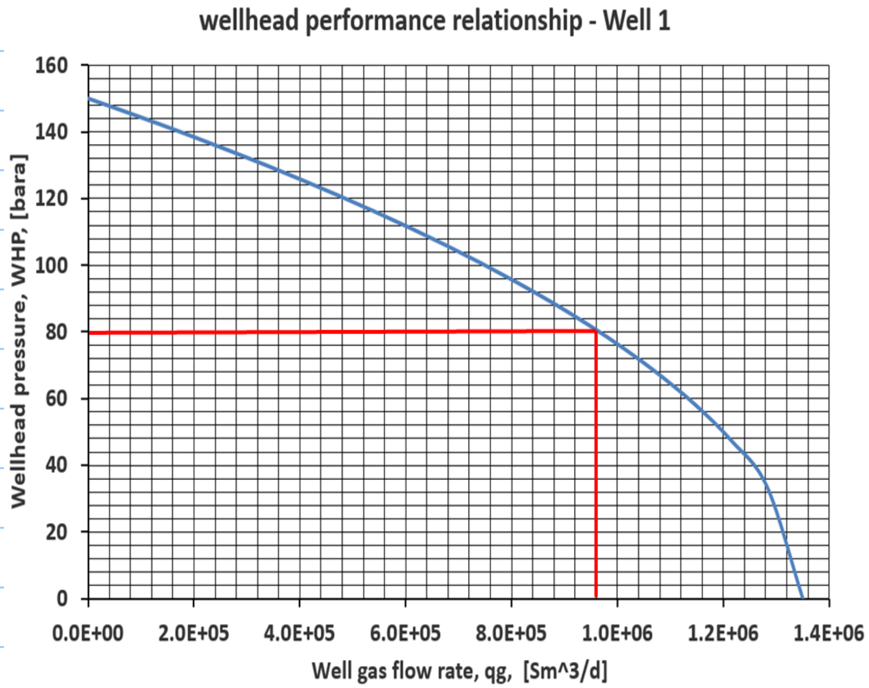
yes → solution



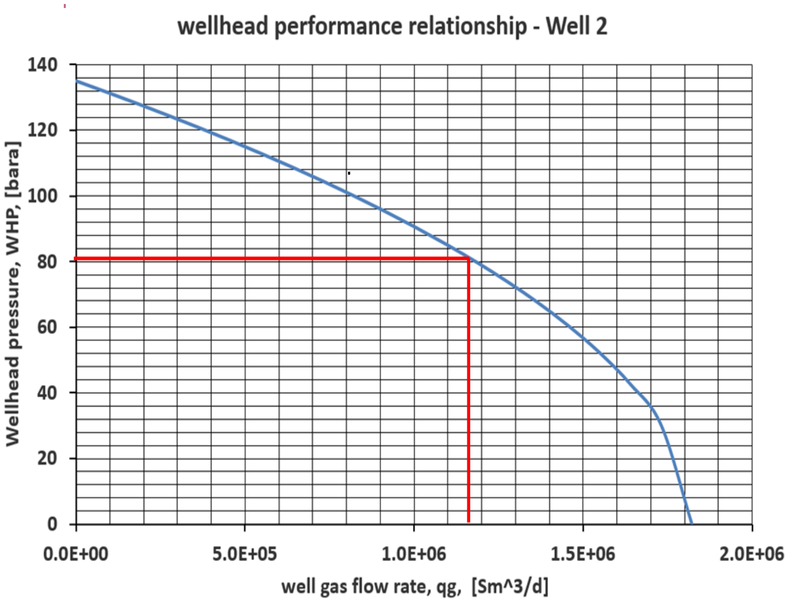
class exercise:



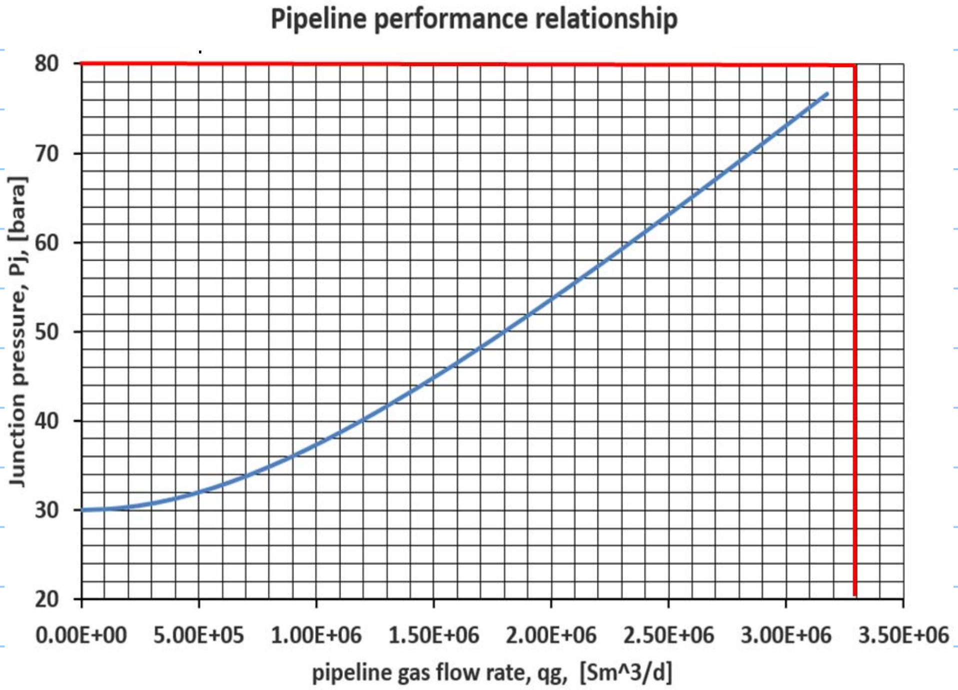
iteration 1



assume $p_1^k = 80$ bara
$q_1^k = 9.6E5$ Sm^3/d



$p_1^k = 80$ bara
$q_2^k = 1.17E6$ Sm^3/d



$p_j^* = 80$ bara

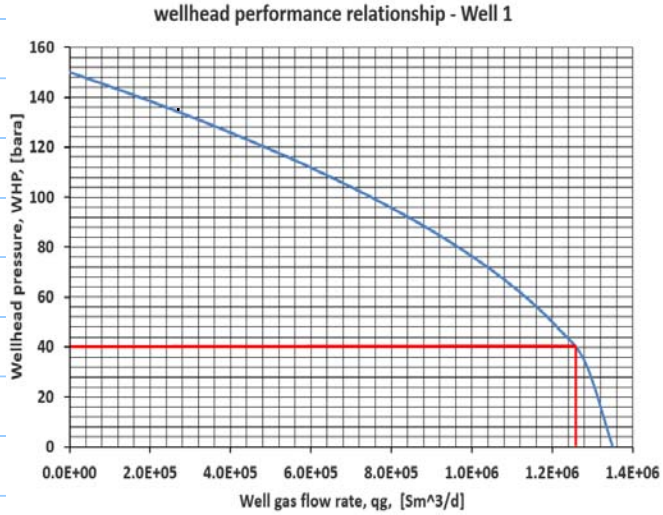
$q_F^* = 3.3E6$ Sm³/d

$$\underbrace{9.6E5 \text{ Sm}^3/d + 1.17E6 \text{ Sm}^3/d} \overset{?}{=} \underbrace{3.3E6 \text{ Sm}^3/d}$$

$\varepsilon = (q_F - q_1 - q_2)$

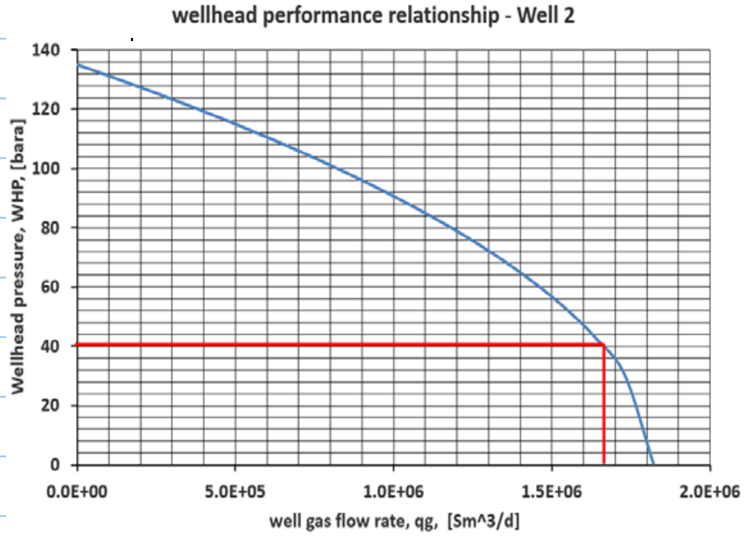
$\varepsilon^{①} = 1.17E6$ Sm³/d (+)

Second iteration $p_j^* = 40$ bara

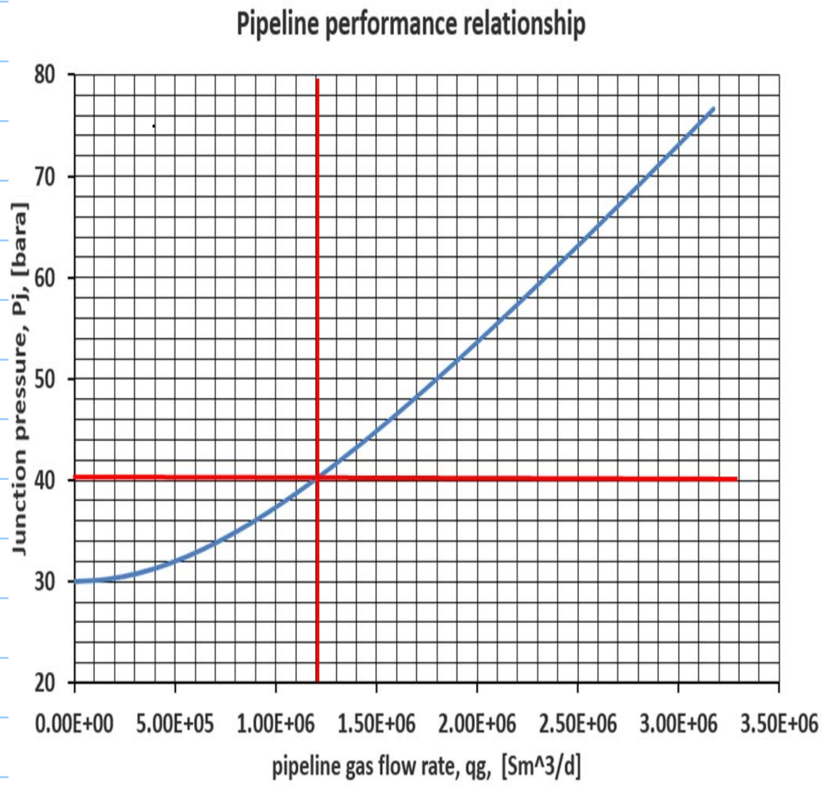


$p_j^* = 40$ bara

$q_{g1}^* = 1.25E6$ Sm³/d



$q_2^* = 1.67 E6 Sm^3/d$

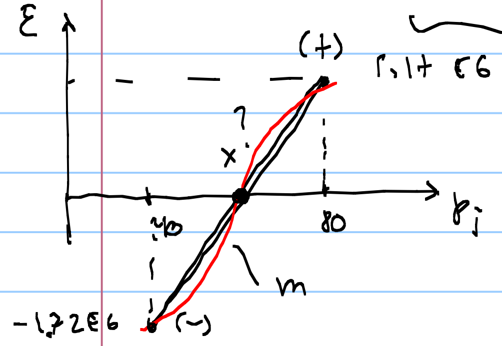


$q_F = 1.2 E6 Sm^3/d$

$$q_1^* + q_2^* \overset{?}{=} q_F^*$$

$$\underbrace{1.25 E6 Sm^3/d + 1.67 E6 Sm^3/d} = \underbrace{1.2 E6 Sm^3/d}$$

$\varepsilon^{L2} = -1.72 E6 Sm^3/d$

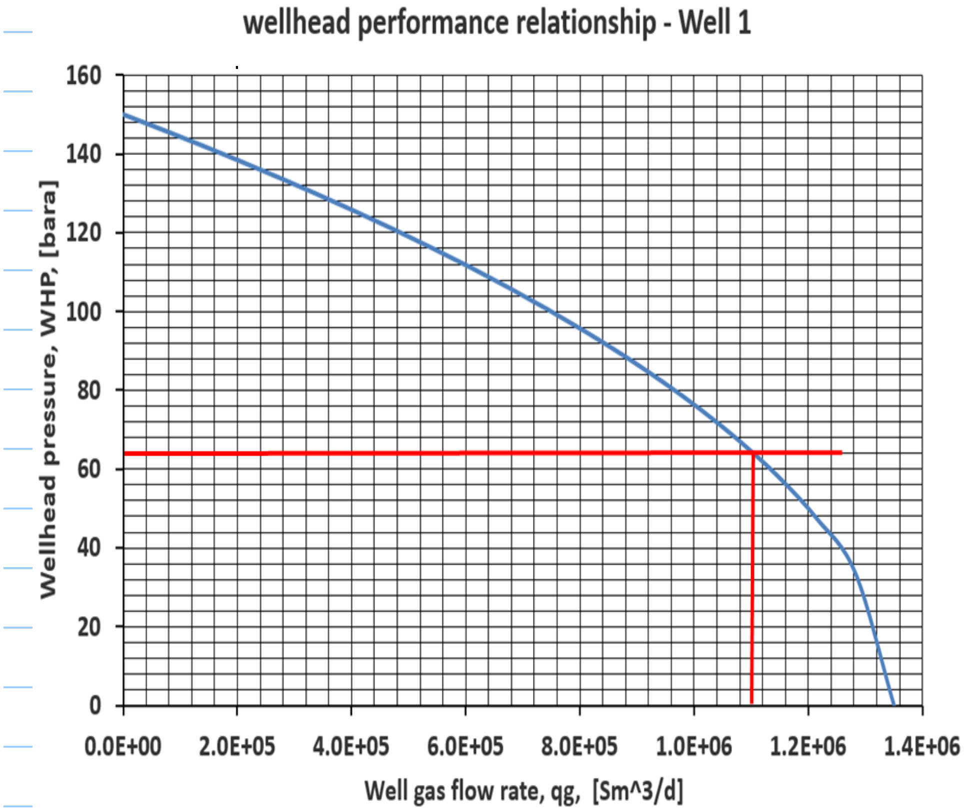


$$m = \frac{y_2 - y_1}{x_2 - x_1} = \frac{1.17E6 - (-1.72E6)}{80 - 40} = 0.07225\ E6$$

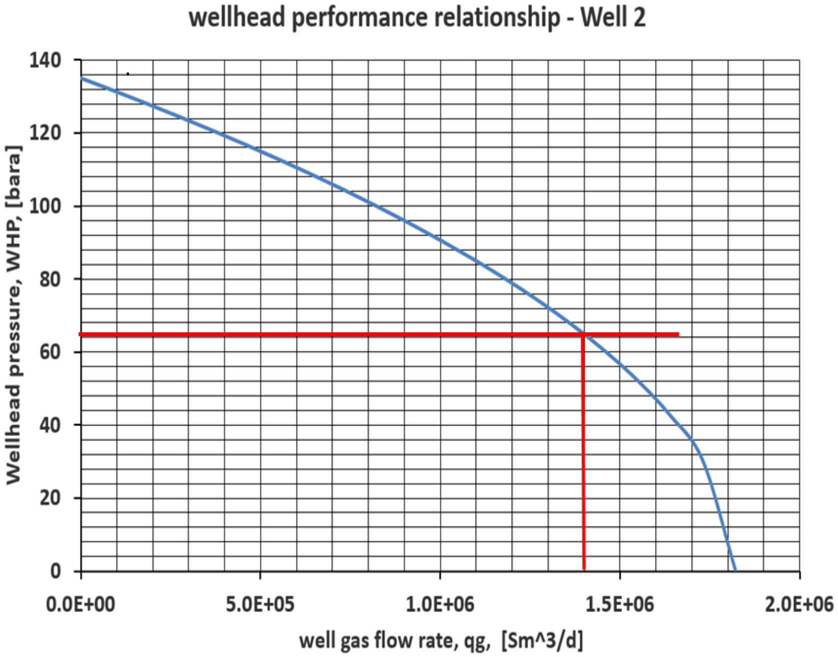
$$m = \frac{y_2 - y}{x_2 - x} = \frac{1.17E6 - 0}{80 - x} = 0.07225\ E6$$

$$x = 80 - \frac{1.17\cancel{E6}}{0.07225\cancel{E6}} = 63.8 \text{ bara}$$

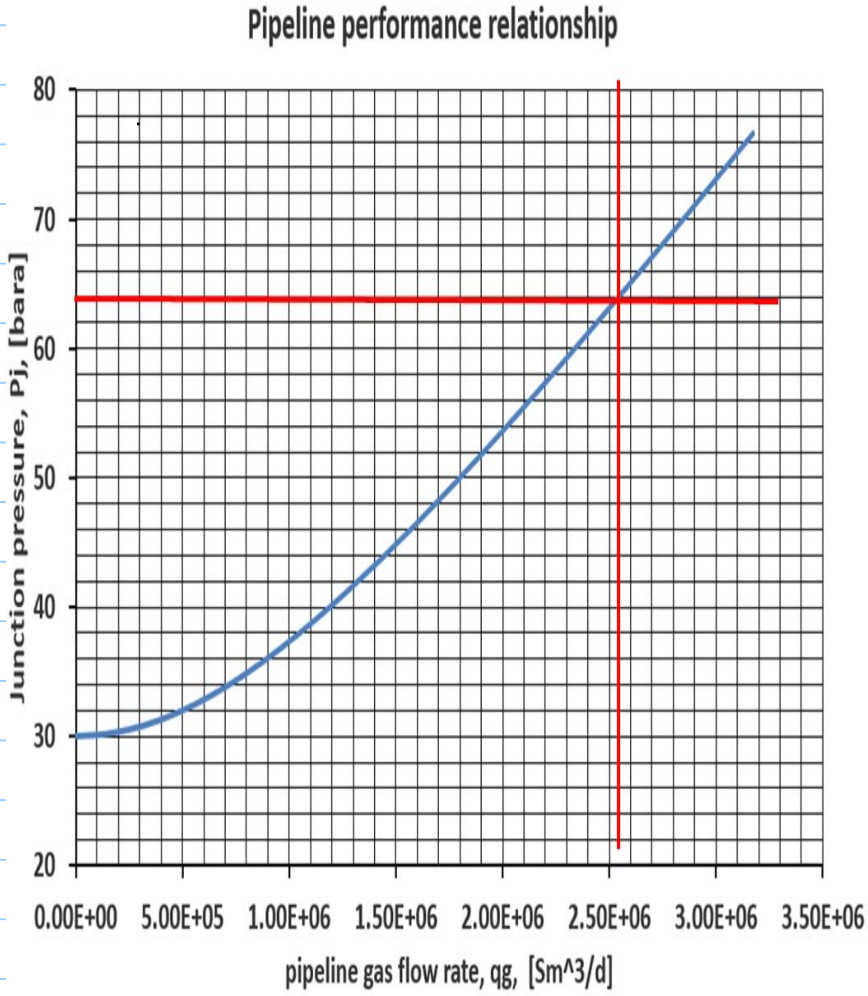
Iteration 3 $P_J^* = 64$ bara



$q_1 = 1.1E6\ Sm^3/d$



$q_2 = 1.4E6$ Sm³/d



$q_F = 2.55 E6$ Sm³/d

$P_J = q_F = 2.55$ Sm³/d

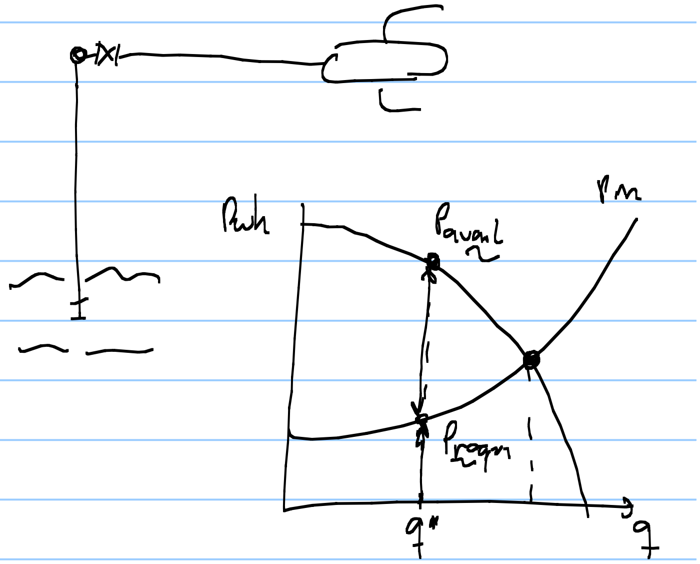
1.1E6 + 1.4E6 = 2.55 E6 ✓

2.5 = 2.55

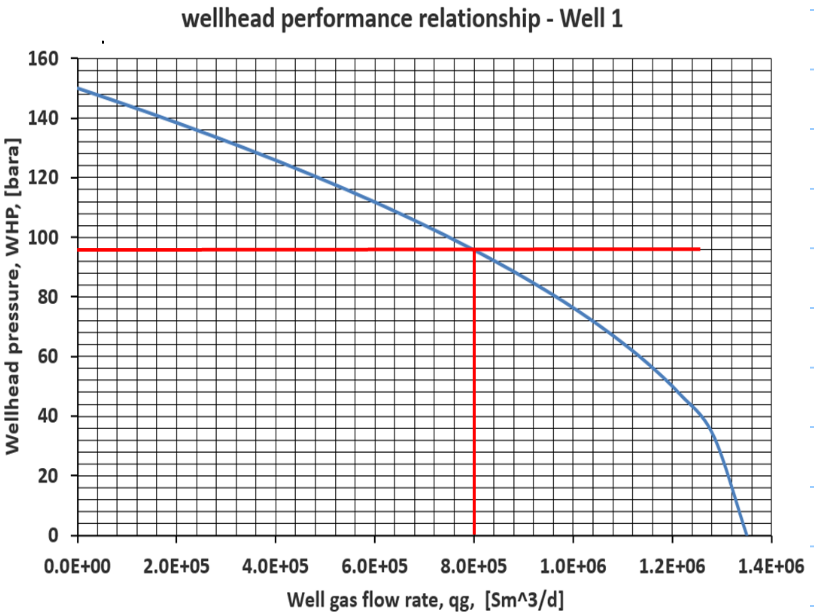
According to reservoir engineer

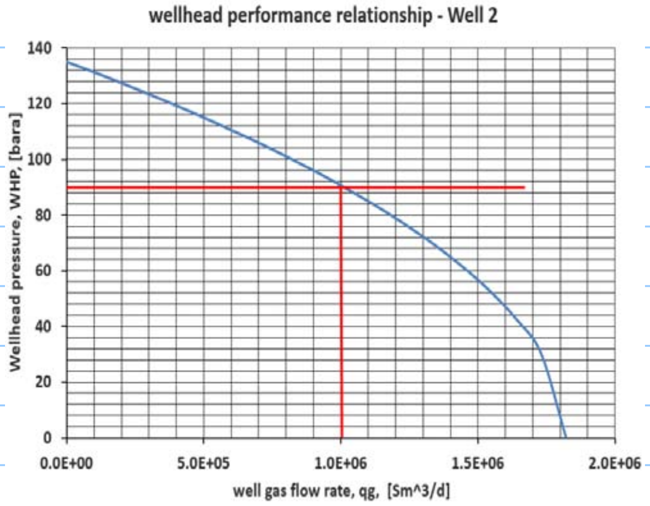
$8E5\ Sm^3/d > q_1$

$1E6\ Sm^3/d > q_2$

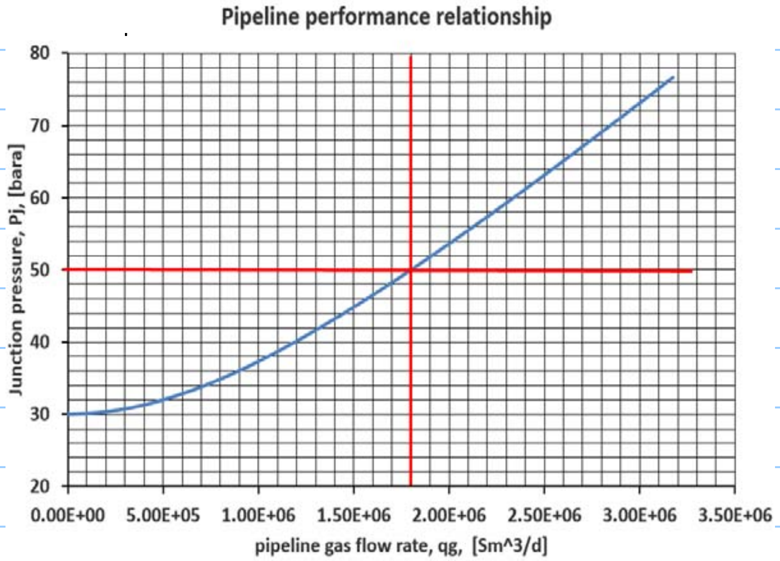


Pwh available (w1) = 96 bara





Pwh available 2 = 90 bara



$P_{in\ flowline} = 50$ bara

$P_{wh_1} = 96$ bara

$P_{wh_2} = 90$ bara

$P_{in} = 50$ bara

$P_{wh_1} > P_{in}$
$P_{wh_2} > P_{in}$ } the rates are feasible

$\Delta p_{choke_1} = 96 - 50 = 46$ bar

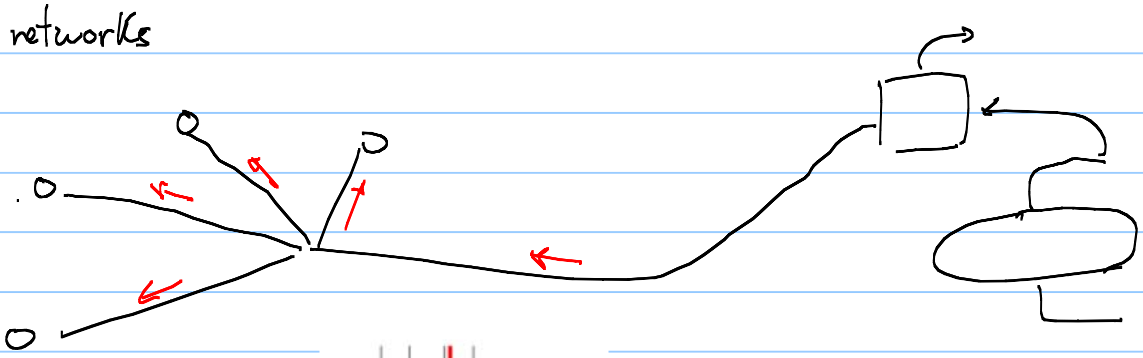
$\Delta p_{choke_2} = 90 - 50 = 40$ bar

		unknowns	equations
w1 =	$\overset{?}{q_{g_1}} = C_{R_1}(P_{R_1}^2 - \overset{?}{P_{wf_1}^2})^{n_1}$	2	1 ✓
	$\overset{?}{q_{g_1}} = C_{T_1}\left(\frac{\overset{?}{P_{wf_1}^2}}{e^{S_1}} - \overset{?}{P_{wh_1}^2}\right)^{0.5}$	1	1
w2	$\overset{?}{q_{g_2}} = \overset{\checkmark}{C_{R_2}}(\overset{\checkmark}{P_{R_2}^2} - \overset{?}{P_{wf_2}^2})^{n_2}$	2	1
	$q_{g_2} = C_{T_2}\left(\frac{P_{wf_2}^2}{e^{S_2}} - \overset{\checkmark}{P_{wh}^2}\right)^{0.5}$	1	1
flowline	$q_F = C_{F_2}(\overset{\checkmark}{P_{in}^2} - P_{sep}^2)^{0.5}$	2	1
mass balance	$q_F = q_1 + q_2$	0	1
	$P_{in} = P_{wh_1}$	0	1
	$P_{in} = P_{wh_2}$	0	1

8 equations and 8 unknowns !

there are other types of network in petroleum production systems

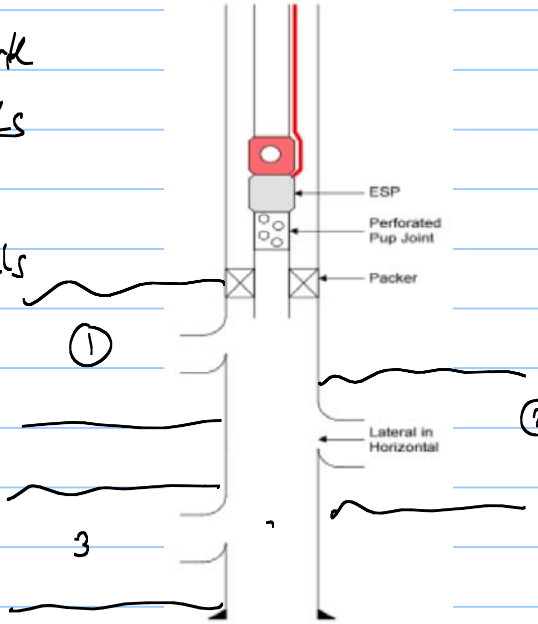
injection networks

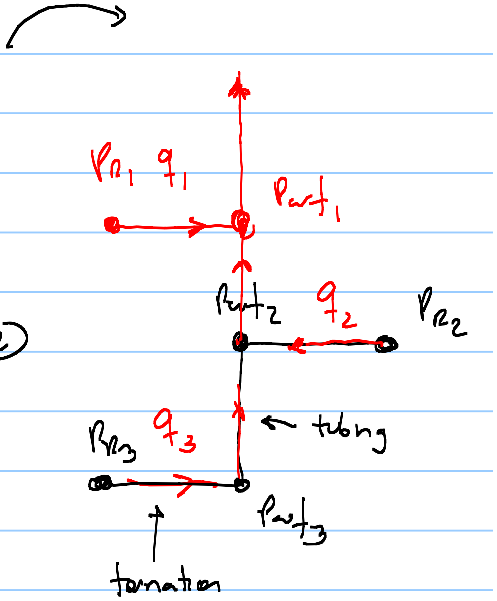


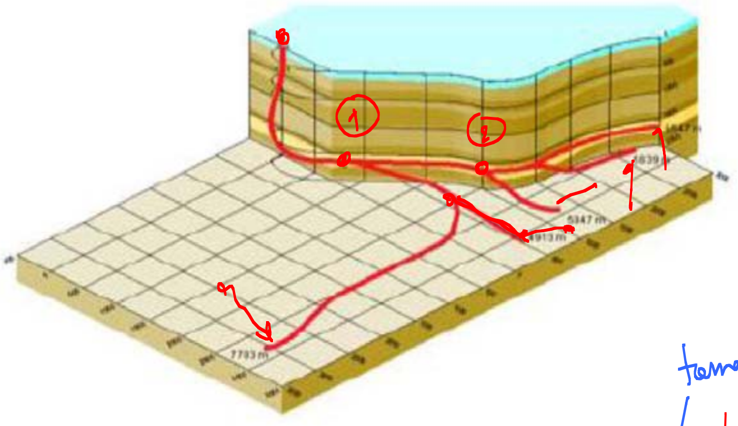
distributing network

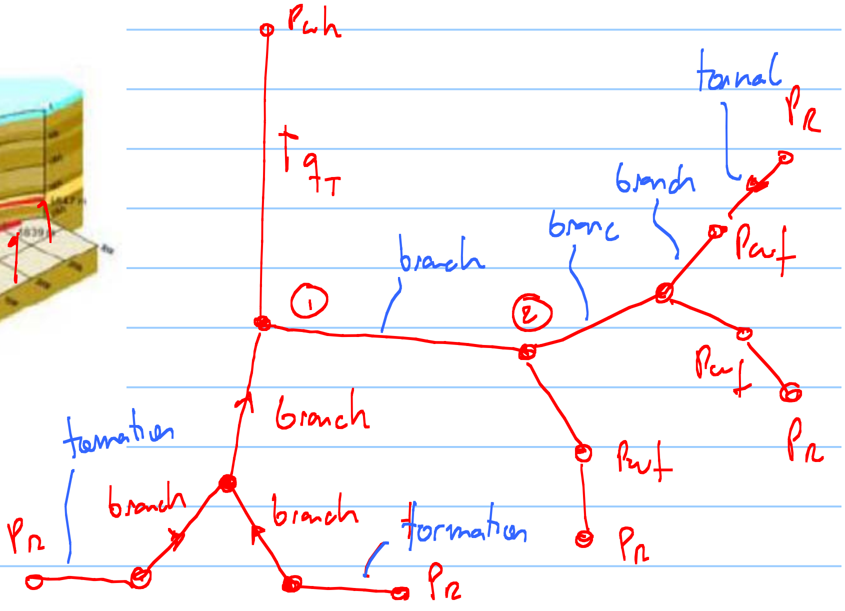
Downhole Networks

multi-zone wells









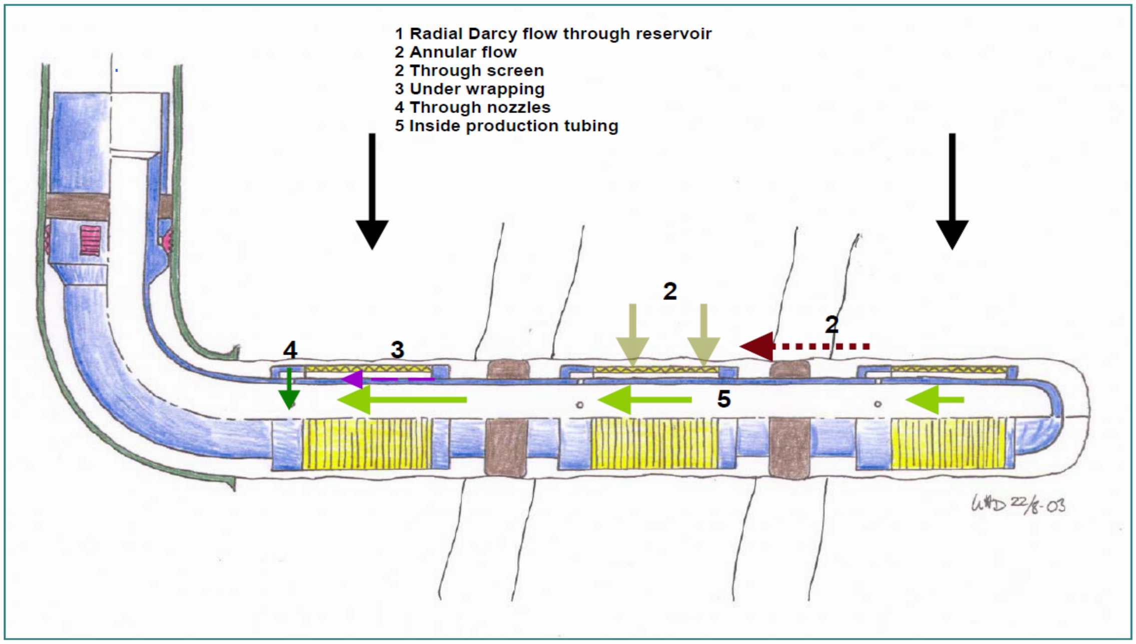
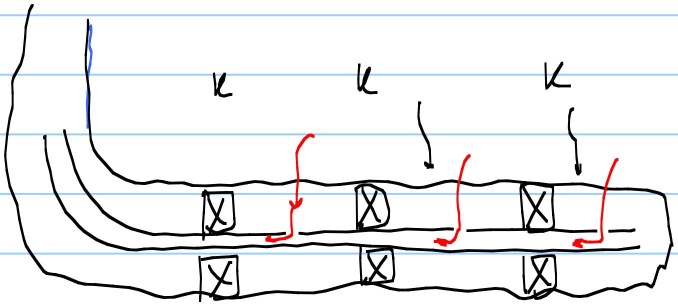
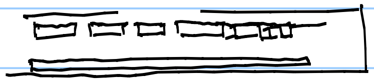
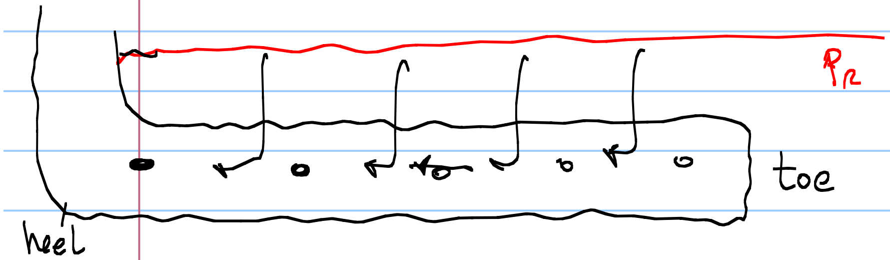
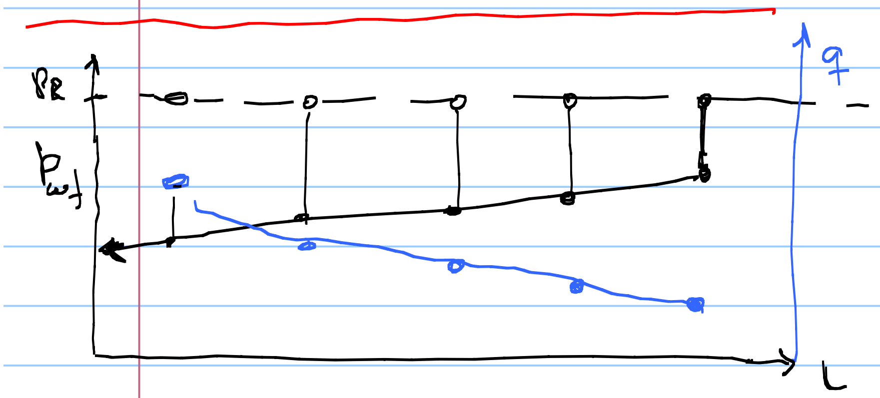


Figure-8 Functioning and interplay of an ICD completion architecture. Fluids enter the screen and flow between the axial wires and the un-perforated base pipe into the ICD housing, before passing through the nozzles and entering into the base pipe. All these flow issues are properly analyzed and put in the right perspective to achieve an optimal well completion design and solution.

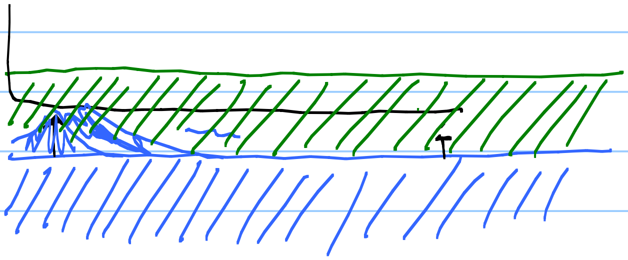


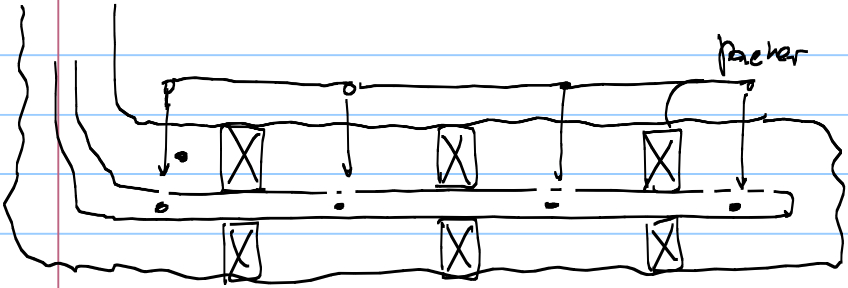


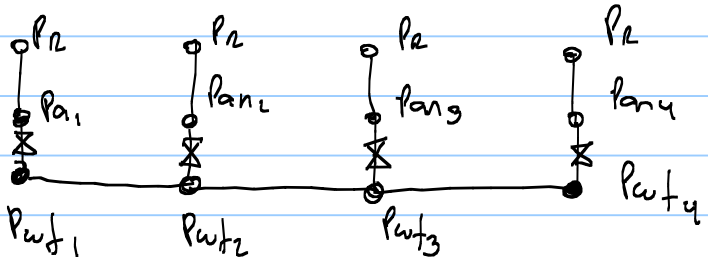


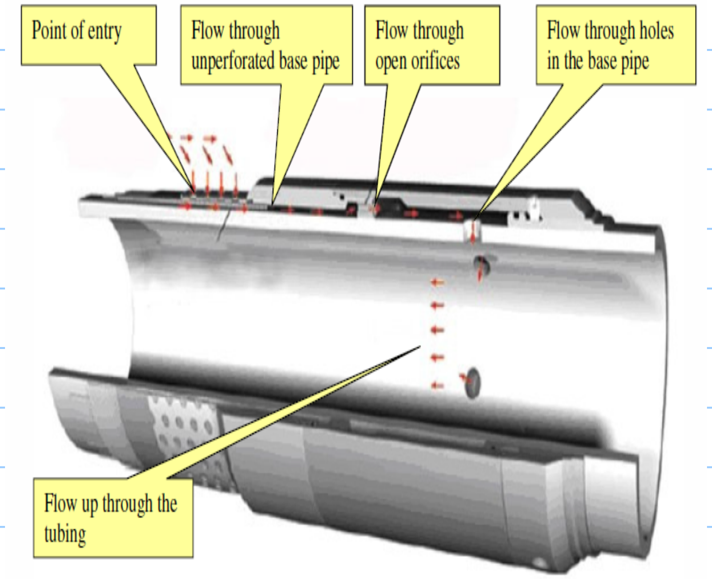


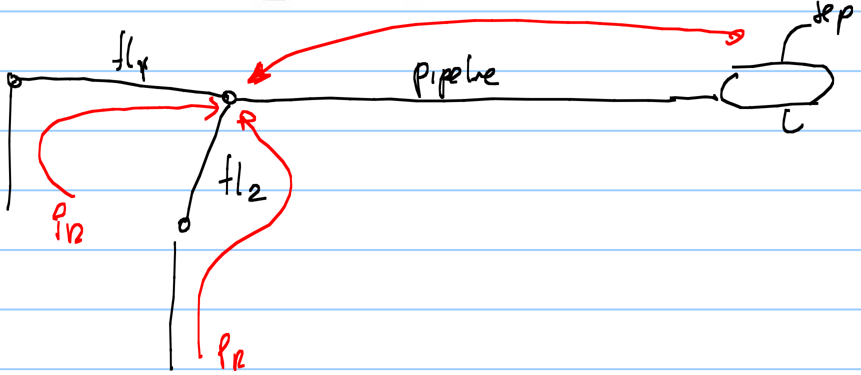
$$\underline{q_o} = J\,\underline{(P_R - P_{wf})}$$




packer


Pr
Pr
Pr
Pr
Pa1
Pan2
Pan3
Pan4
Pwf1
Pwf2
Pwf3
Pwf4


Point of entry
Flow through unperforated base pipe
Flow through open orifices
Flow through holes in the base pipe
Flow up through the tubing

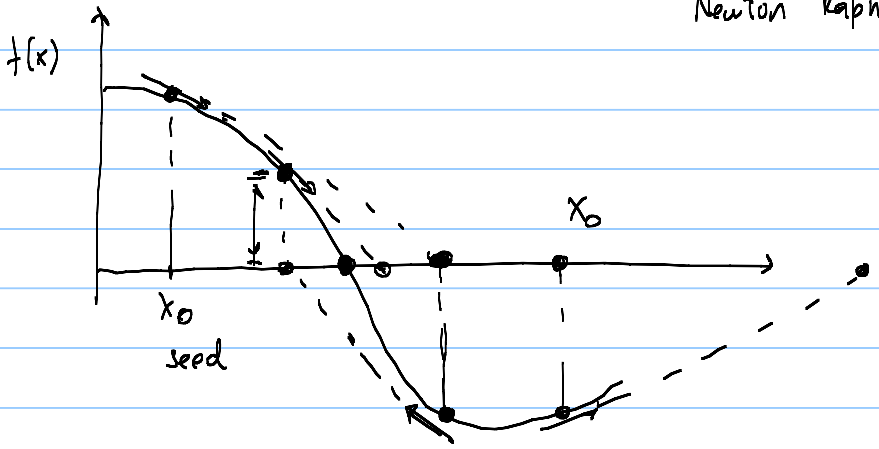

fl1
fl2
pipeline
sep
Pr
Pr

P_j	Error
P_{j1}	$(P_{j1} - P_{av})^2$
P_{j2}	$(P_{j2} - P_{av})^2$
P_{jn}	$(P_{jn} - P_{av})^2$
$P_{av} = \left(\frac{P_{j1} + P_{j2} + P_{jn}}{3} \right)$	Σ

$$\Sigma = (P_{j1} - P_{av})^2 + (P_{j2} - P_{av})^2 + (P_{jn} - P_{av})^2 \longrightarrow 0$$

$$\underset{(-)}{(P_{j1} - P_{av})} + \underset{+}{(P_{j2} - P_{av})} = 0$$

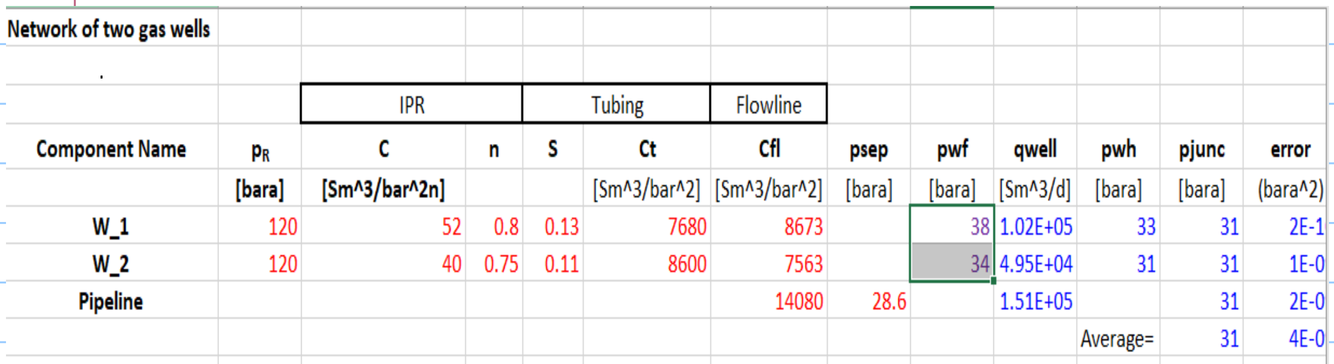
Newton Raphson



$f(x) = 0$ tol = 1E-3

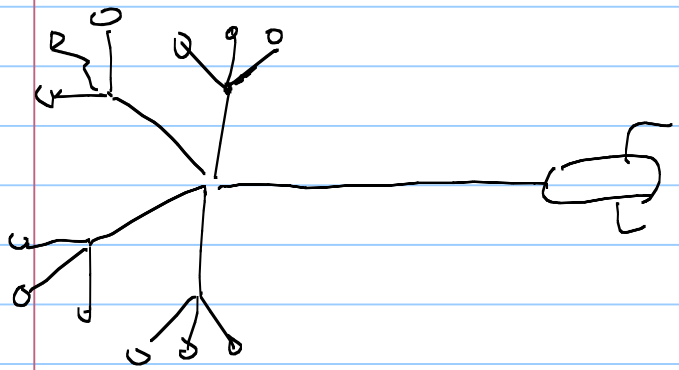
$f(x) < \text{tol}$ 1E-4

1E-10



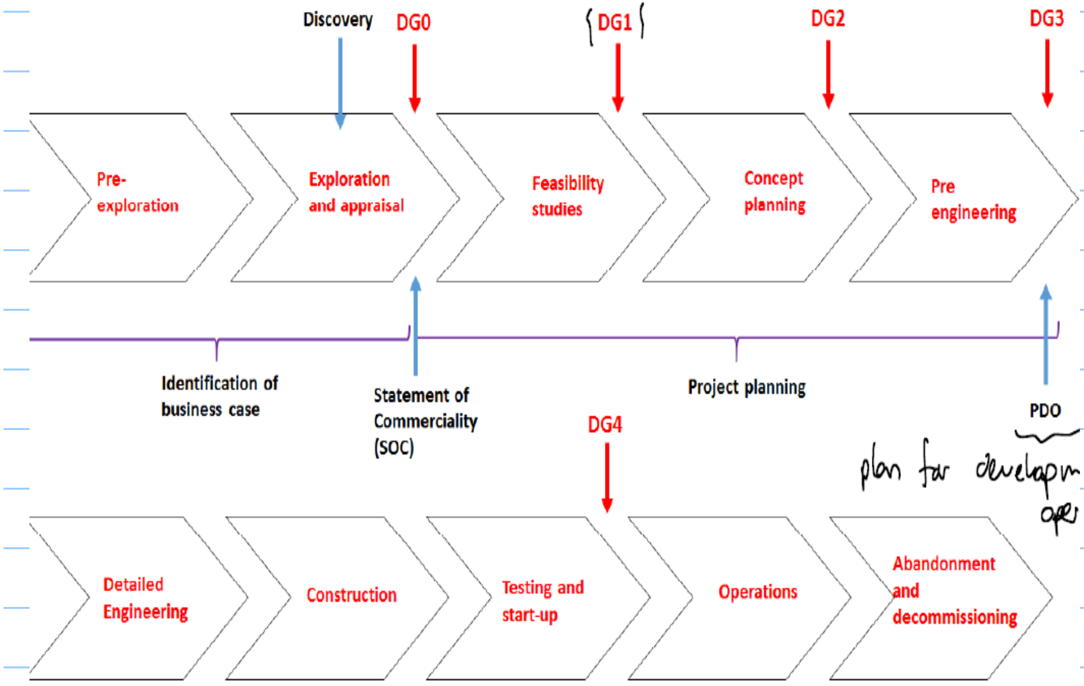
Network of two gas wells												
		IPR		Tubing		Flowline						
Component Name	p_R	C	n	S	Ct	Cfl	psep	pwf	qwell	pwh	pjunc	error
	[bara]	[Sm^3/bar^2n]			[Sm^3/bar^2]	[Sm^3/bar^2]	[bara]	[bara]	[Sm^3/d]	[bara]	[bara]	(bara^2)
W_1	120	52	0.8	0.13	7680	8673		38	1.02E+05	33	31	2E-1
W_2	120	40	0.75	0.11	8600	7563		34	4.95E+04	31	31	1E-0
Pipeline						14080	28.6		1.51E+05		31	2E-0
										Average=	31	4E-0

time	q field	Δpchoke1	Δpchoke2
0			
1			
2			



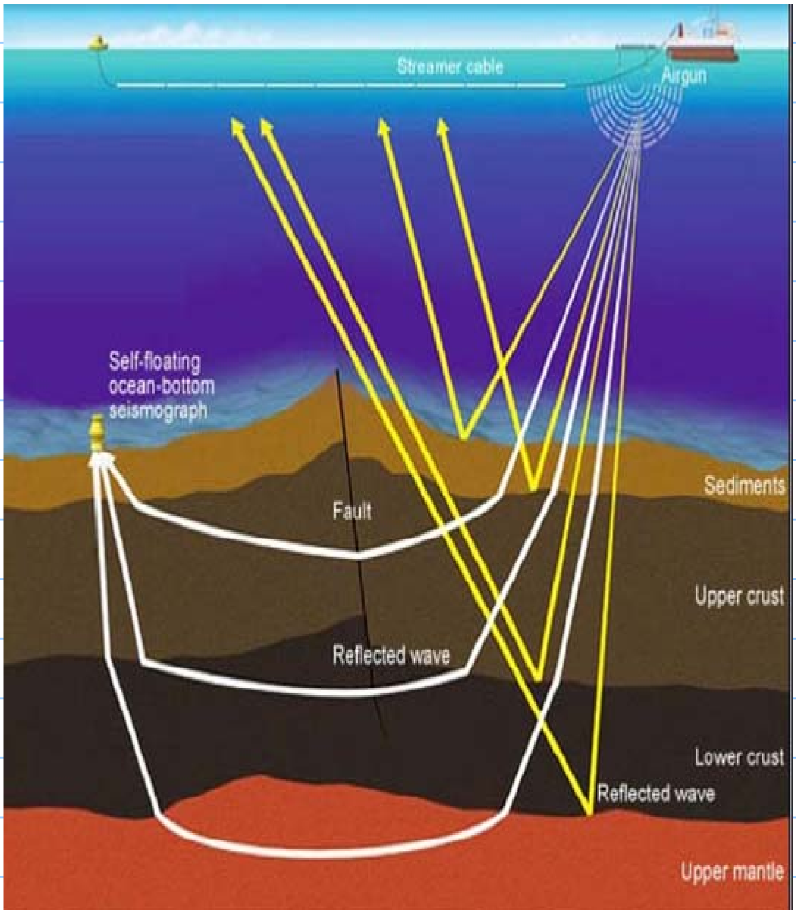
Reserve estimation

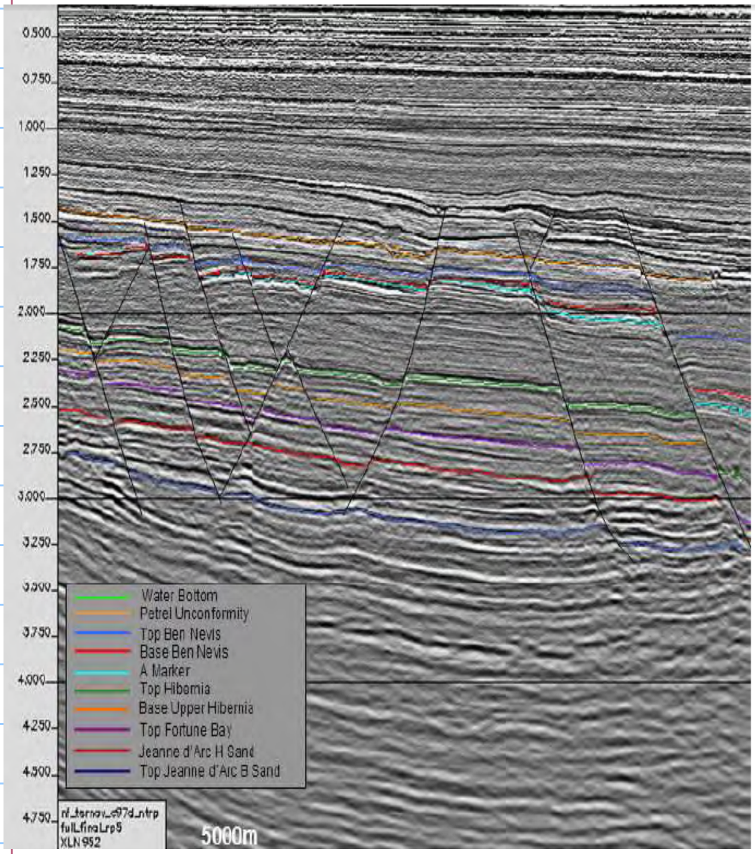
- N, G OOIP, OGIP
- N_{po}, G_{po} TRR Total recoverable reserves



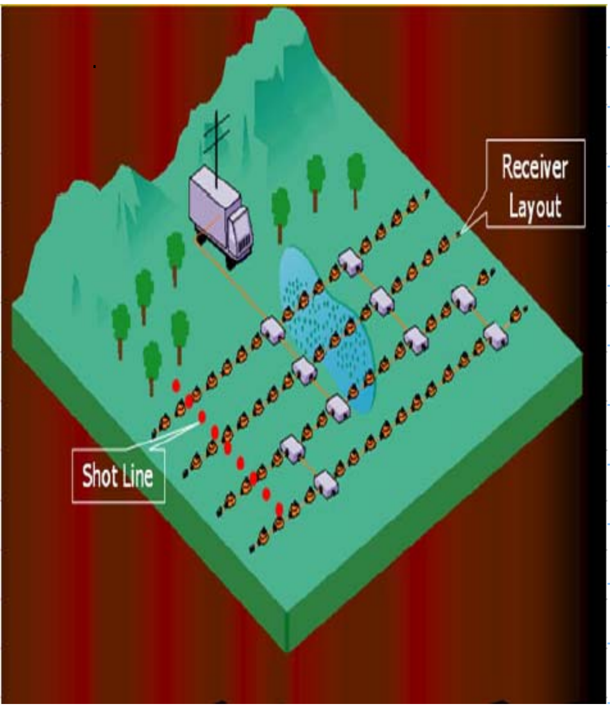
plan for developm ope

exploration seismic (offshore)





Geophysicist

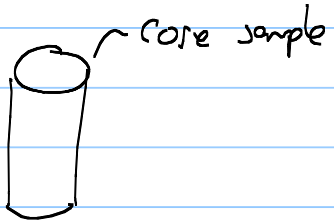


land-based seismic

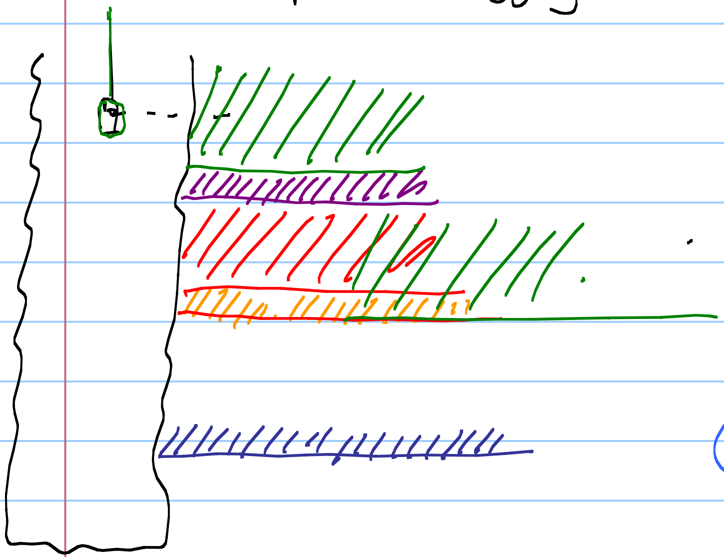
exploration drilling

porosity permeability

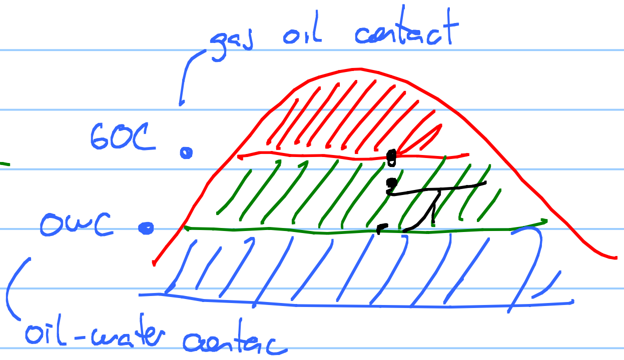
- φ Sw, K

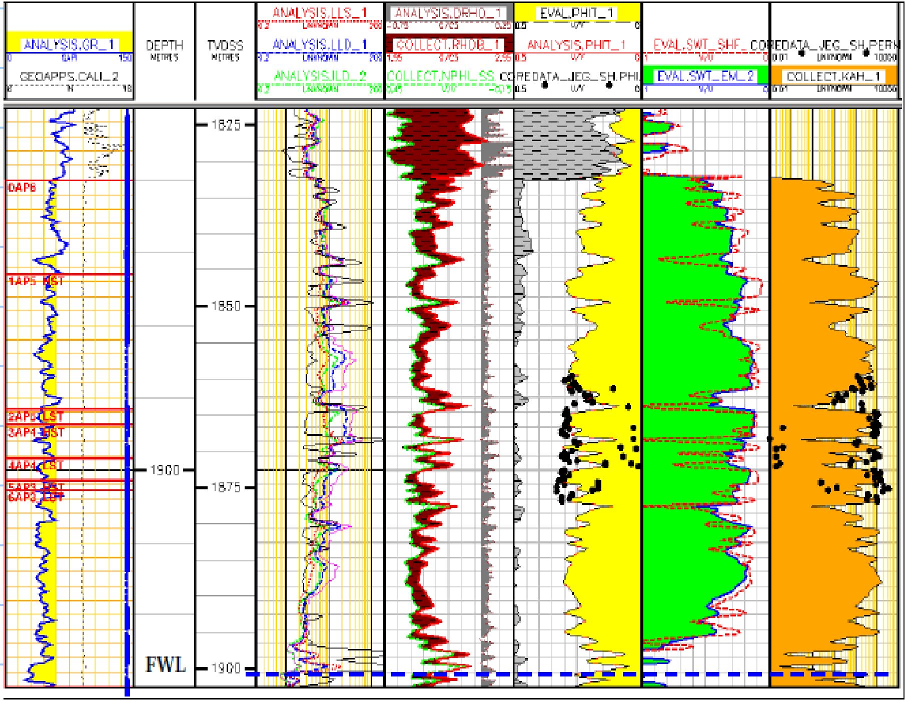


exploration logging



Sw, detecting Hydrocarbon bearing rock



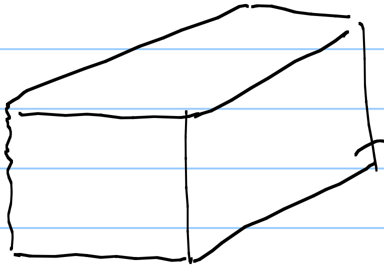


oil reservoir

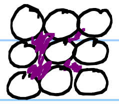
connate water saturation

net to gross

$$TRR = N_{pu} = \frac{\overbrace{\underset{\sim}{V_R} \cdot \phi}^{V_{Fluid}} \cdot \overset{(1-S_w)}{S_o}\,(N_{TG})}{B_o}$$

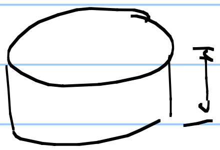


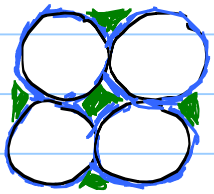
$V_R = a.b.c$



$\pi \phi^2 . 0.25 . h$

porosity $\phi = \frac{V_{cavities}}{V_R}$



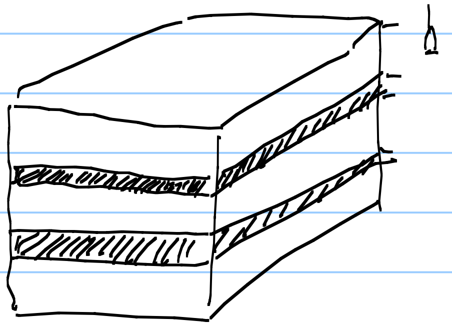


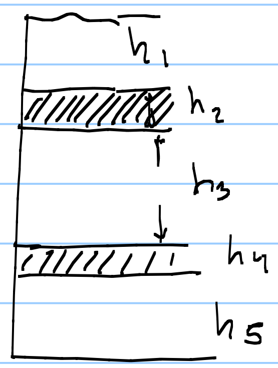
$S_w = \frac{V_{water}}{V_{cavity}}$

S_o

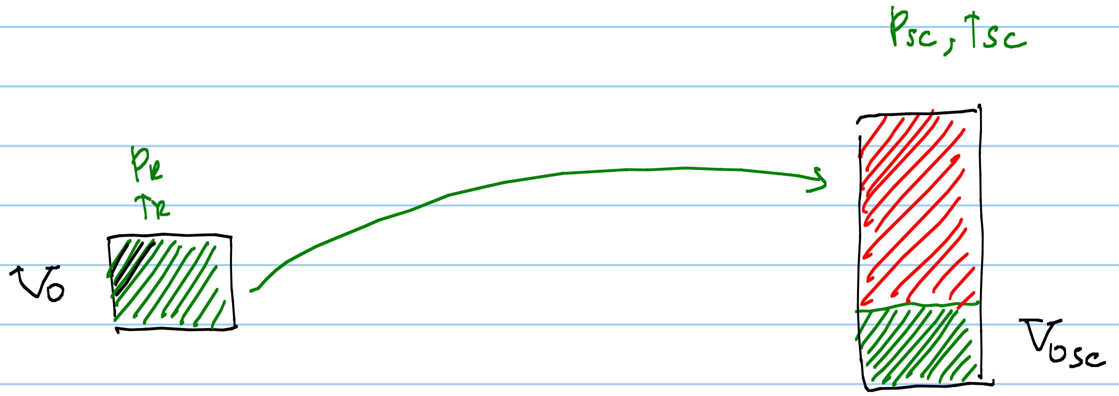
S_g

$S_w + S_o + S_g = 1$





$$(\text{Net to Gross}) = \frac{(h_1 + h_3 + h_5)}{(h_1 + h_2 + h_3 + h_4 + h_5)}$$



$V_{\bar{o}}$

oil formation volume factor $B_o(P,T)$

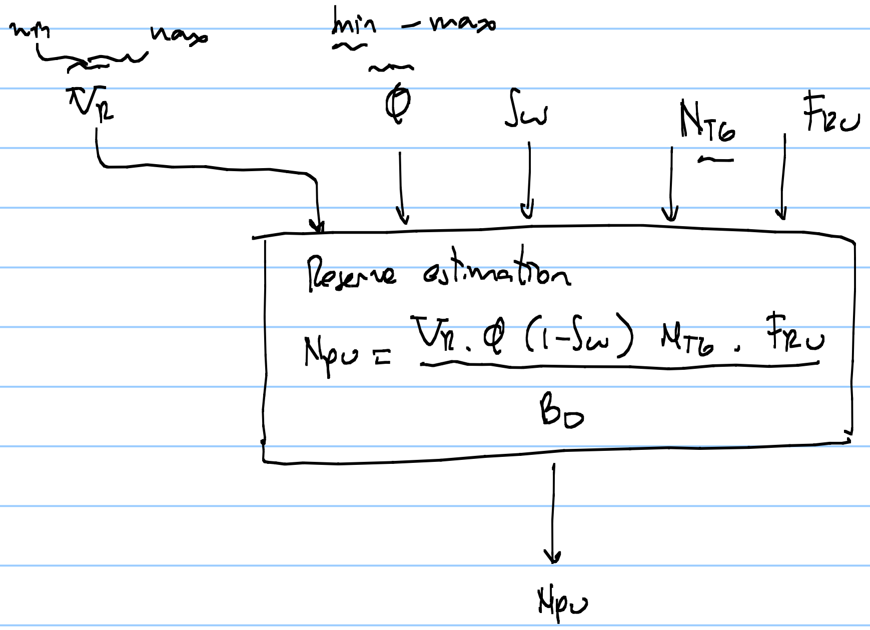
$$B_o = \frac{V_o(P,T)}{V_{\bar{o}}} \simeq 1 \rightsquigarrow 2$$

1.2, 1.3

$$N = \frac{\overbrace{(V_R \cdot \phi \cdot (1-S_w) \cdot N_{TG})}^{V_o(P_R,T_R)}}{B_o}$$

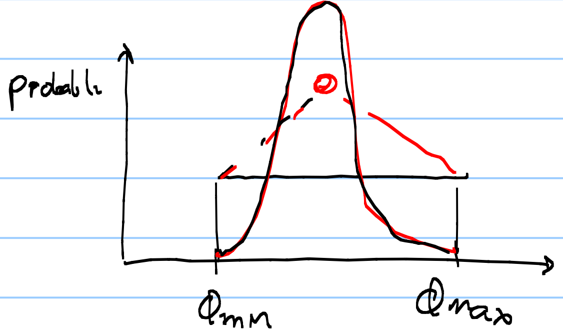
recovery factor $F_R = \frac{N_{pu}}{N}$

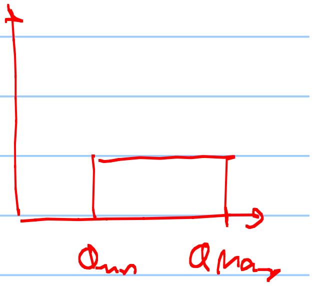
$$N_{pu} = TRR = \underbrace{\frac{V_R \cdot \phi (1-S_w) N_{TG}}{B_o} \cdot F_R}$$



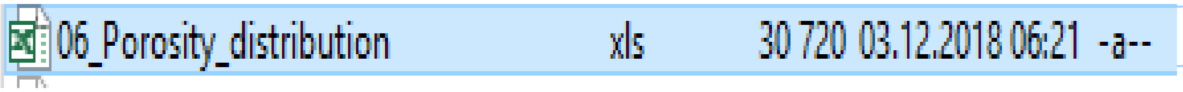
this calculation is NOT determinisc (one input → one output)

probability distribution function pdf

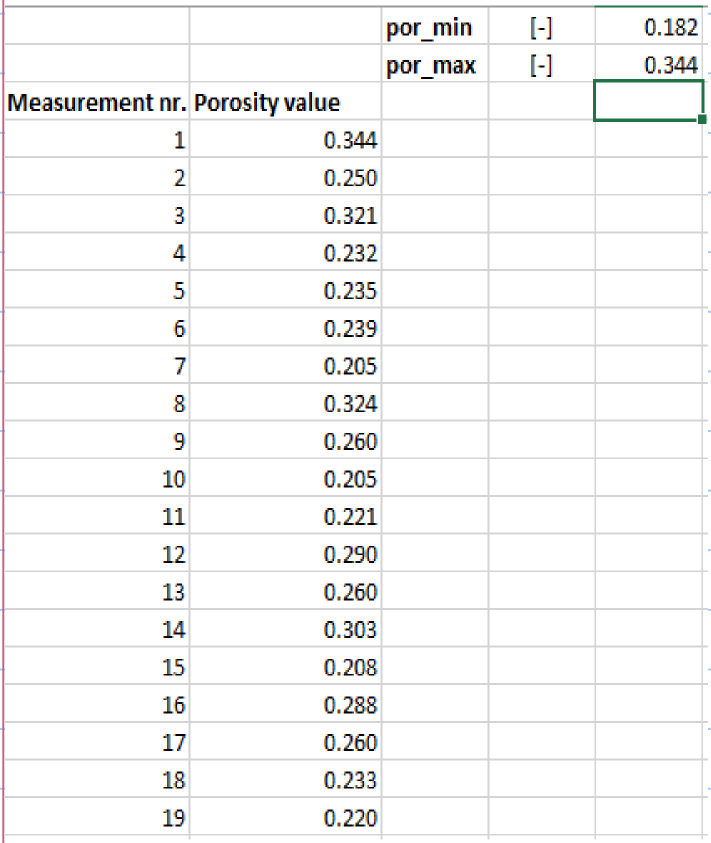




Class exercise to find pdf of porosity based on coring measurement
100



06_Porosity_distribution xls 30 720 03.12.2018 06:21 -a--



		por_min	[-]	0.182
		por_max	[-]	0.344
Measurement nr.	**Porosity value**			
1	0.344			
2	0.250			
3	0.321			
4	0.232			
5	0.235			
6	0.239			
7	0.205			
8	0.324			
9	0.260			
10	0.205			
11	0.221			
12	0.290			
13	0.260			
14	0.303			
15	0.208			
16	0.288			
17	0.260			
18	0.233			
19	0.220			

ϕ $\quad$ ϕ

min $\quad$ ϕ_{min}

$- \phi_1$ $\quad$ $\frac{(\phi_{max}-\phi_{min})}{Npoints-1} +$

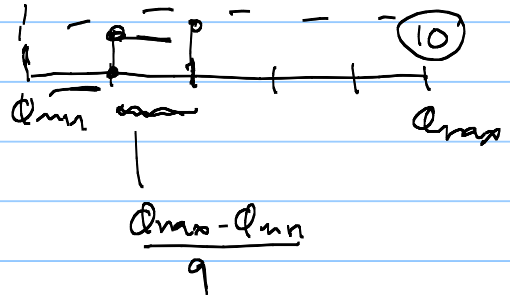
$- \phi_2$

$- \phi_3$

$- \phi_4$

$- \phi_5$

max



11 7 9

3 8

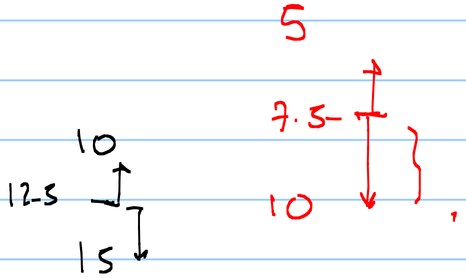
12

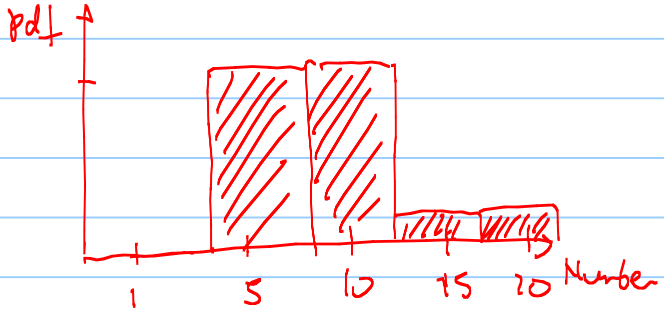
5 4

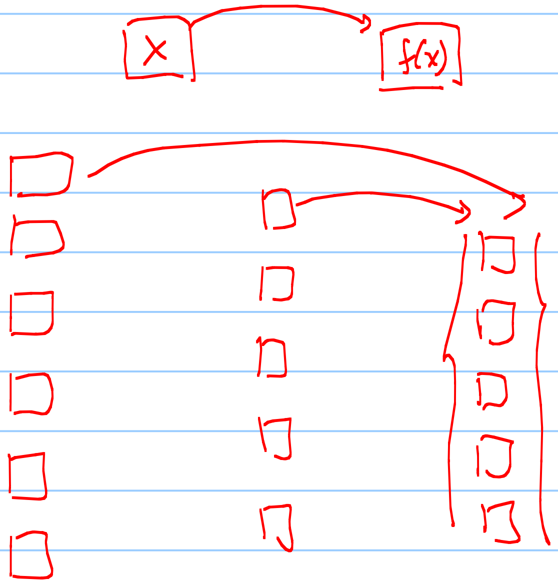
15 20

bin

1	0
5	4
10	4
15	1
20	1

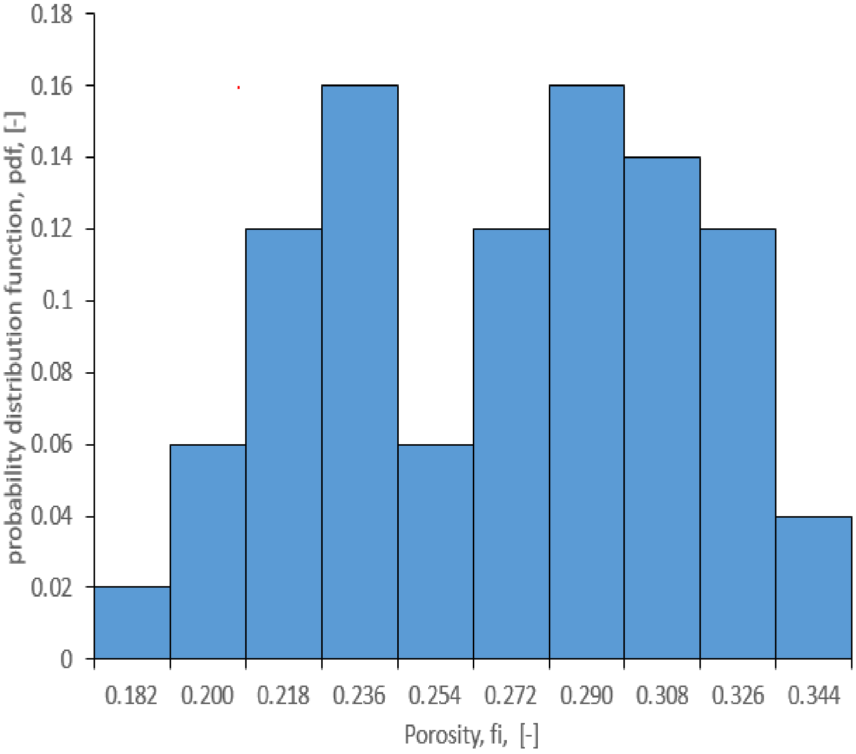




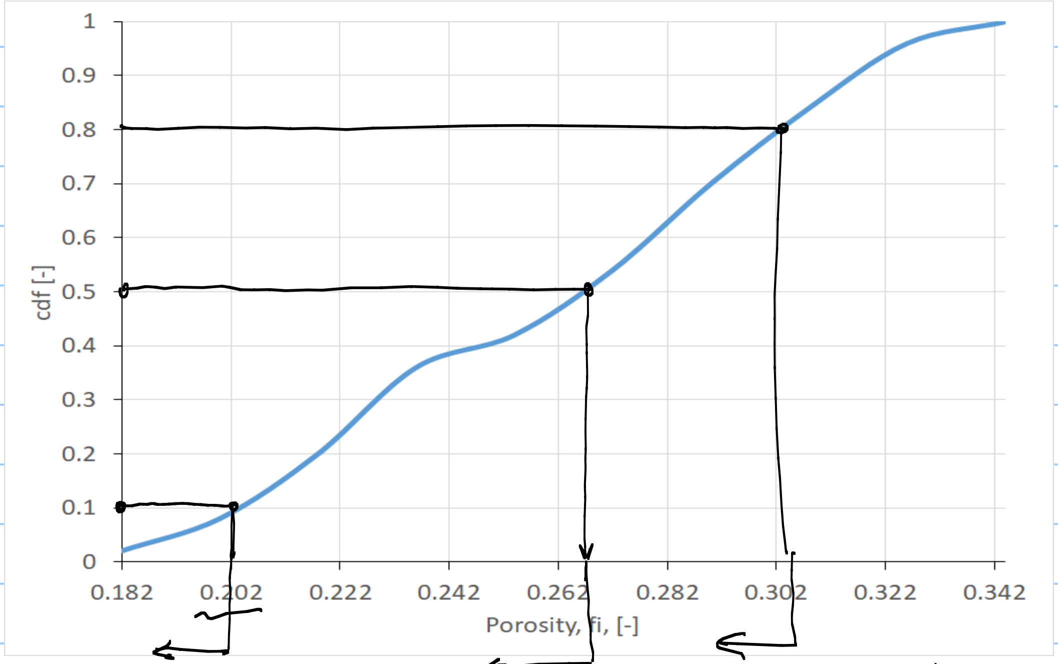


ctrl + shift + enter

$\vec{x} \to \vec{F}(\vec{x})$



cdf cumulative distribution function

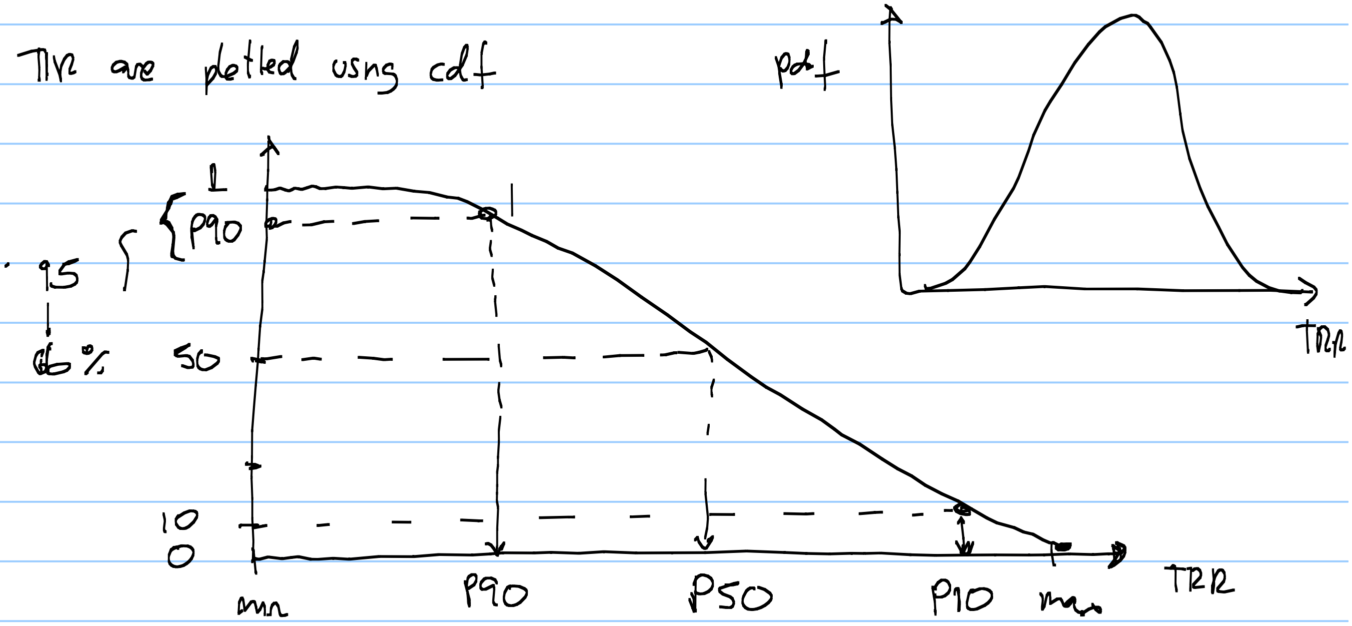


10% of samples have a porosity of 0.202 or lower

50% of sample have a porosity of 0.27 or lower

80% of the samples have a porosity of 0.302 or lower

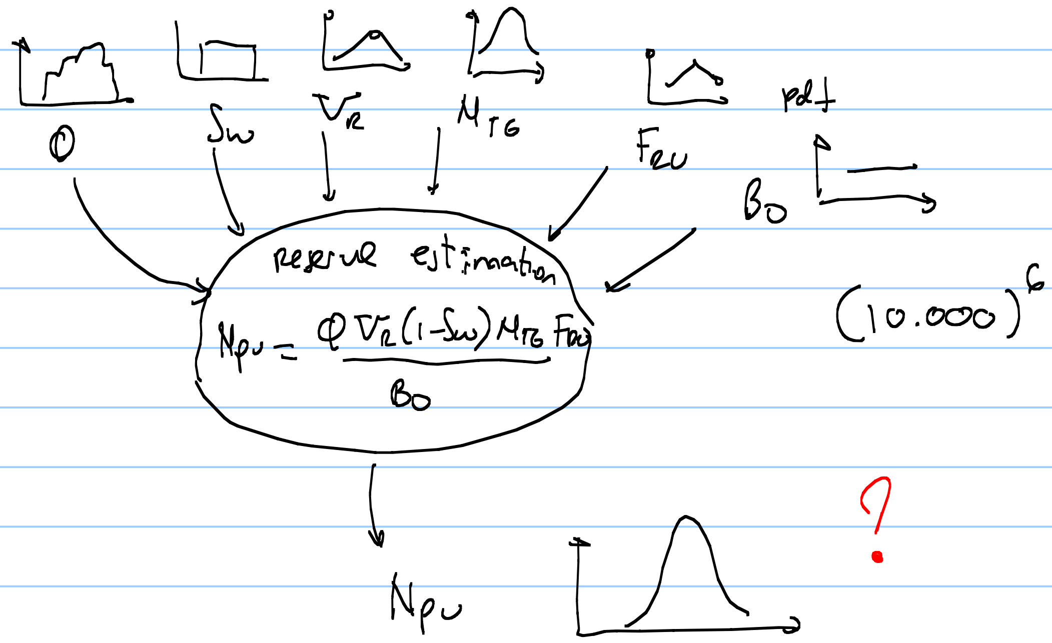
TRR are plotted using cdf



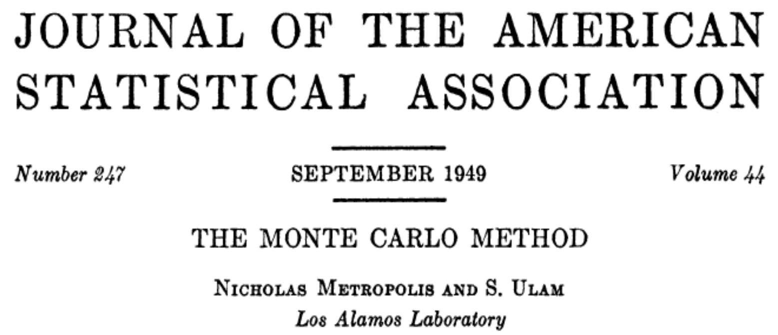
there is a 90% probability that reserves are equal of higher than P90

there is a 50% probability that reserves will be equal or higher than P50

there is a 10% probability that reserver will be equal or higher than P10



Los Alamos Laboratory



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Number 247 SEPTEMBER 1949 *Volume 44*

THE MONTE CARLO METHOD

NICHOLAS METROPOLIS AND S. ULAM
Los Alamos Laboratory

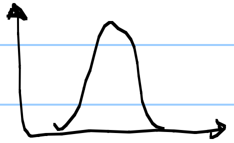
1) assume a random number for each parameter (be inside distribution)

2) Compute Npu

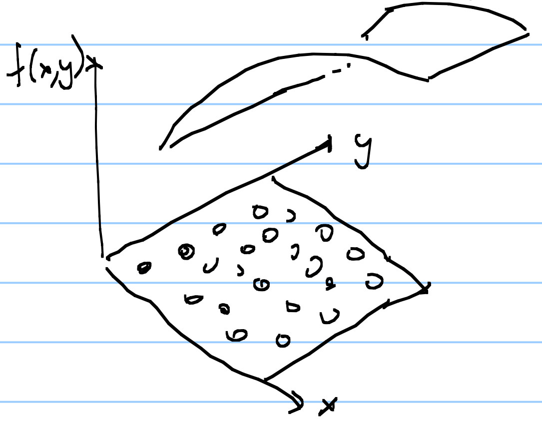
3) Repeat for many, many, many times

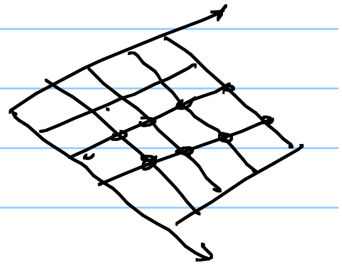
MC iteration	Npu
1	N_{pu_1}
2	N_{pu_2}
3	N_{pu_3}
4	

④ ~ apply a frequency analysis on the output values !

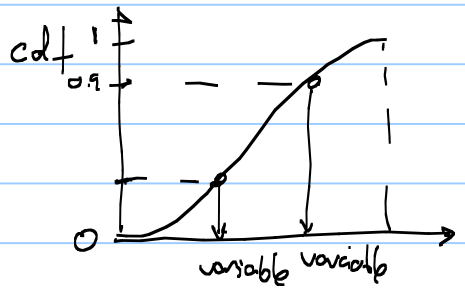


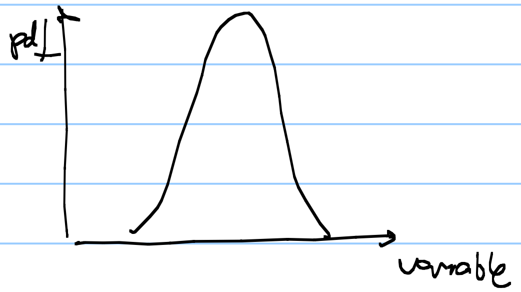
Monte carlo is a sampling method
to find a representative sample of
the whole population



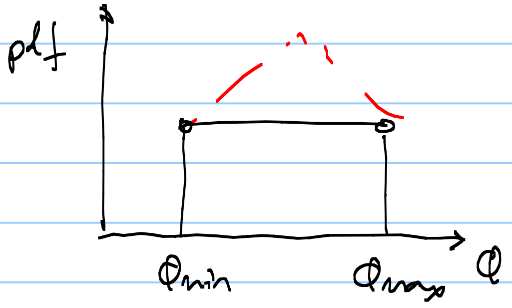


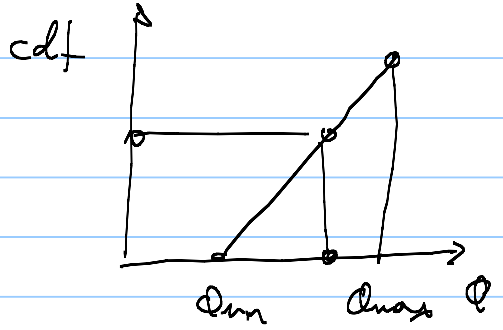
How to generate the random values of input ?



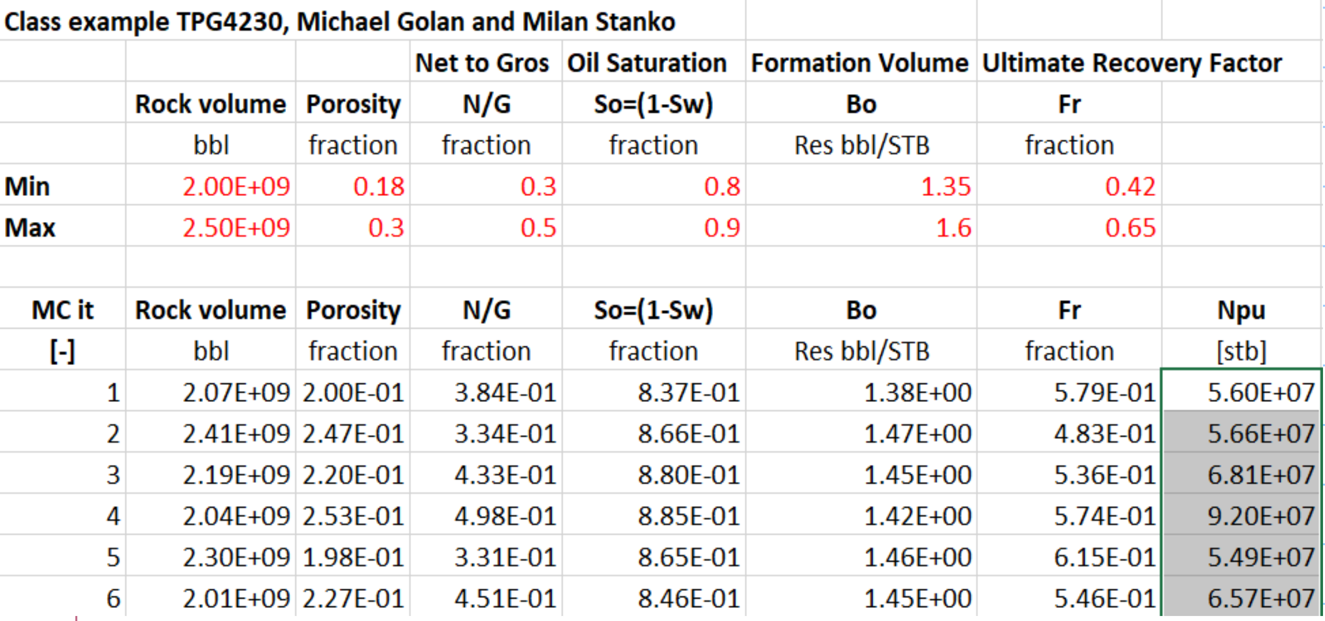


use for our input only uniform distribution

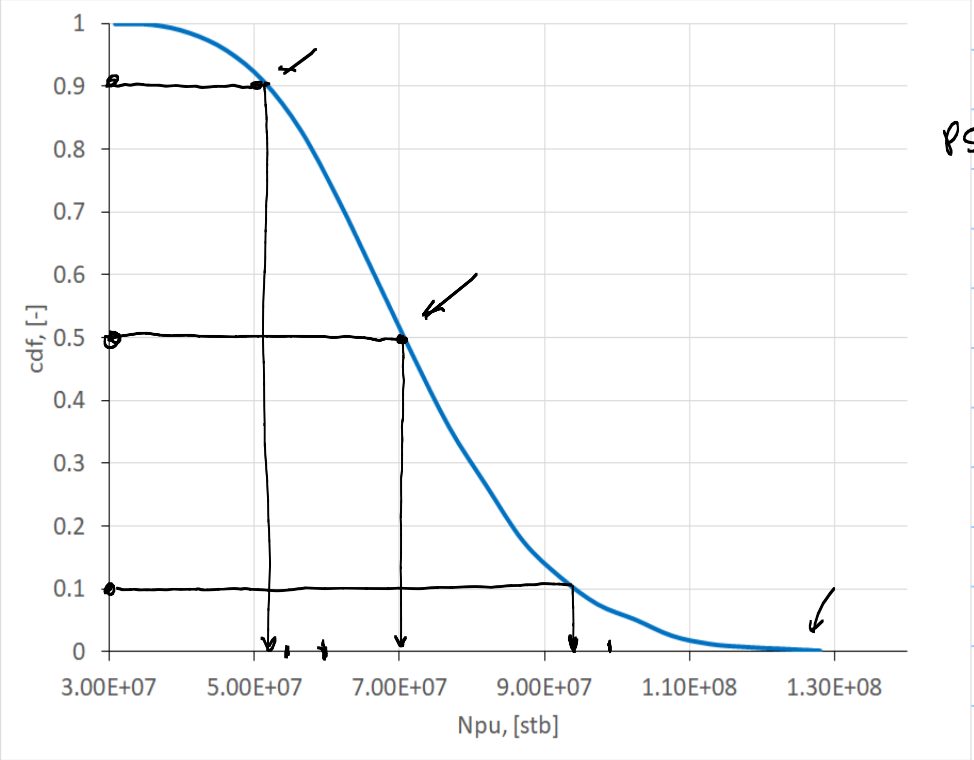




$$\underbrace{Q = Q_{min} + \overbrace{RAND()}^{0-1}\left(Q_{max}-Q_{min}\right)}$$



Class example TPG4230, Michael Golan and Milan Stanko							
			Net to Gros	Oil Saturation	Formation Volume	Ultimate Recovery Factor	
	Rock volume	Porosity	N/G	So=(1-Sw)	Bo	Fr	
	bbl	fraction	fraction	fraction	Res bbl/STB	fraction	
Min	2.00E+09	0.18	0.3	0.8	1.35	0.42	
Max	2.50E+09	0.3	0.5	0.9	1.6	0.65	
MC it	Rock volume	Porosity	N/G	So=(1-Sw)	Bo	Fr	Npu
[-]	bbl	fraction	fraction	fraction	Res bbl/STB	fraction	[stb]
1	2.07E+09	2.00E-01	3.84E-01	8.37E-01	1.38E+00	5.79E-01	5.60E+07
2	2.41E+09	2.47E-01	3.34E-01	8.66E-01	1.47E+00	4.83E-01	5.66E+07
3	2.19E+09	2.20E-01	4.33E-01	8.80E-01	1.45E+00	5.36E-01	6.81E+07
4	2.04E+09	2.53E-01	4.98E-01	8.85E-01	1.42E+00	5.74E-01	9.20E+07
5	2.30E+09	1.98E-01	3.31E-01	8.65E-01	1.46E+00	6.15E-01	5.49E+07
6	2.01E+09	2.27E-01	4.51E-01	8.46E-01	1.45E+00	5.46E-01	6.57E+07

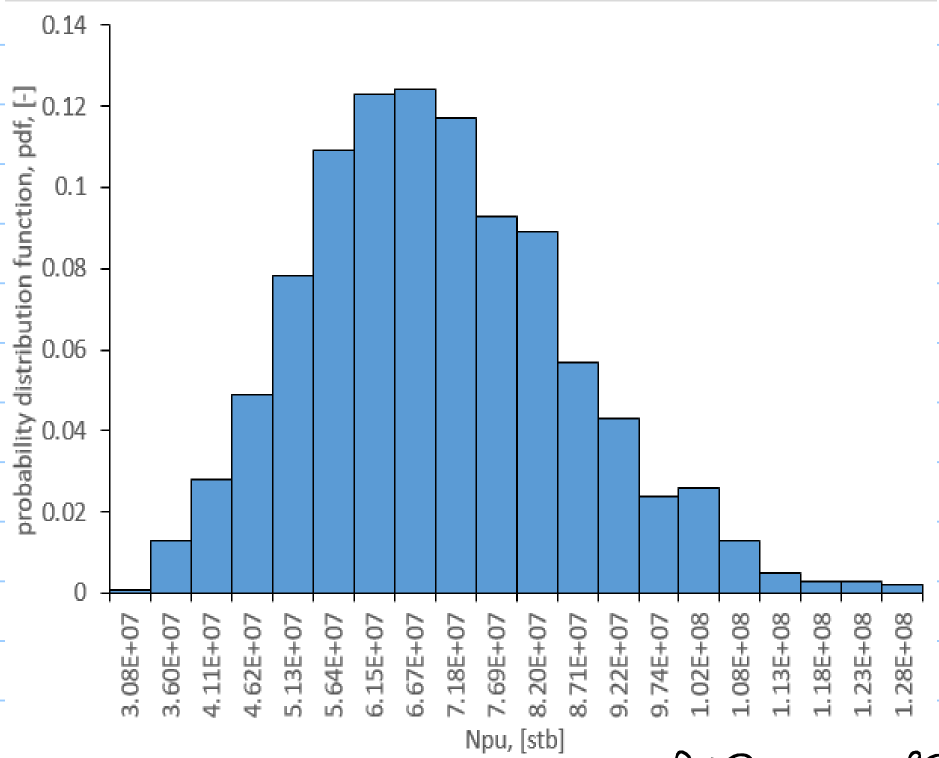


P50 is usually used for production profile forecasting

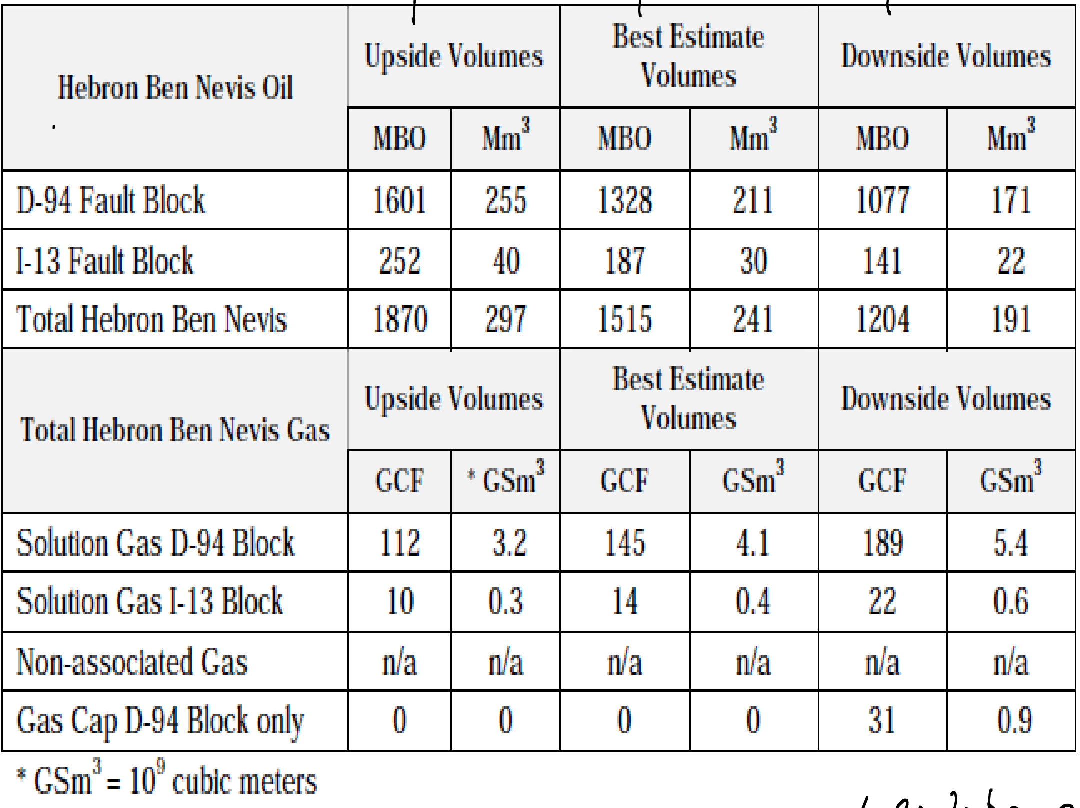
P10 = 95 E6 stb

{P50 = 70 E6 stb

P90 = 52 E6 stb



~P10 P50 P90



Hebron Ben Nevis Oil	Upside Volumes		Best Estimate Volumes		Downside Volumes	
	MBO	Mm^3	MBO	Mm^3	MBO	Mm^3
D-94 Fault Block	1601	255	1328	211	1077	171
I-13 Fault Block	252	40	187	30	141	22
Total Hebron Ben Nevis	1870	297	1515	241	1204	191
Total Hebron Ben Nevis Gas	Upside Volumes		Best Estimate Volumes		Downside Volumes	
	GCF	* GSm^3	GCF	GSm^3	GCF	GSm^3
Solution Gas D-94 Block	112	3.2	145	4.1	189	5.4
Solution Gas I-13 Block	10	0.3	14	0.4	22	0.6
Non-associated Gas	n/a	n/a	n/a	n/a	n/a	n/a
Gas Cap D-94 Block only	0	0	0	0	31	0.9

* $GSm^3 = 10^9$ cubic meters

from Hebron PDO

- when the simulation takes long time } production profiles
  Cost estimation
  NPV calculation

Monte Carlo is impractical (too long running times) → use probability trees.

Class 5

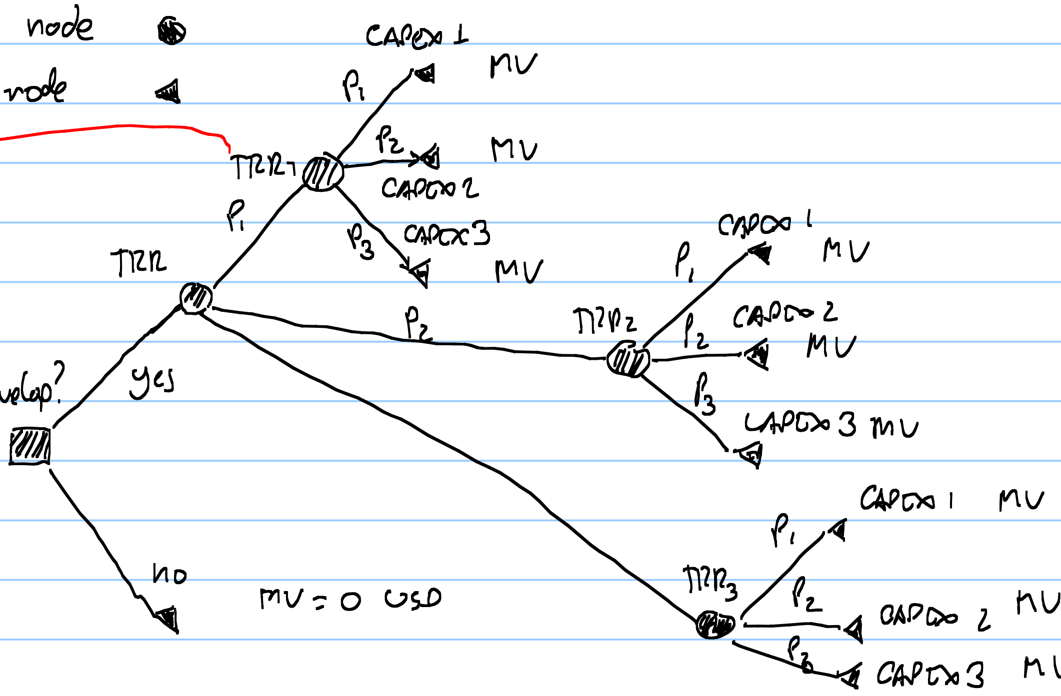
- Probability trees
- Field development
- Offshore structures for HC production

Probability trees → • traditional approach requires less computing power
- discrete variables   vessel type
    decision variable
    sequence
- when simulations take a long time

is used often in appraisal

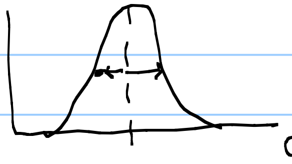
- Identify how many variables the probability tree has
  - (1) • develop or not (2)
  - TRR (3)
  - CAPEX (3)

decision node ▨
chance node ●
end node ◀

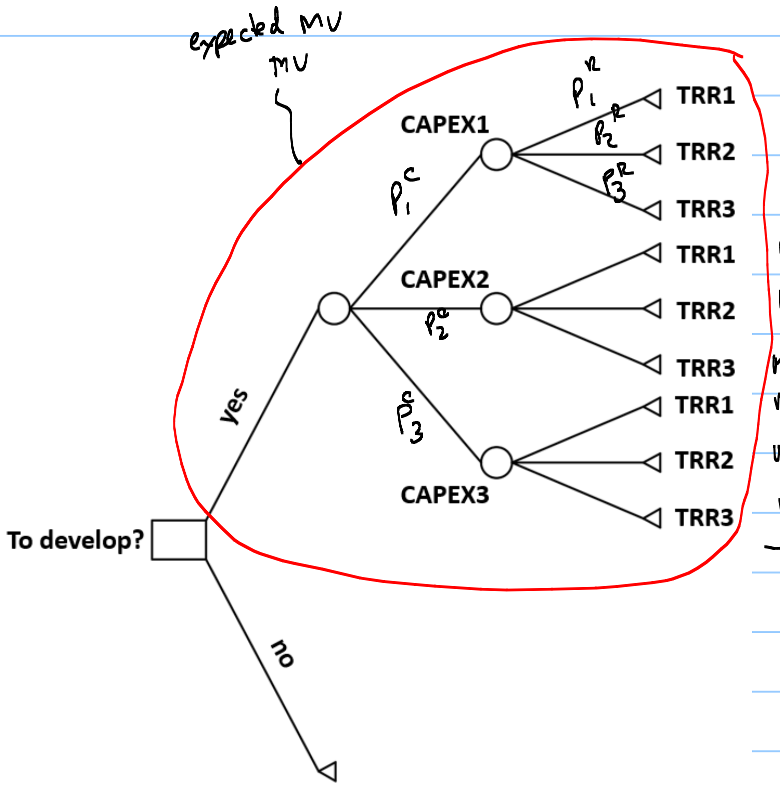


requires discretizing continuous distribution

Cost values (OPEX, CAPEX, DRILLEX) usually display a Gaussian/Normal distribution



σ = ± 20 (mean)



$MV \cdot (p_1^c \cdot p_1^R)$

$MV \cdot (p_1^c \cdot p_2^R)$

$MV \cdot (p_1^c \cdot p_3^R)$

$MV \cdot (p_2^c \cdot p_1^R)$

$MV \cdot (p_2^c \cdot p_2^R)$

$MV \cdot (p_2^c \cdot p_3^R)$

$MV \cdot (p_3^c \; p_1^R)$

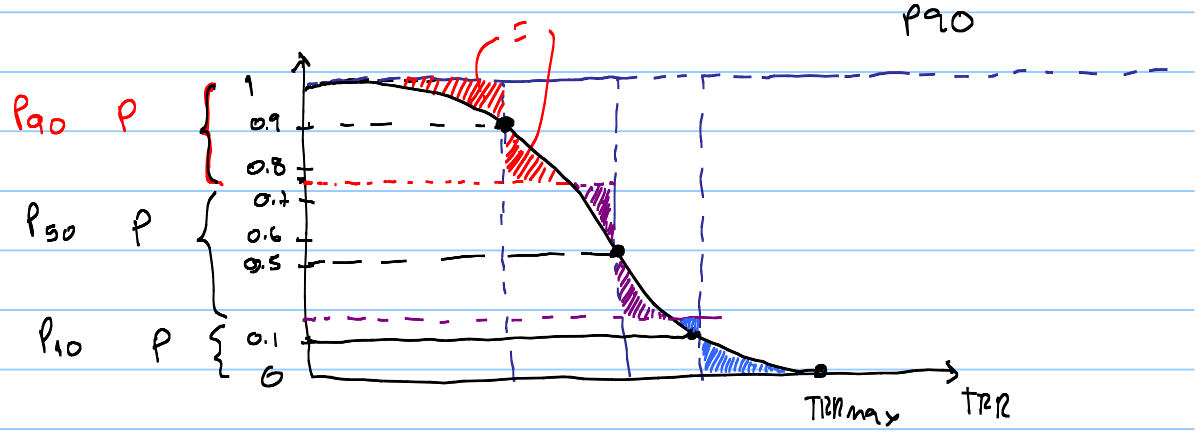
$MV \cdot (p_3^c \; p_2^R)$

$MV \cdot (p_3^c \cdot p_3^R)$

$\Sigma = EMV$

How do we get discretized values of TRR, CAPEX from a continuous function

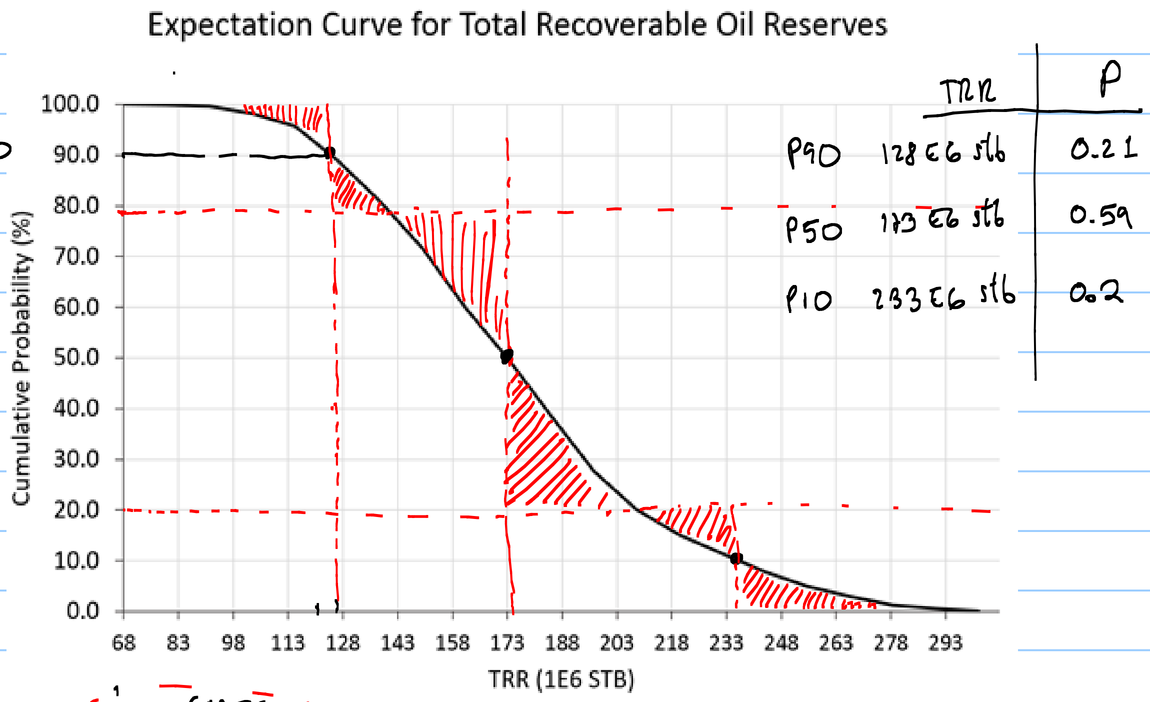
for TRR, people like to use P10 P50 P90



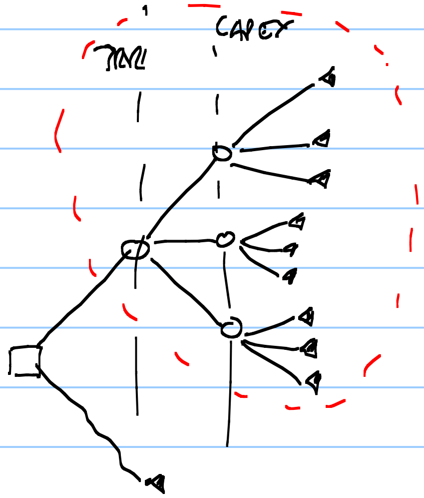
P=0.21 P90

79-20
0.59 P50

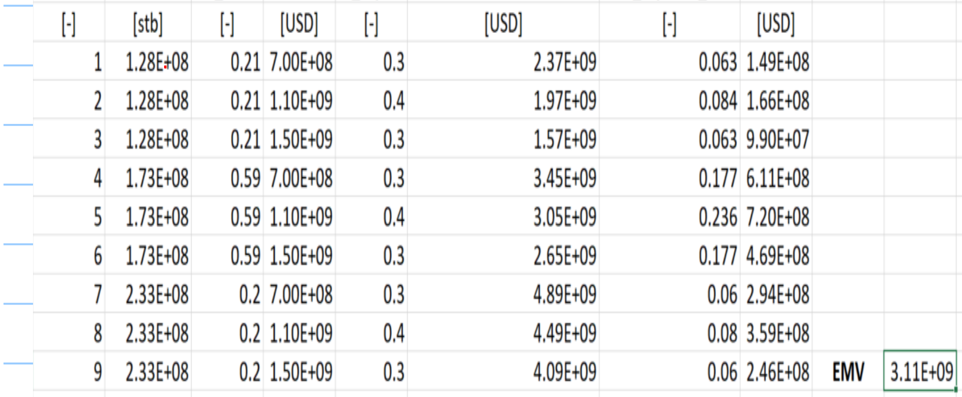
P=0.2 P10



	TRR	P
P90	128 E6 stb	0.21
P50	173 E6 stb	0.59
P10	233 E6 stb	0.2



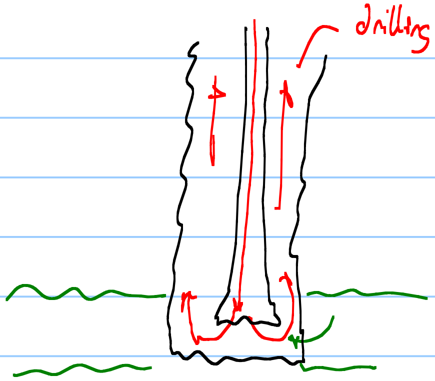
EMV = 3.11 E9 USD !



OPTION	TRR	P_TRR	CAPEX	P_capex	MV = TRR*60*0.4-CAPEX	P=P_capex*P_TRR	MV*P		
[-]	[stb]	[-]	[USD]	[-]	[USD]	[-]	[USD]		
1	1.28E+08	0.21	7.00E+08	0.3	2.37E+09	0.063	1.49E+08		
2	1.28E+08	0.21	1.10E+09	0.4	1.97E+09	0.084	1.66E+08		
3	1.28E+08	0.21	1.50E+09	0.3	1.57E+09	0.063	9.90E+07		
4	1.73E+08	0.59	7.00E+08	0.3	3.45E+09	0.177	6.11E+08		
5	1.73E+08	0.59	1.10E+09	0.4	3.05E+09	0.236	7.20E+08		
6	1.73E+08	0.59	1.50E+09	0.3	2.65E+09	0.177	4.69E+08		
7	2.33E+08	0.2	7.00E+08	0.3	4.89E+09	0.06	2.94E+08		
8	2.33E+08	0.2	1.10E+09	0.4	4.49E+09	0.08	3.59E+08		
9	2.33E+08	0.2	1.50E+09	0.3	4.09E+09	0.06	2.46E+08	EMV	3.11E+09

Answer: yes to development!

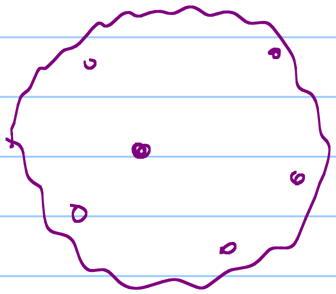
field development process

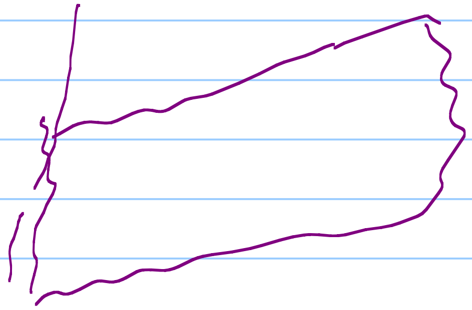


drilling mud : functions:

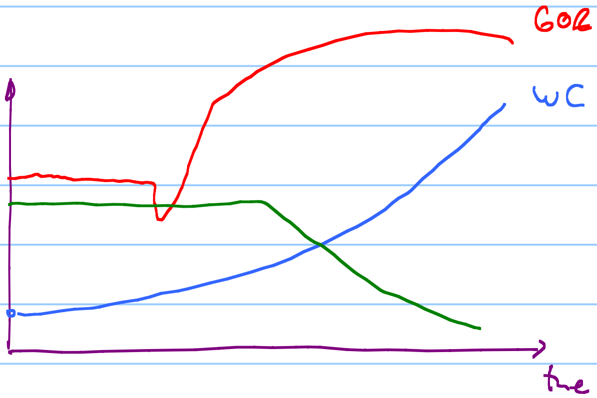
- carry cuttings to surface
- cool the bit
- lubricate
- pressure control of reservoir fluid

top view of reservoir

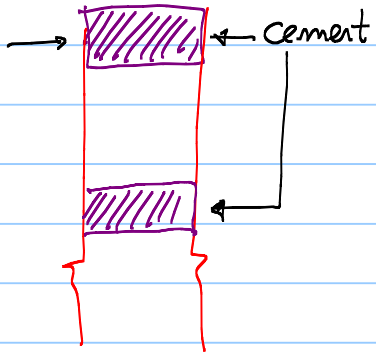


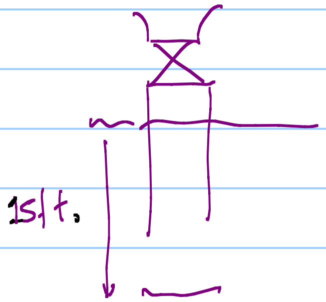


Debottlenecking



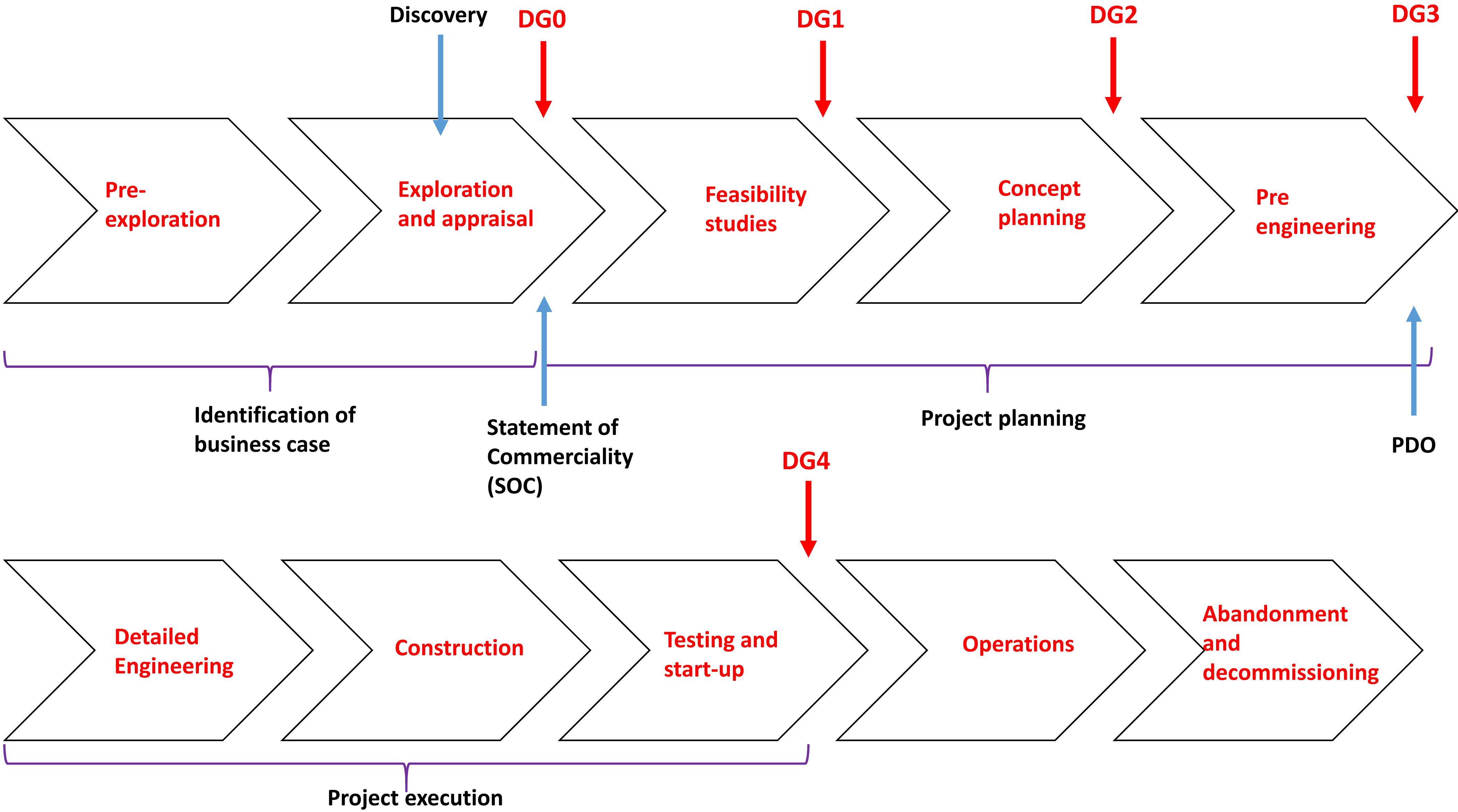
Plug and abandonment





THE FIELD DEVELOPMENT PROCESS

Prof. Milan Stanko (NTNU)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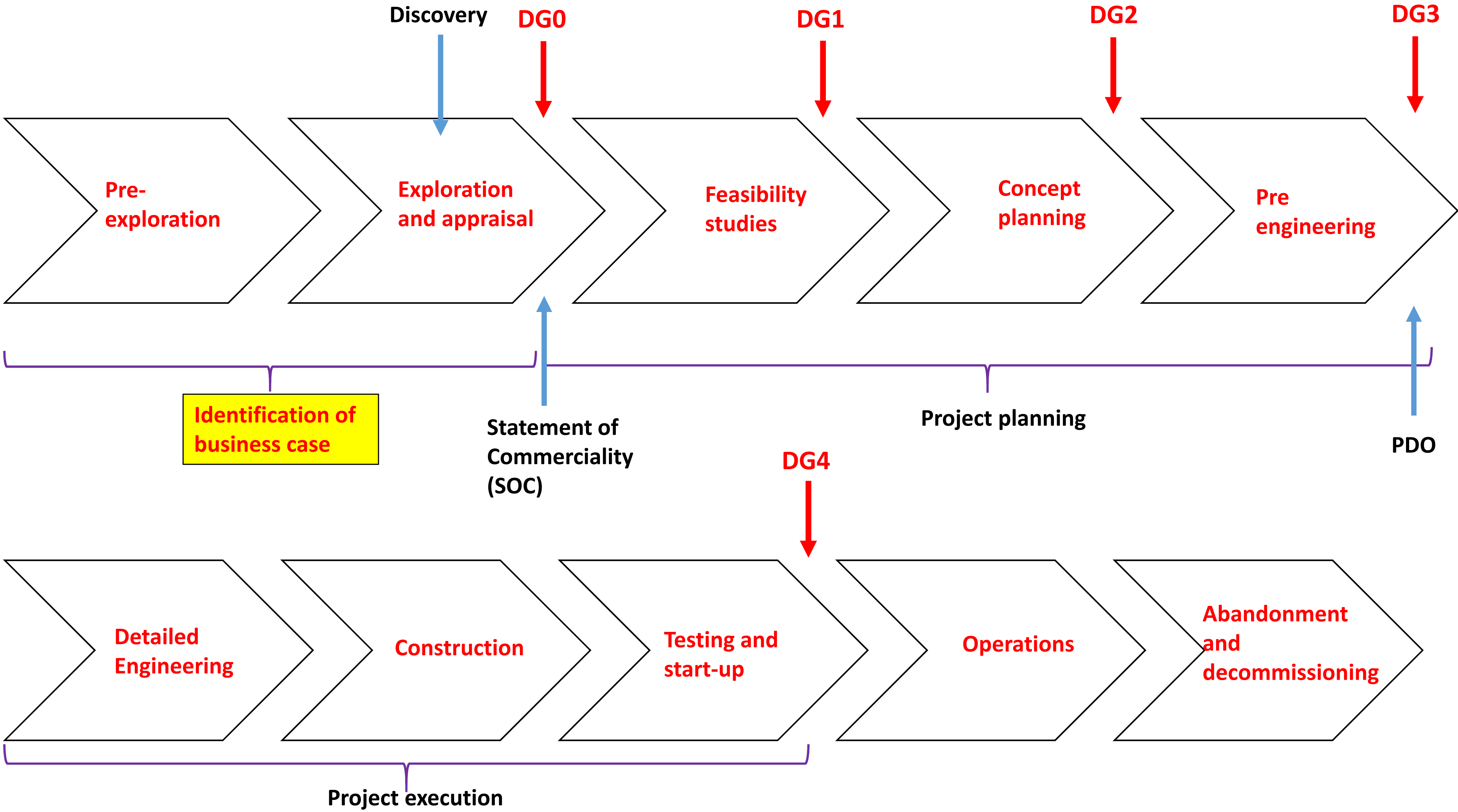
Project execution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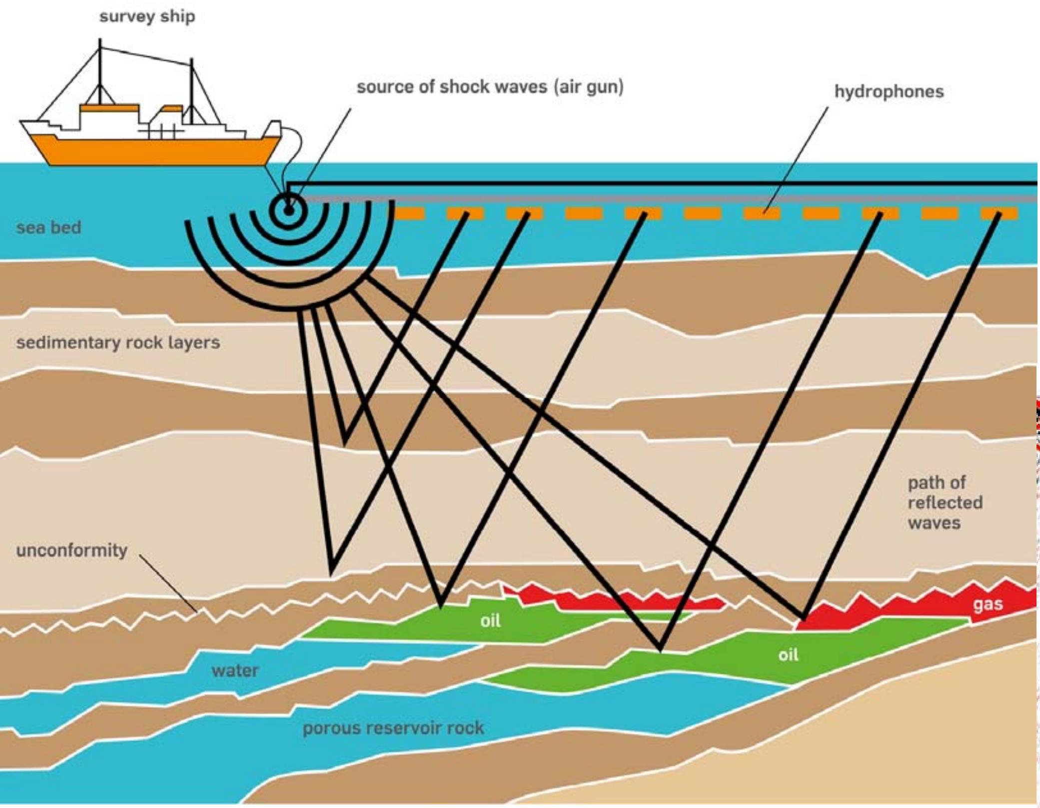
IDENTIFICATION OF BUSINESS CASE

The main goal of this stage is to prove economic potential of the discovery and quantify and reduce the uncertainty in the estimation of reserves.

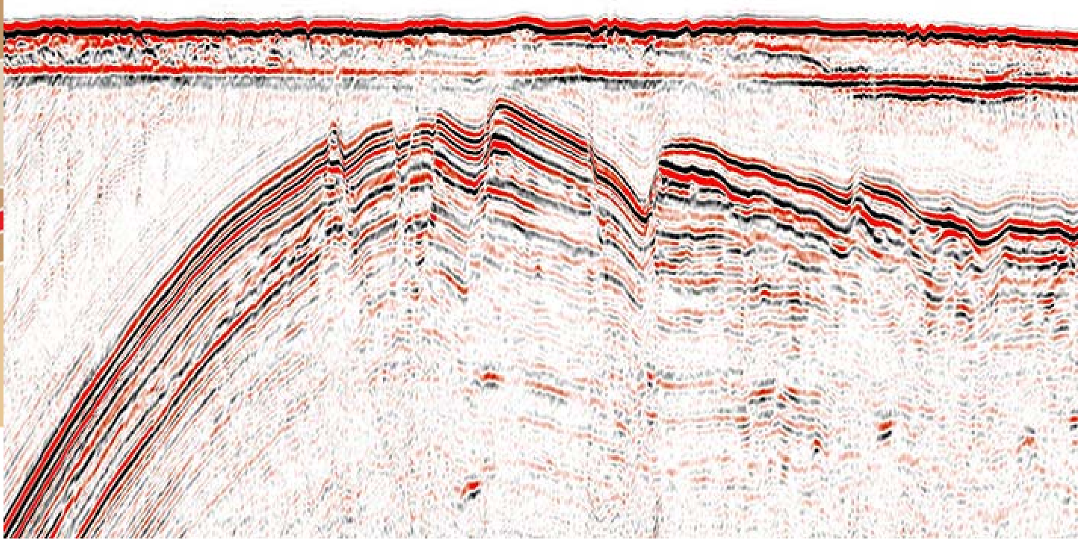
IDENTIFICATION OF BUSINESS CASE - TASKS

- Pre-exploration – scouting: collecting information on areas of interests. Technical, political, geological, geographical, social, environmental considerations are taken into account. E.g. expected size of reserves, political regime, government stability, technical challenges of the area, taxation regime, personnel security, environmental sensitivity, previous experience in the region, etc.
- Getting pre-exploration access – The exploration license (usually non-exclusive). In the NCS only seismic and shallow wells are allowed. This is usually done by specialized companies selling data to oil companies.
- Identify prospects.

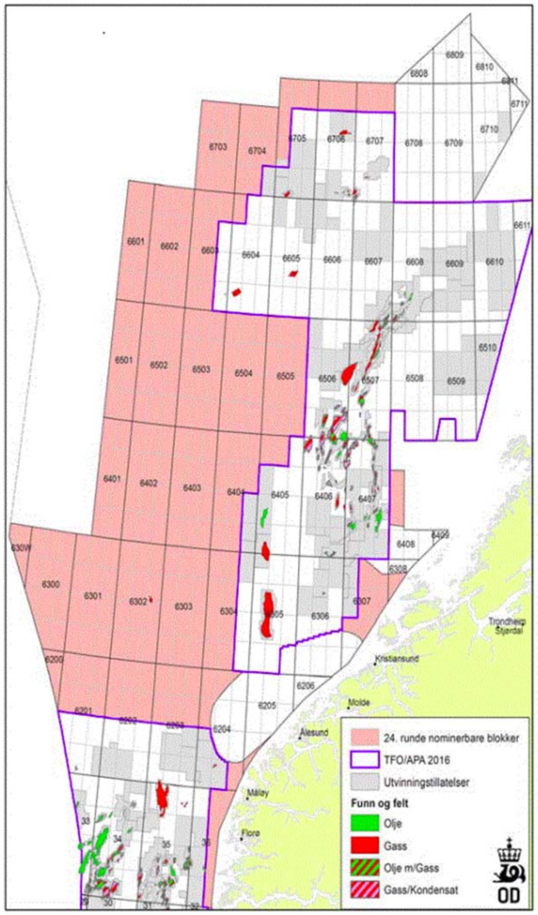
IDENTIFICATION OF BUSINESS CASE - TASKS



Seismic exploration



IDENTIFICATION OF BUSINESS CASE - TASKS



- Apply and obtain exclusive production license. In the NCS: Licensing rounds (frontier areas) or Awards in predefined areas (APA). The current fees are 34 000 NOK/km^2 for the first year, 68 000 NOK/km^2 for the second year and 137 000 NOK/km^2 per year thereafter.

IDENTIFICATION OF BUSINESS CASE - TASKS

- Exploration. Perform geological studies, geophysical surveys, seismic, exploration drilling (Well cores, wall cores, cuttings samples, fluid samples, wireline logs, productivity test).
- Discovery!

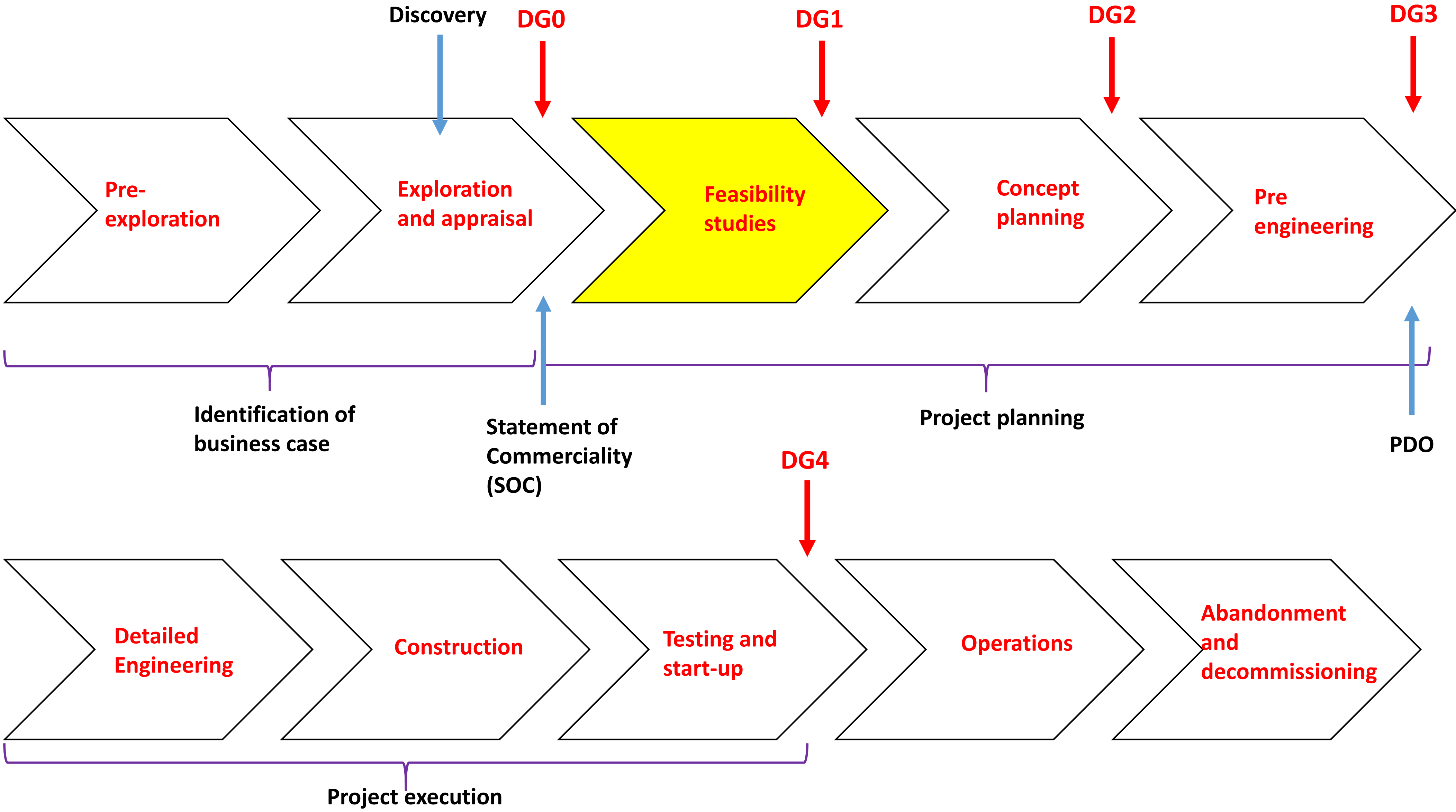
IDENTIFICATION OF BUSINESS CASE - TASKS

- Assessment of the discovery and the associated uncertainty. Risk management:
  - **Probabilistic reserve estimation.** Identify and assess additional segments.
  - Perform **simplified economic valuation** of the resources.
  - Field **appraisal** to reduce uncertainty: more exploration wells and seismic to determine for example: fault communication, reservoir extent, aquifer behavior, location of water oil contact or gas oil contact.

IDENTIFICATION OF BUSINESS CASE - TASKS

DG0:

- Issue a SOC (Statement of Commerciality) and proceed with development.
- Continue with more appraisal
- Sell the discovery.
- Do nothing (wait)
- Relinquish to the government



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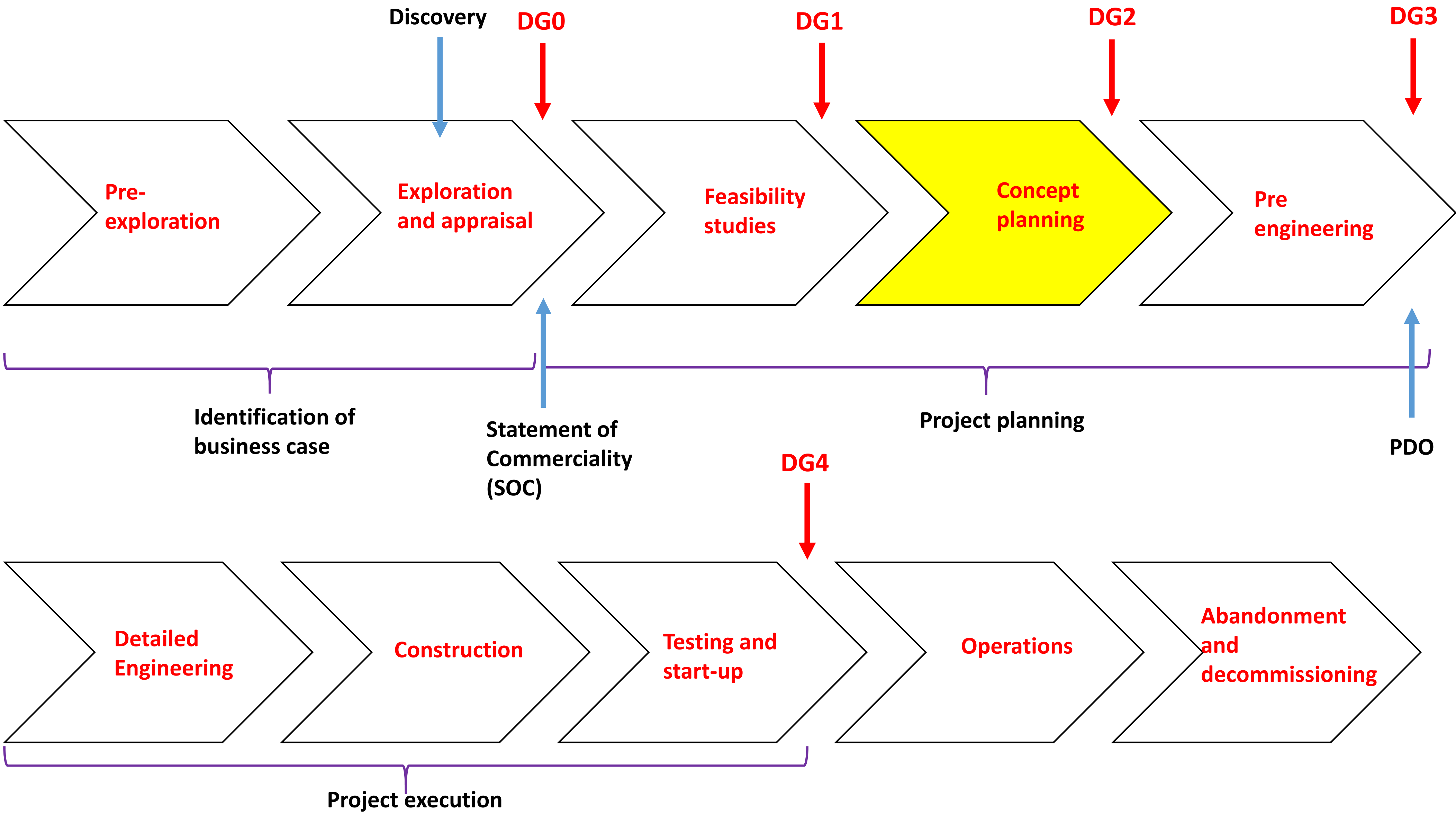
FEASIBILITY STUDIES - TASKS

OBJECTIVE: Justify further development of the project, finding one or more concepts that are technically, commercially and organizationally feasible

- Define objectives of the development in line with the corporate strategy.
- Establish feasible development scenarios.
- Create a project timeline and a workplan.

FEASIBILITY STUDIES - TASKS

- Identify possible technology gaps and blockers.
- Identify the needs for new technology.
- Identify added value opportunities.
- Cost evaluation for all options (at this stage, cost figures are ±40% uncertain)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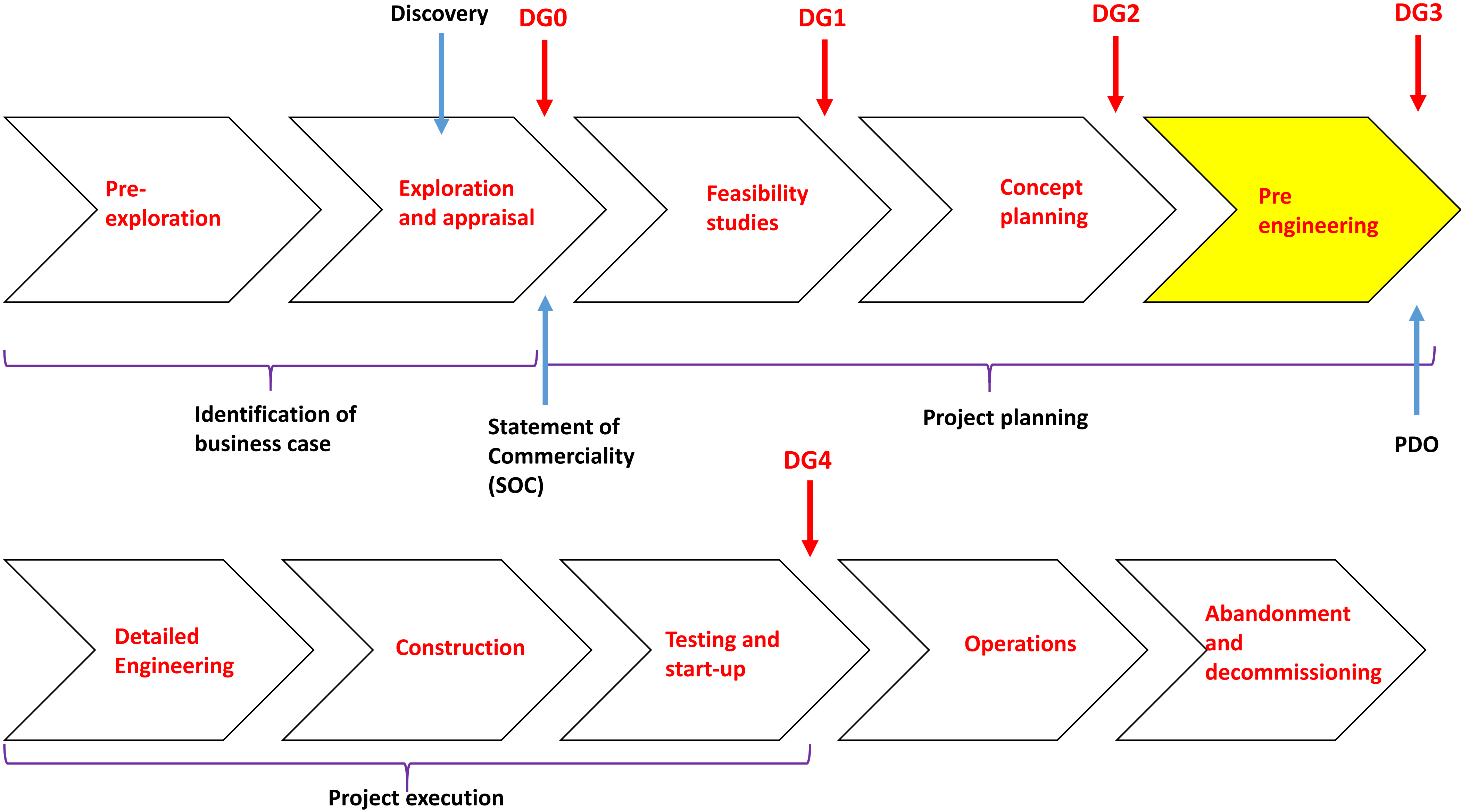
CONCEPT PLANNING - TASKS

OBJECTIVE: Identify development concepts, rank them and select and document a viable concept (Base Case Scenario).

- Evaluate and compare alternatives for development and screen out non-viable options.
- Elaborate a Project Execution Plan (PEP) which describes the project and management system.
- Define the commercial aspects, legislation, agreements, licensing, financing, marketing and supply, taxes.

CONCEPT PLANNING - TASKS

- Create and refine a static and a dynamic model of reservoir. **Define the depletion and production strategy.**
- Define an HSE program
- **Flow assurance evaluation.** Identification of challenges related with fluid properties, multiphase handling and driving pressure.
- Drilling and well planning
- Pre-design of facilities
- Planning of operations, start-up and maintenance
- Cost and manpower estimates of the best viable concept.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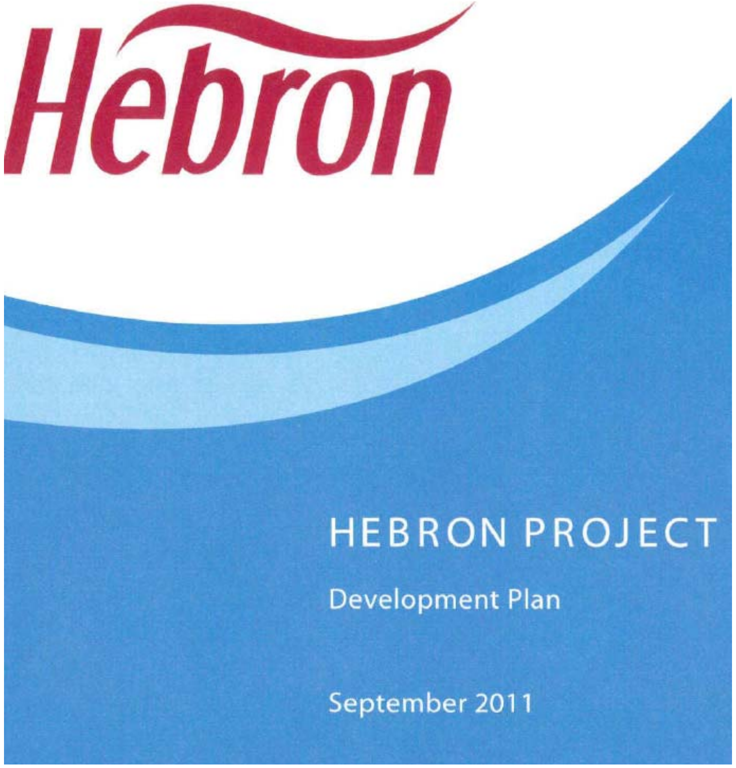
PRE-ENGINEERING - TASKS

OBJECTIVE: Further mature, define and document the development solution based on the selected concept.

- Selection of the final technical solution. Decide and define all remaining critical technical alternatives.
- Execute Front End Engineering Design (FEED) Studies: determine technical requirements (arranged in packages) for the project based on the final solution chosen. Estimate cost of each package.
- Plan and prepare the execution phase.

PRE-ENGINEERING - TASKS

- Prepare for submission of the application to the authorities.
- Perform the Environmental impact assessment.
- Establish the basis for awarding contracts.
- Issue:
  - Plan for development and operations
  - Plan for installation and operations of facilities for transport and utilization of petroleum (PIO)
  - Impact assessment report



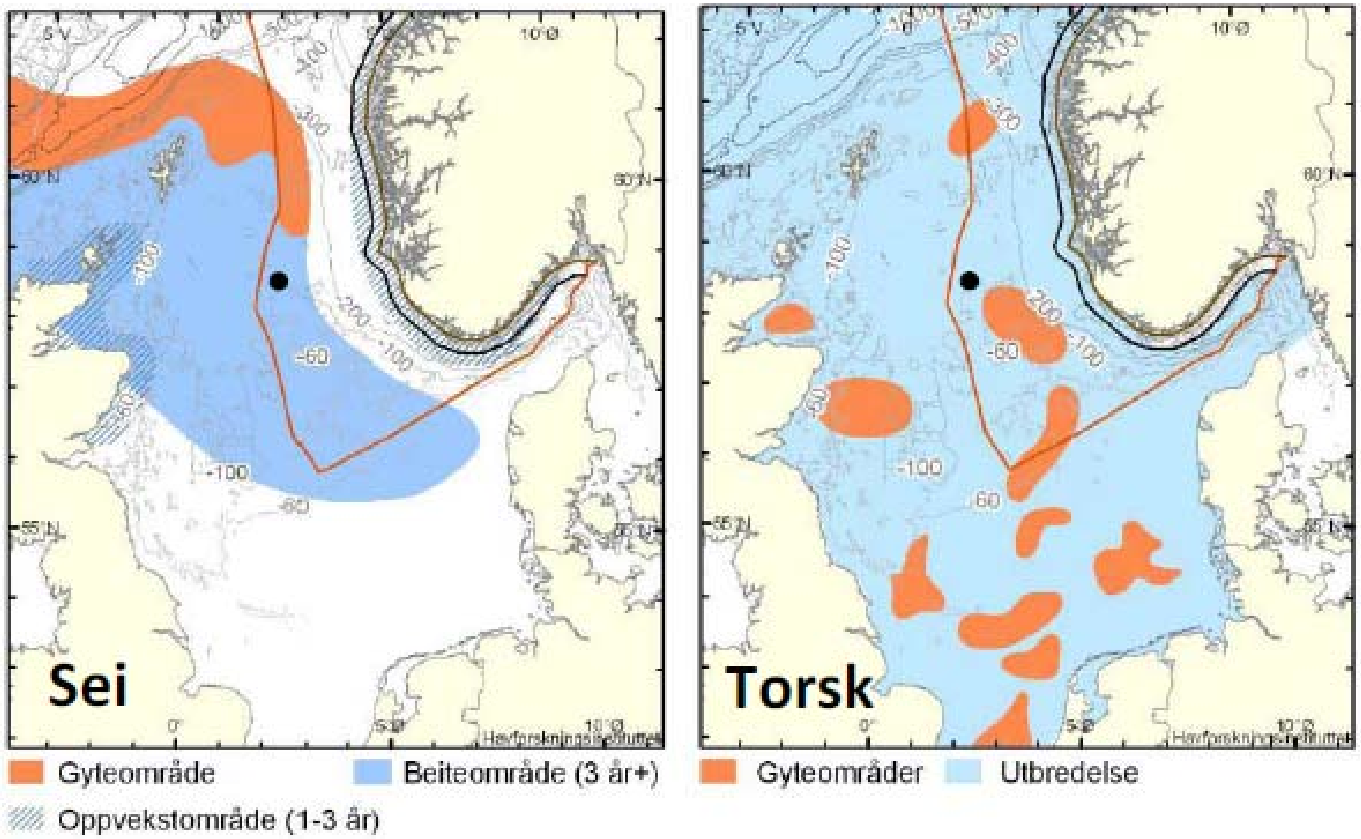
Hebron

HEBRON PROJECT

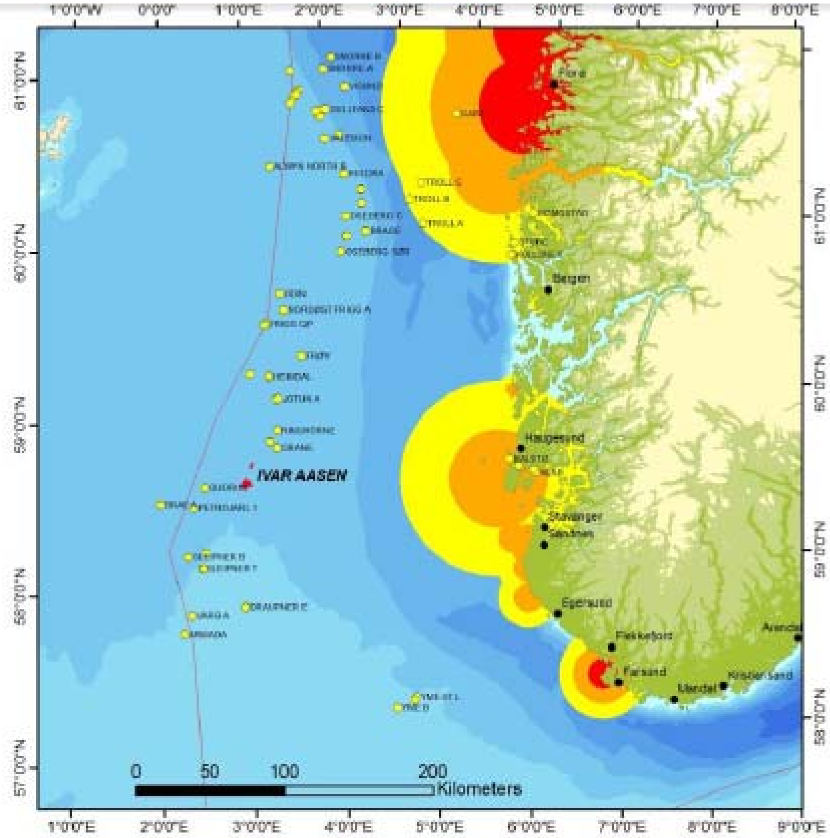
Development Plan

September 2011

PRE-ENGINEERING - TASKS

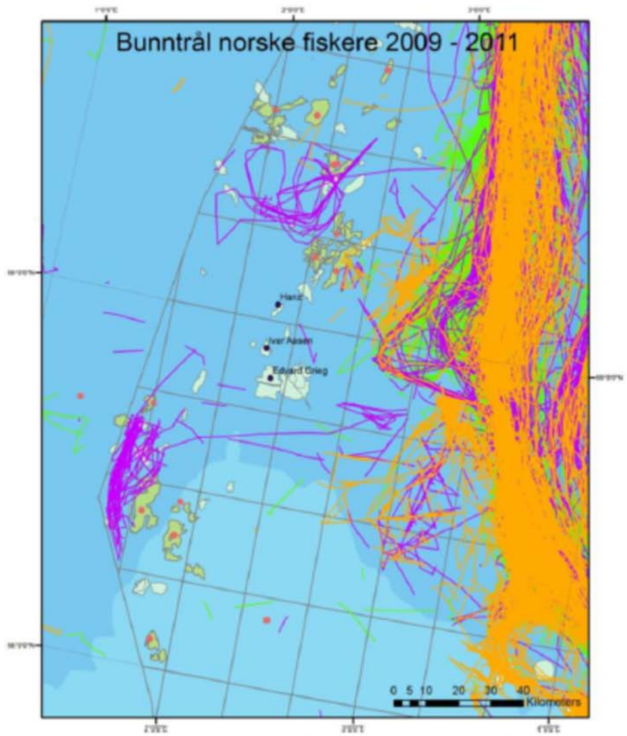


PRE-ENGINEERING - TASKS



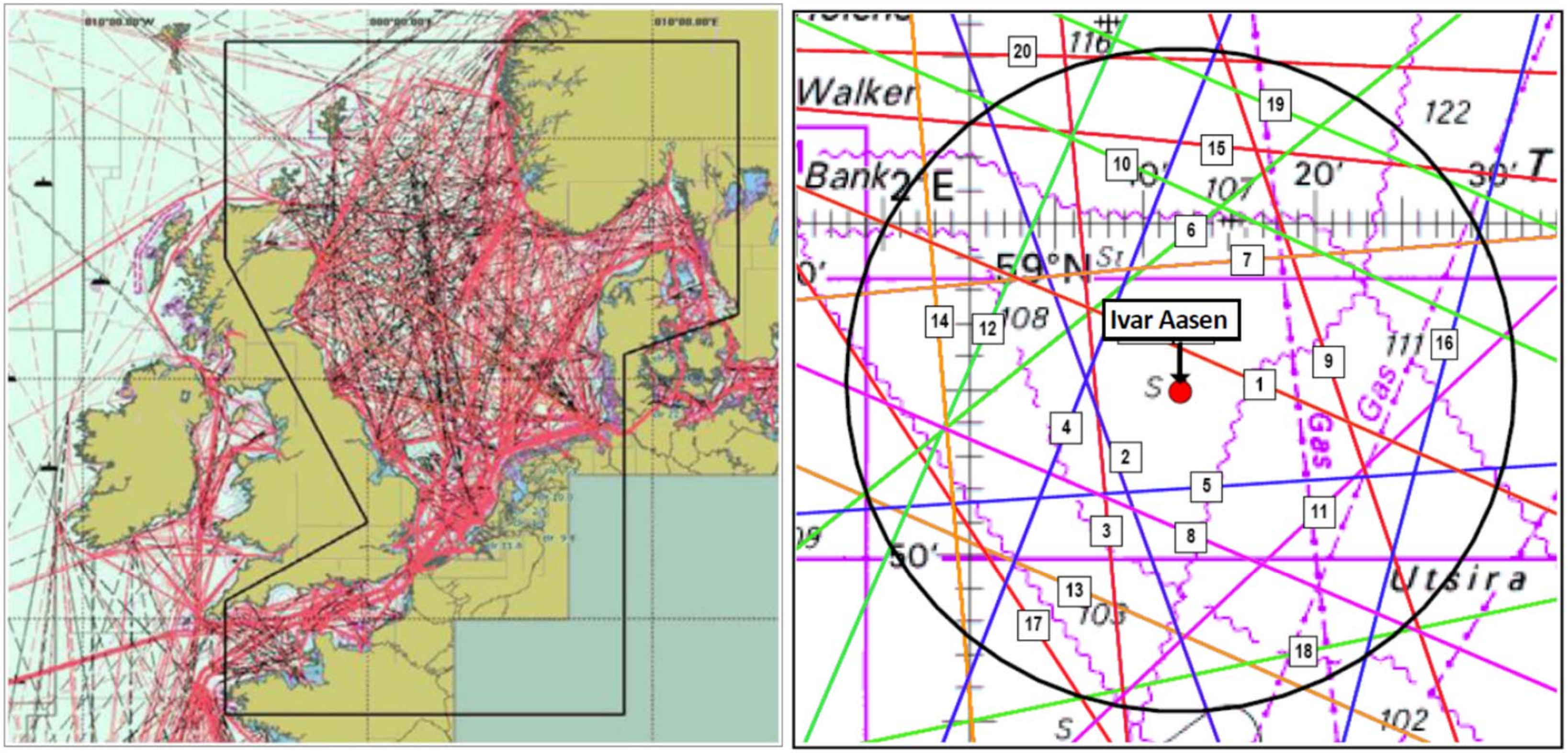
Figur 18. Svært viktige (rød), viktige (oransje) og nokså viktige (gule) leveområder for sjøfugl langs kysten av Nordsjøen i hekketiden. Kartet markerer buffersoner rundt de viktige hekkelokalitetene (NINA)

PRE-ENGINEERING - TASKS



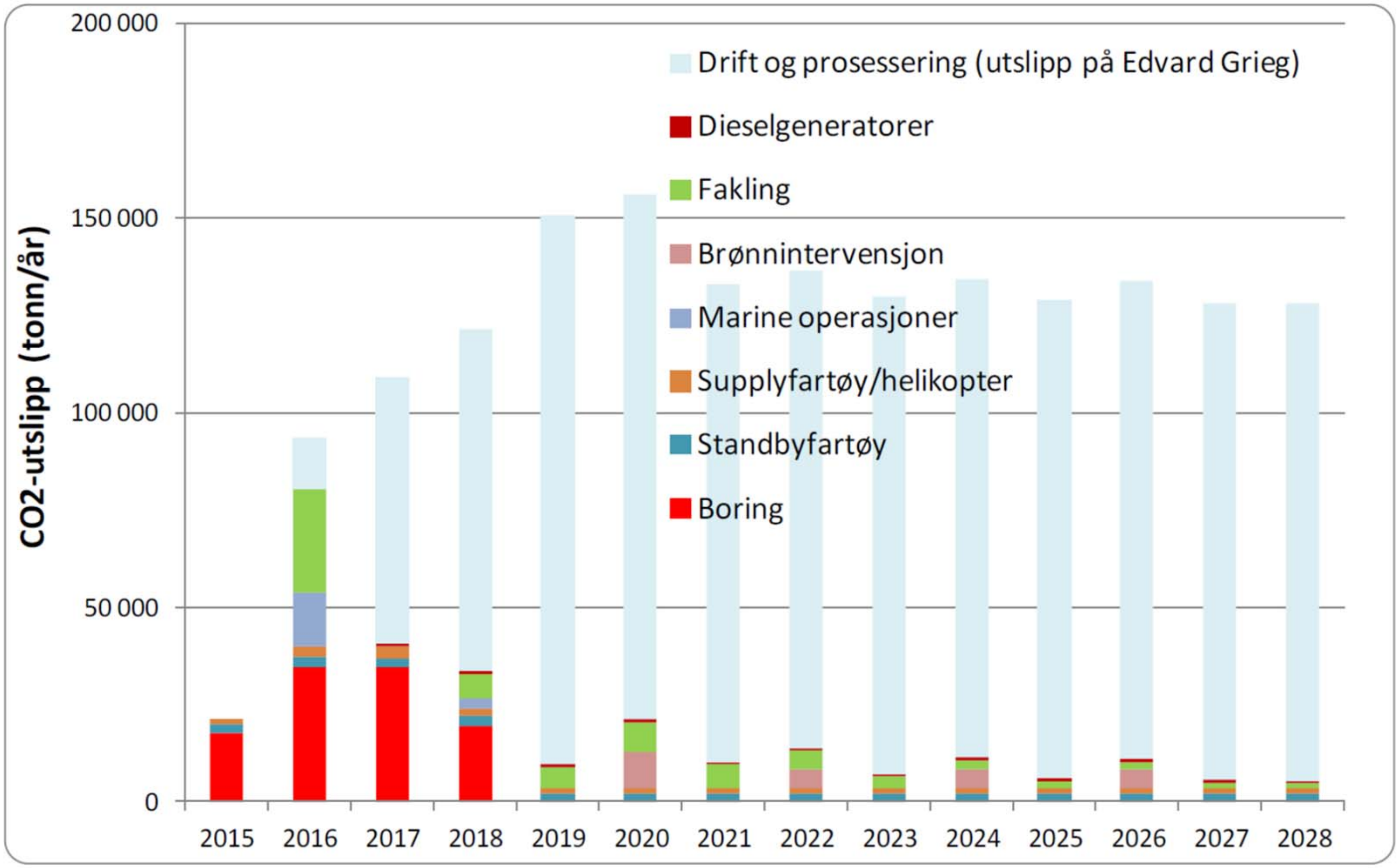
Figur 23. Registrert norsk fiskeriaktivitet med bunntrål i området omkring Aasen i 2009 (grønn), 2010 (fiolett) og 2011 (oransje). Figur utarbeidet på grunnlag av data fra Fiskeridirektoratets satellittsporing av større fiskefartøyer

PRE-ENGINEERING - TASKS



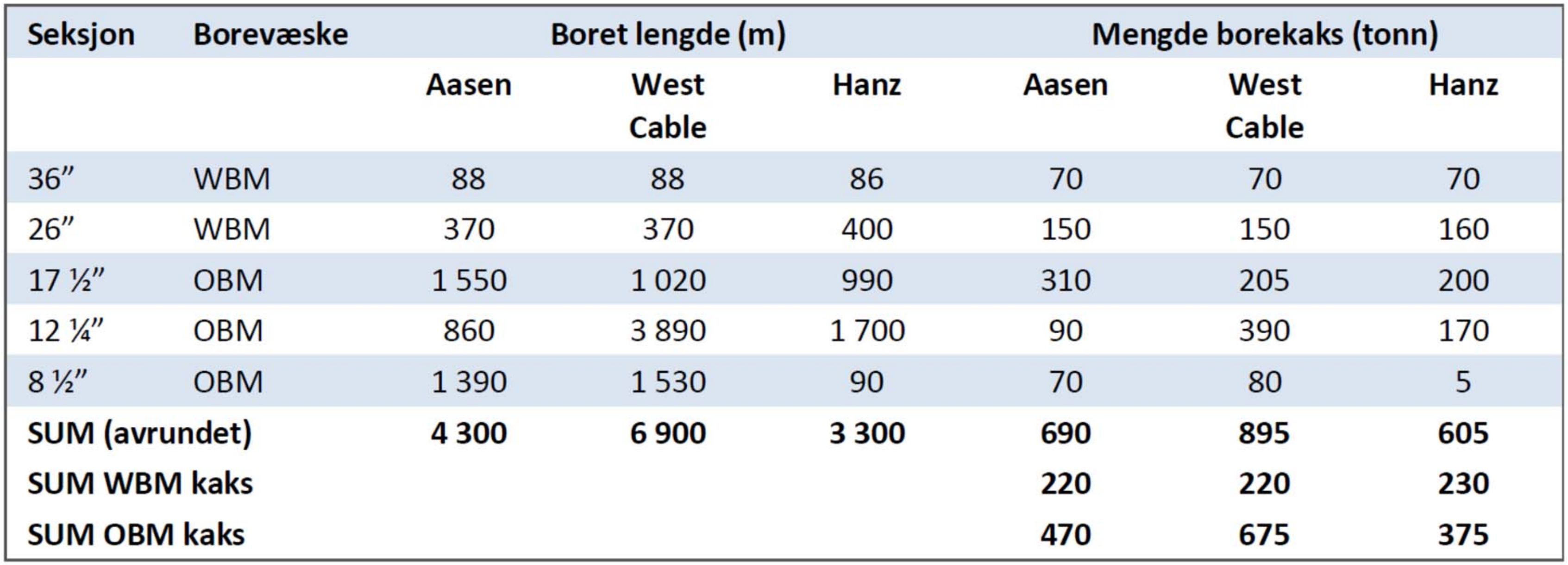
Figur 24. Trafikkompleksitet i Nordsjøen (venstre) og skipsleder for handels- og offshorefartøy innenfor en radius på 10 nautiske mil fra Aasen (høyre)

PRE-ENGINEERING - TASKS



Figur 25. Samlede utslipp av CO_2 fra Aasenfeltet i perioden 2015 – 2028

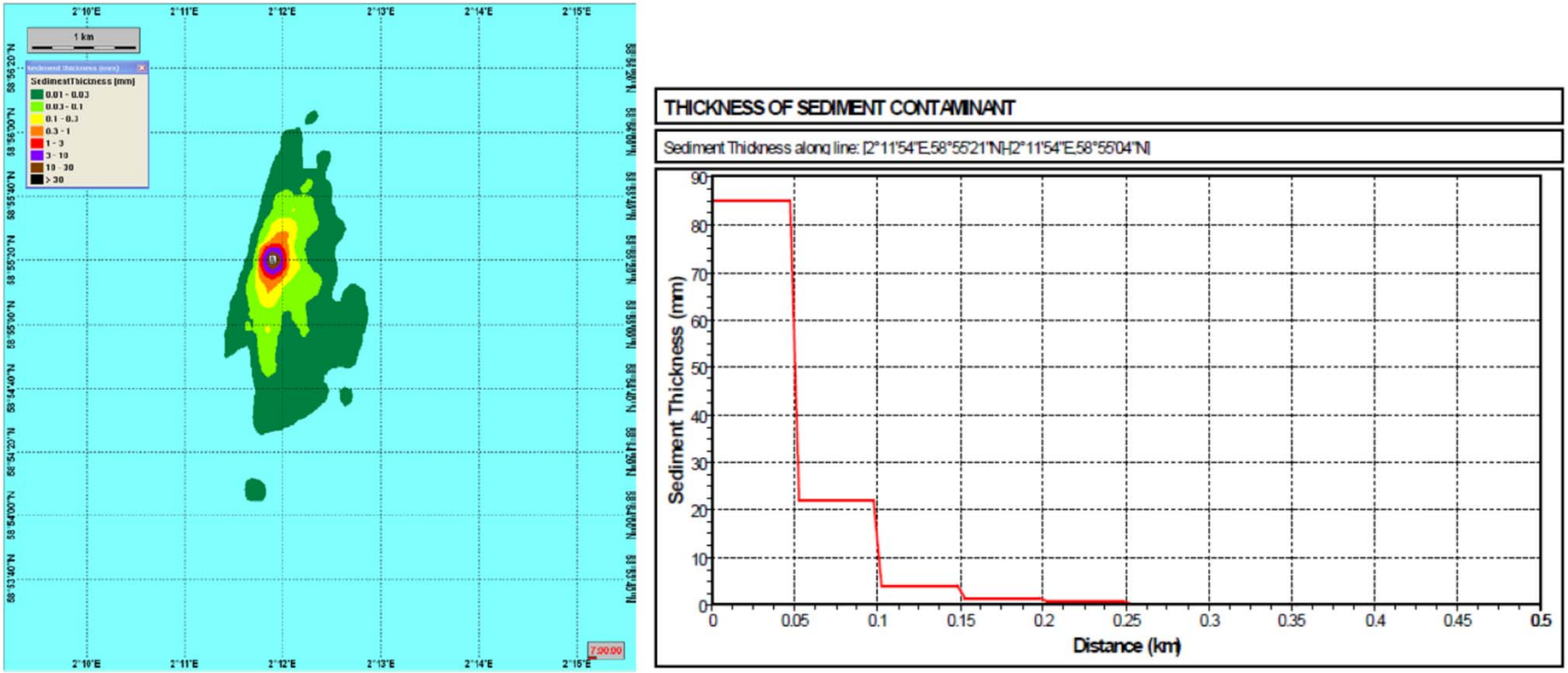
PRE-ENGINEERING - TASKS



Tabell 5-1. Foreløpig oversikt over estimerte mengder kaks for typiske produksjonsbrønner på Aasen, West Cable og Hanz

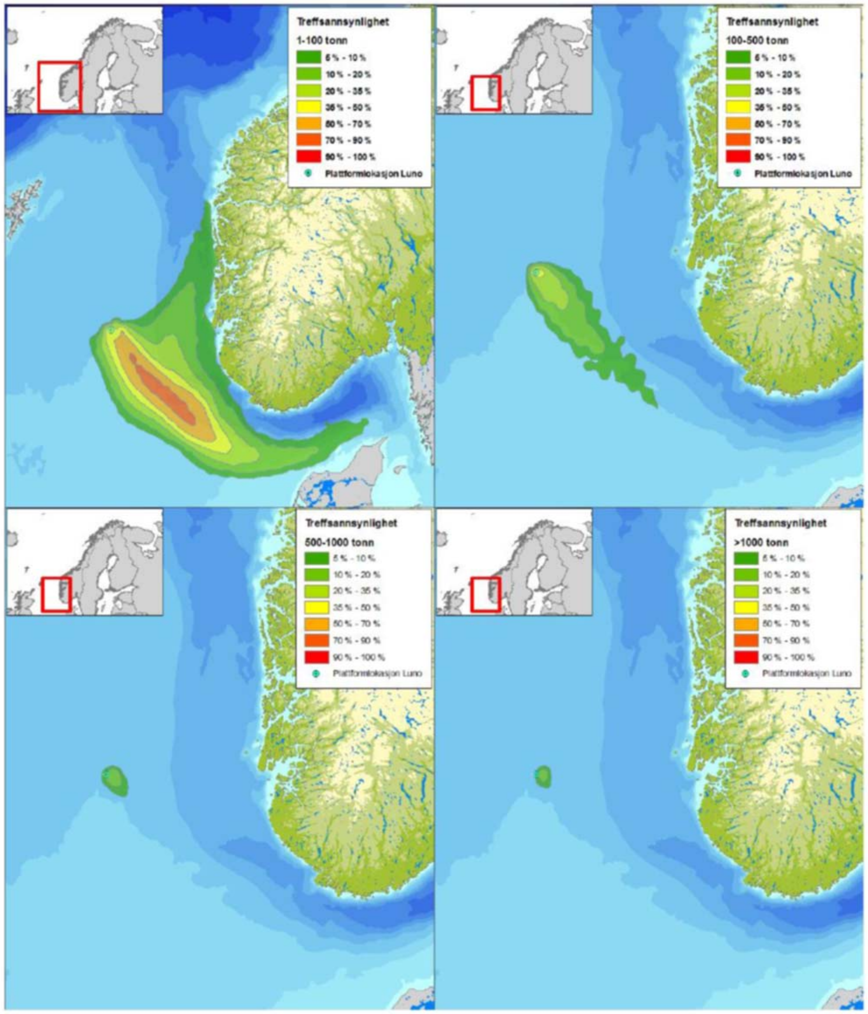
Seksjon	**Borevæske**	**Boret lengde (m)**			**Mengde borekaks (tonn)**		
		Aasen	**West Cable**	**Hanz**	**Aasen**	**West Cable**	**Hanz**
36”	WBM	88	88	86	70	70	70
26”	WBM	370	370	400	150	150	160
17 ½”	OBM	1 550	1 020	990	310	205	200
12 ¼”	OBM	860	3 890	1 700	90	390	170
8 ½”	OBM	1 390	1 530	90	70	80	5
SUM (avrundet)		**4 300**	**6 900**	**3 300**	**690**	**895**	**605**
SUM WBM kaks					**220**	**220**	**230**
SUM OBM kaks					**470**	**675**	**375**

PRE-ENGINEERING - TASKS



Figur 29. Sedimentering ved utslipp av vannbasert kaks ved havbunnen (sommersituasjon)

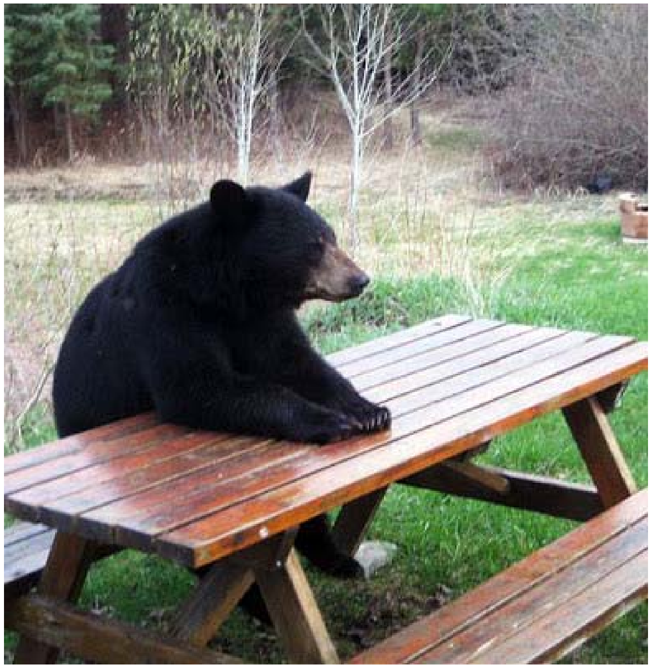
PRE-ENGINEERING - TASKS

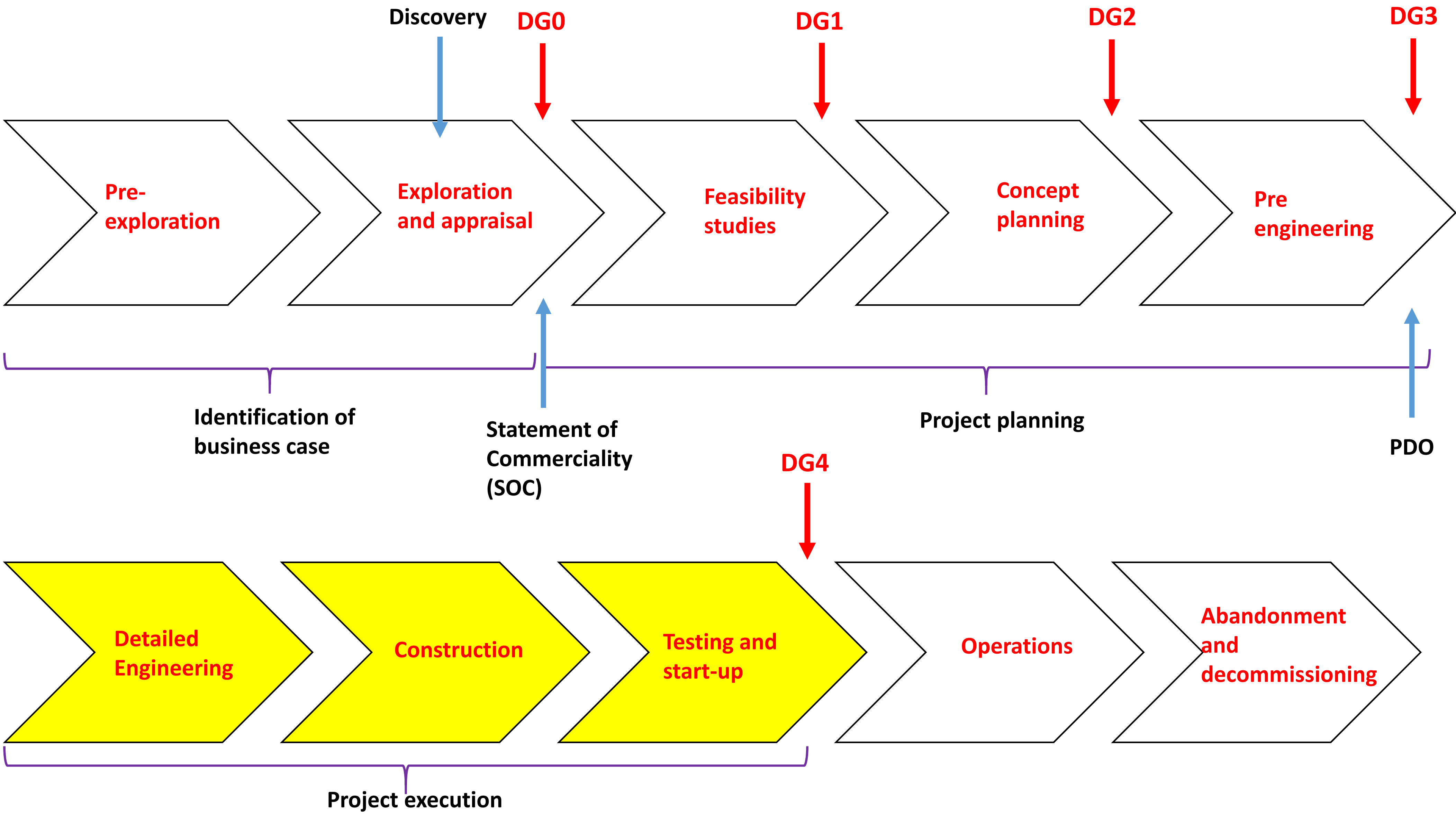


Figur 37. Sannsynligheten for treff av ulike mengdekategorier av olje i 10 × 10 km ruter gitt en sjøbunnsutblåsning fra Aasen/Grieg (helårsstatistikk). Influensområdet er basert på alle utslippsrater og varigheter og deres individuelle sannsynligheter. Merk at det markerte området ikke viser omfanget av et enkelt oljeutslipp, men er det området som berøres i mer enn 5 % av enkeltsimuleringene av oljens drift og spredning (Lundin 2011).

PRE-ENGINEERING - TASKS

- Wait for the government to study the proposal





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DETAILED ENGINEERING, CONSTRUCTION, TESTING AND STARTUP

OBJECTIVE: Detailed design, procurement of the construction materials, construction, installation and commissioning of the agreed facilities.

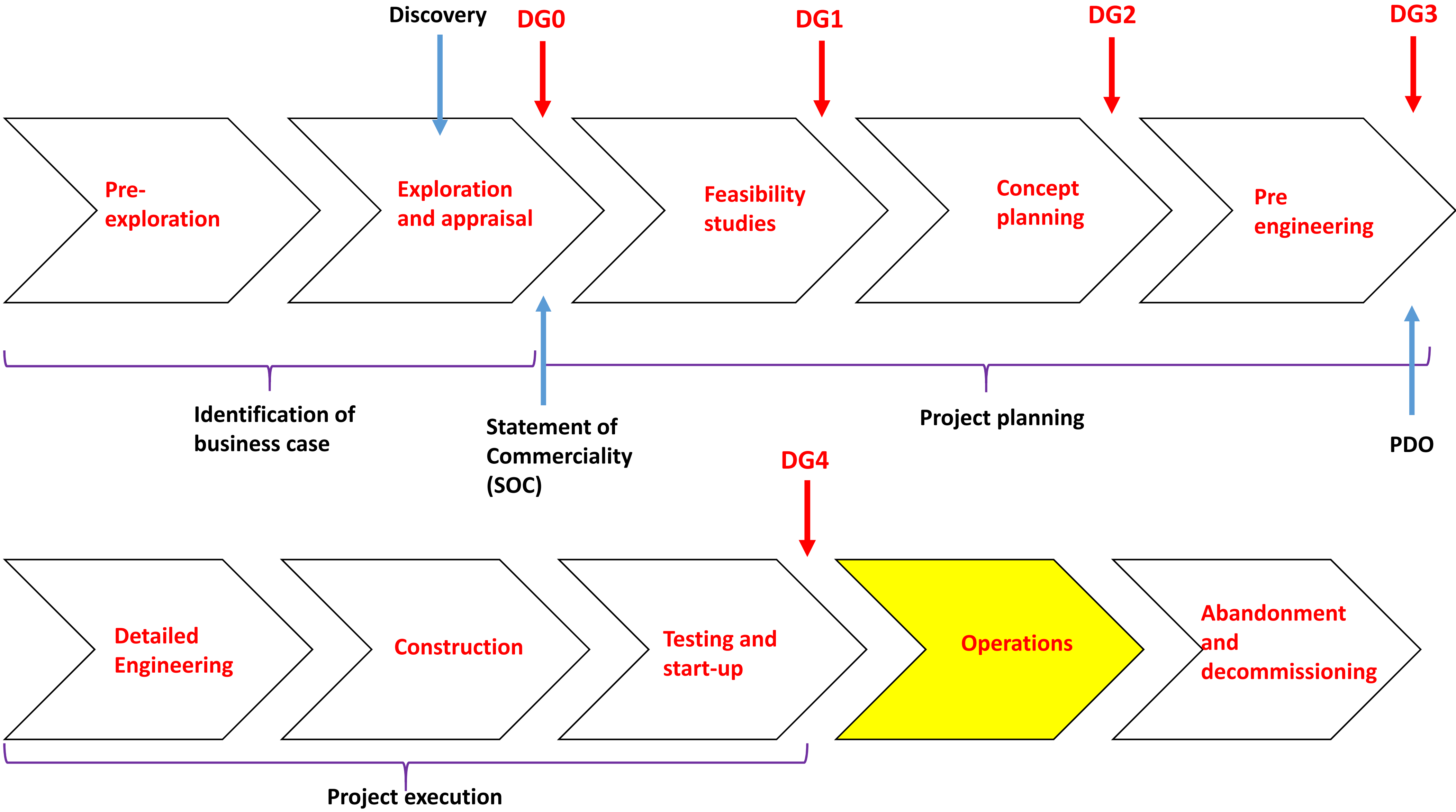
Individual contracts

- Detailed engineering
- Bids, contracts
- Construction, fabrication
- Installation
- Commissioning (Cold or Hot)

EPCM (Engineering, procurement, construction, and management contract) with one main contractor.

DETAILED ENGINEERING, CONSTRUCTION, TESTING AND STARTUP

- Constructing wells.
- Perform hand over to asset, operations
- Prepare for start-up, operation and maintenance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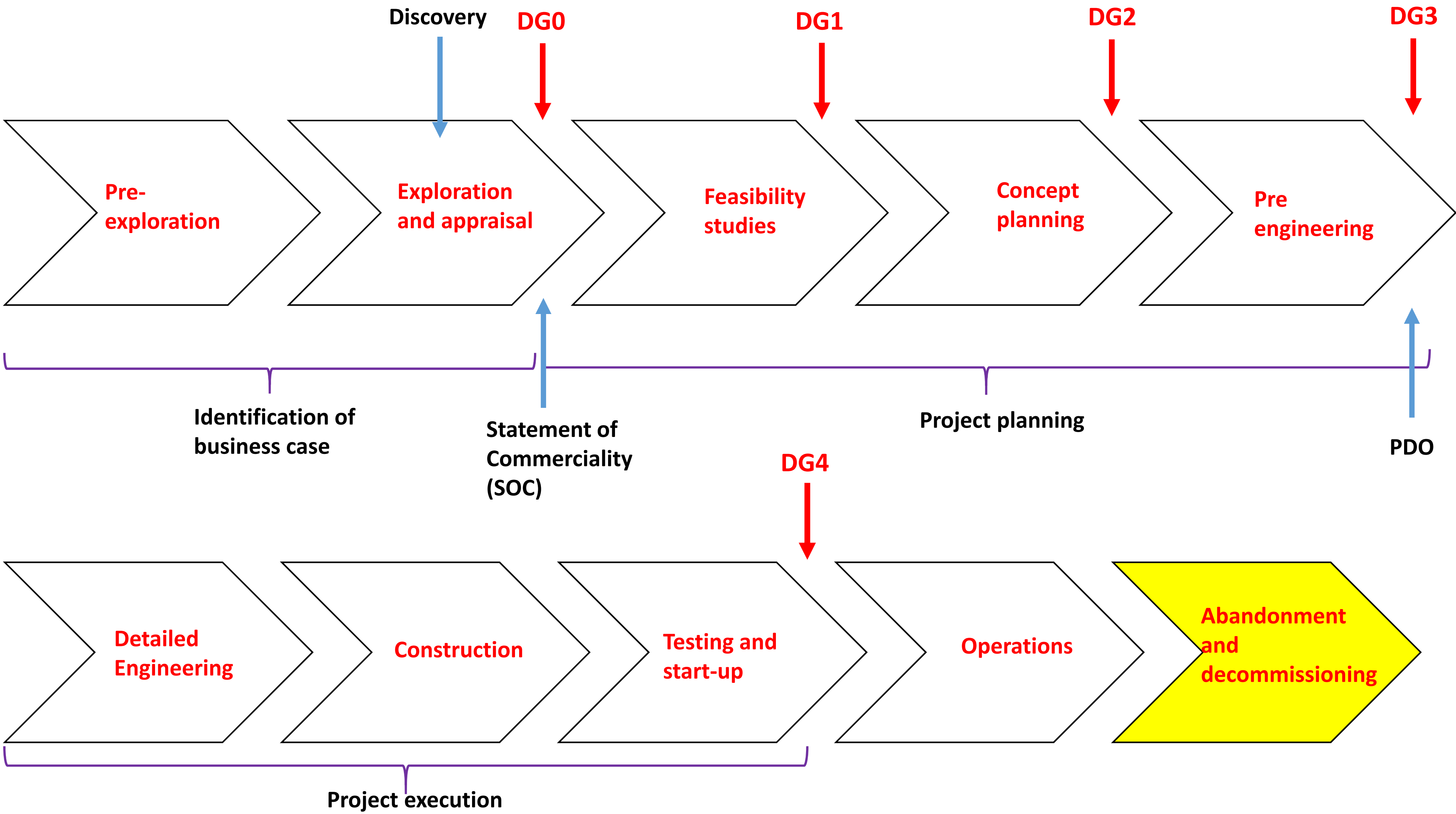
OPERATIONS

- Production startup, Build-up phase, Plateau phase, Decline phase, Tail production, Field shut-down.
- Maintenance.
- Planning Improved Oil recovery methods.
- Allocation and metering.
- De-bottlenecking.
- Troubleshooting.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DECOMISSIONING AND ABANDONMENT

- Engineering “down and clean”: flushing and cleaning tanks, processing equipment, piping.
- Coordinate with relevant environmental and governmental authorities.
- Well plugging and abandonment (P&A)
- Cut and remove well conductor and casing.
- Remove topside equipment.

DECOMISSIONING AND ABANDONMENT

- Removal of the offshore structure: Lifting operations and transport
- Remove or bury subsea pipelines
- Mark and register leftover installations on marine maps
- Monitoring
- Recovery of material: Scrap (steel) and recycling equipment (Gas turbines, separators, heat exchangers, pumps, processing equipment)
- Disposal of residues

DECOMISSIONING AND ABANDONMENT

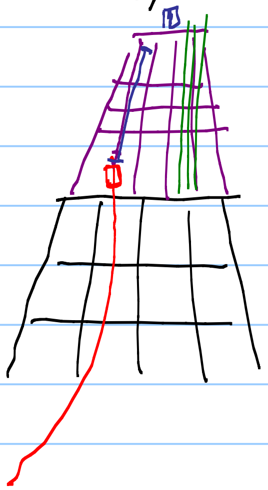
DECOMISSIONING AND ABANDONMENT

Offshore structures for oil and gas production

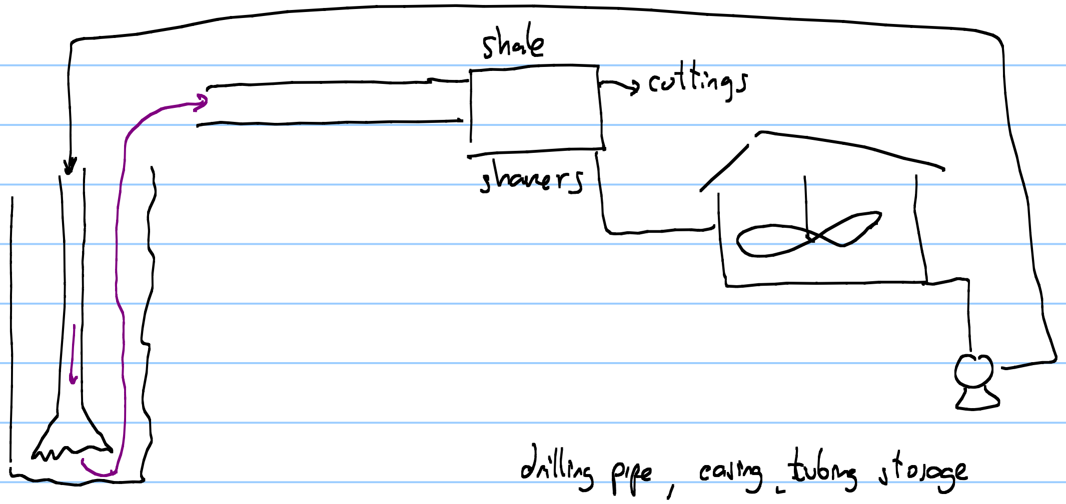
Components of offshore structure:

Blowout preventor

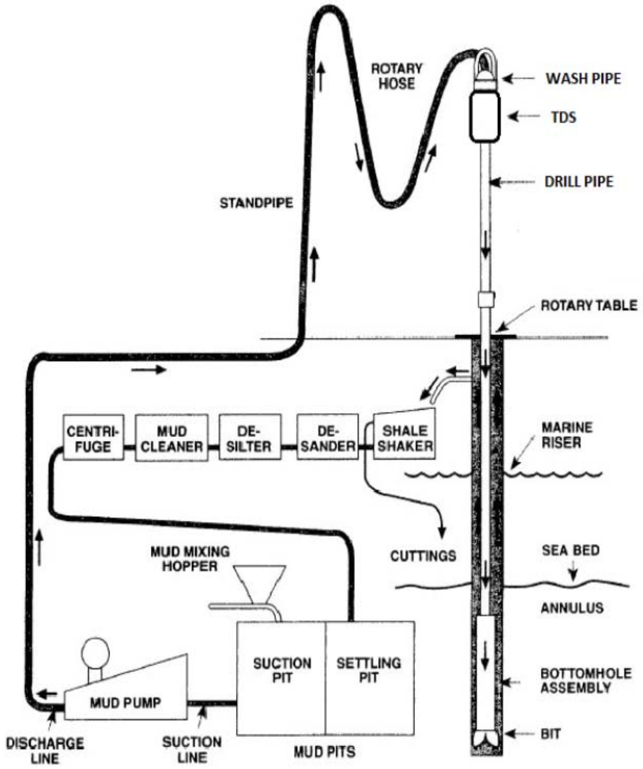
- Facilities for drilling and full intervention. This includes drilling tower, BOP, drilling floor, mud package, cementing pumps, storage deck for drill pipes and tubulars, drilling risers. (optional)
- Facilities for light well intervention. → slickline wireline → coiled tubing
- Processing facilities: separator trains for primary oil, gas and water separation, gas processing train, water processing train.
- Gas injection system
- Gas compression units for pipeline transport
- Water injection system
- Living quarters
- Helideck.
- Power generation. → gas turbines
- Flare system.
- Utilities (hydraulic power fluid, compressed air, drinking water unit, air condition system, ventilation and heating system)
- Bay for wellheads and christmas trees (optional)
- Production manifolds
- Oil storage
- Facilities for oil offloading
- Control system
- Monitoring system
- System for storage, injection and recovery of production chemicals (wax, scale , hydrate or corrosion inhibitors), emulsion inhibitor, biocide
- Repair workshop,



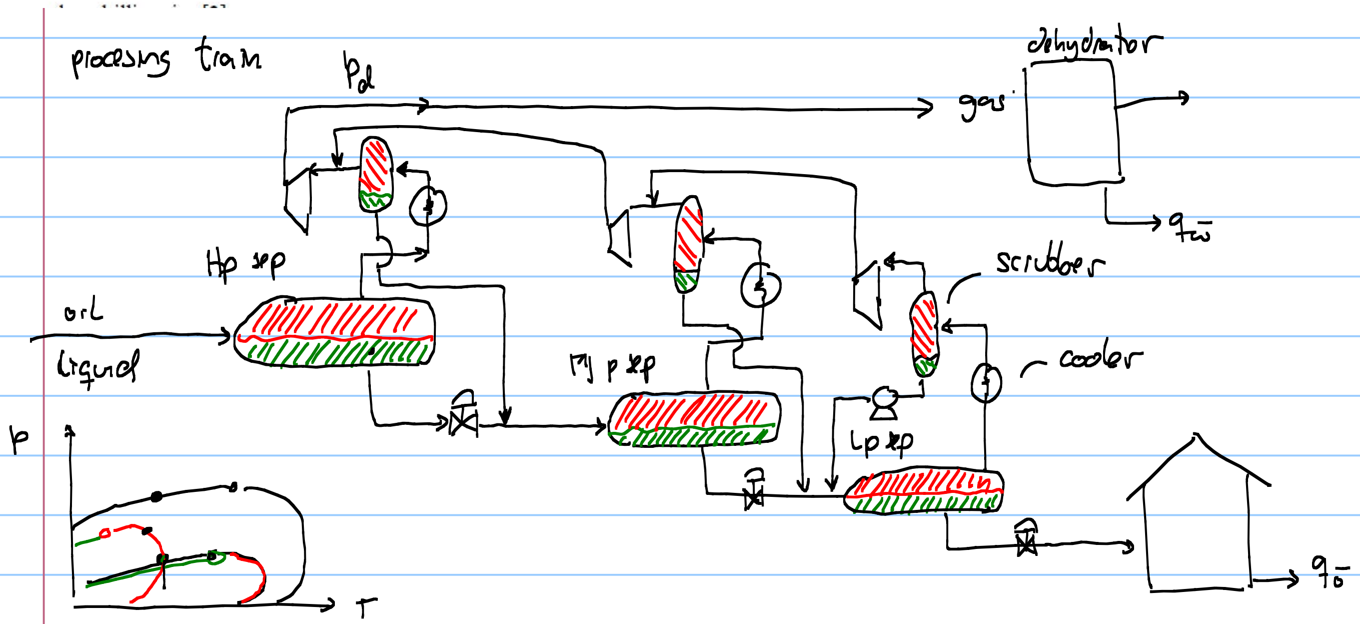
drilling tower

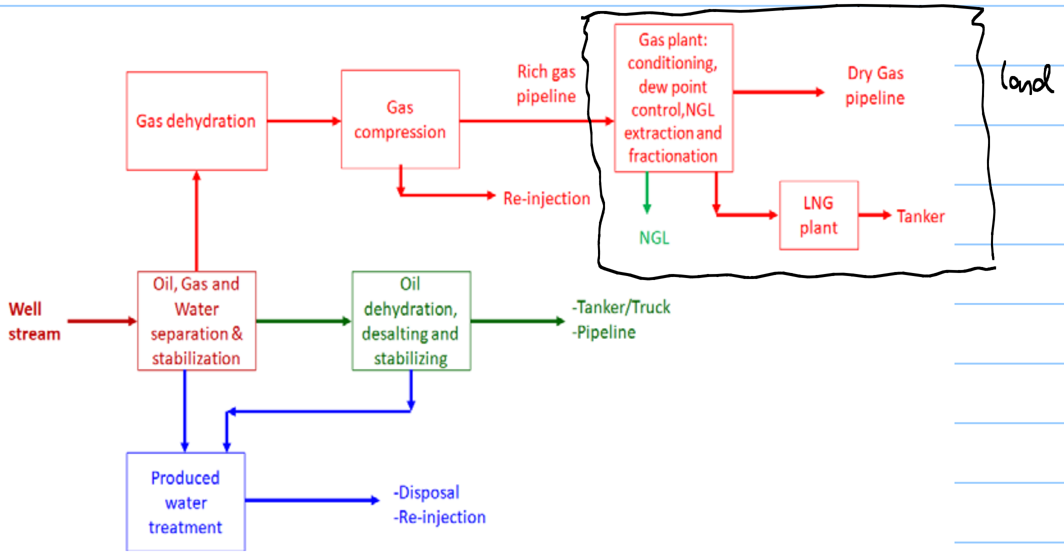


drilling pipe, casing, tubing storage



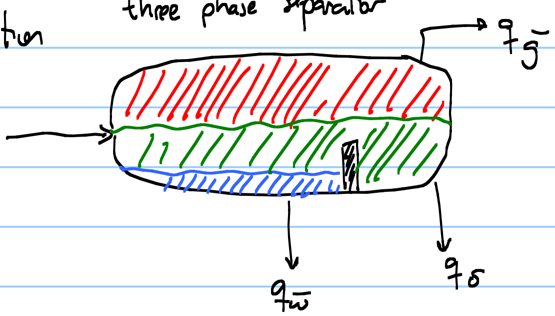
processing train

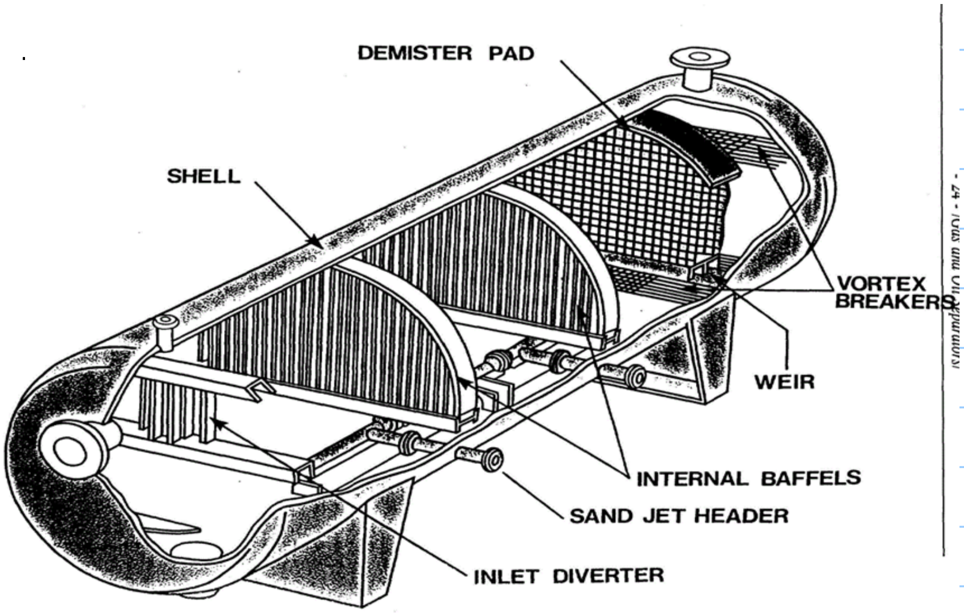




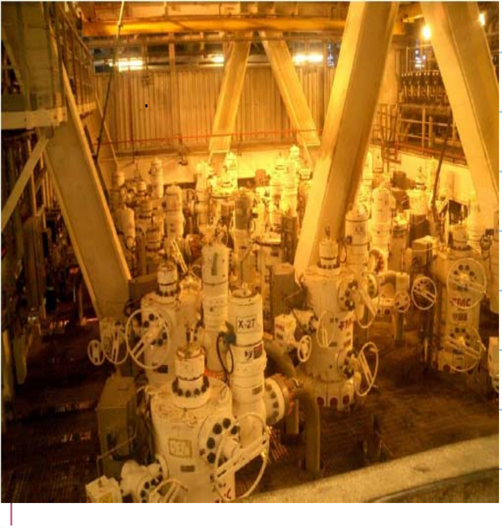
water separation

three phase separator



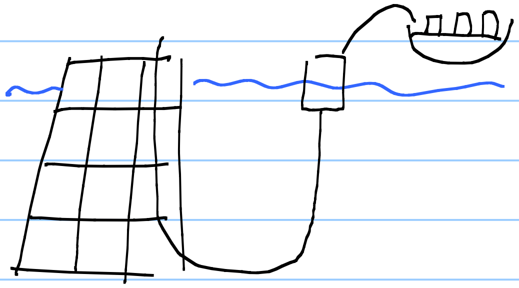


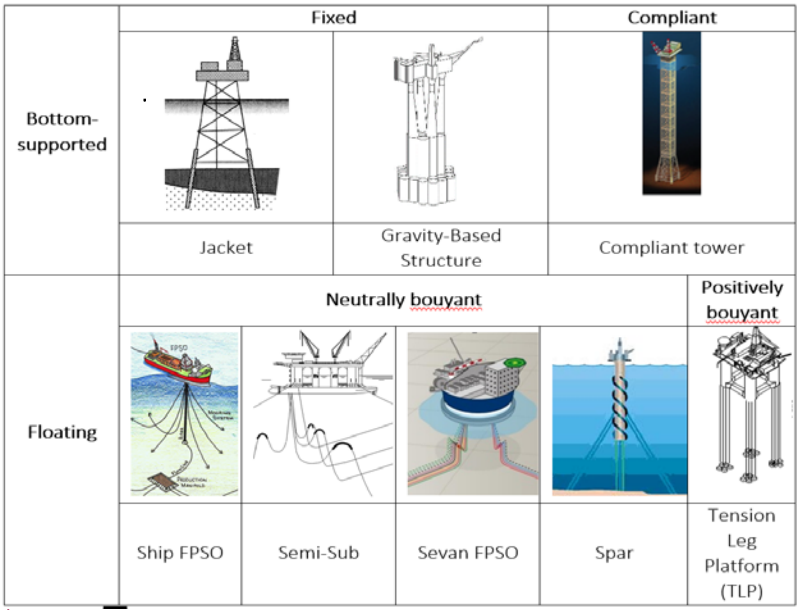
flare



well - bay

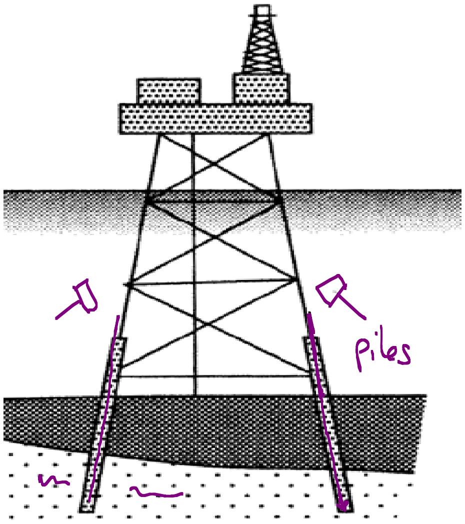
offloading facilities

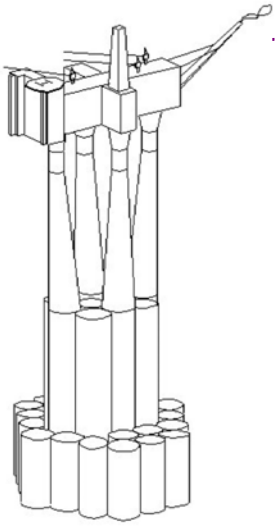


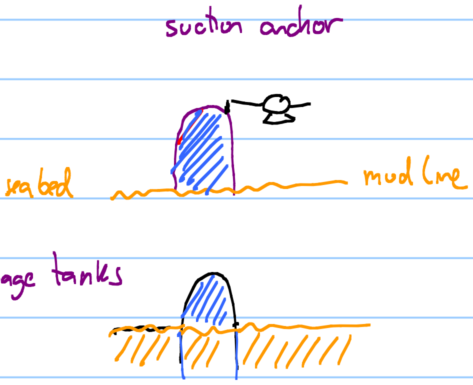


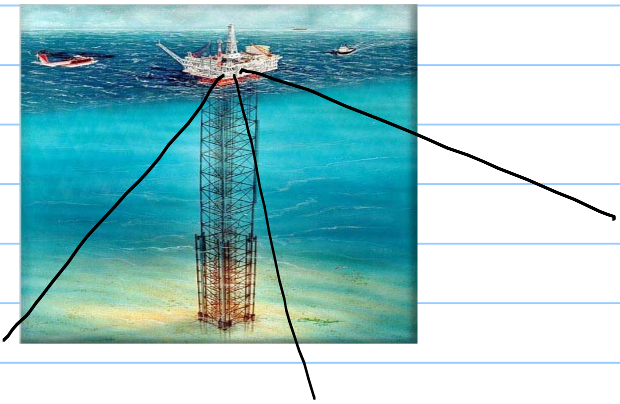
	Fixed		Compliant		
Bottom-supported	Jacket	Gravity-Based Structure	Compliant tower		
Floating	Neutrally bouyant				Positively bouyant
	Ship FPSO	Semi-Sub	Sevan FPSO	Spar	Tension Leg Platform (TLP)

fixed structure



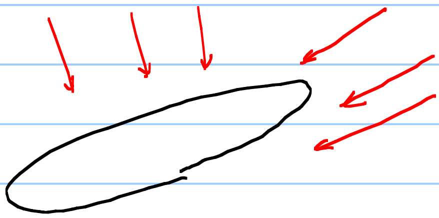


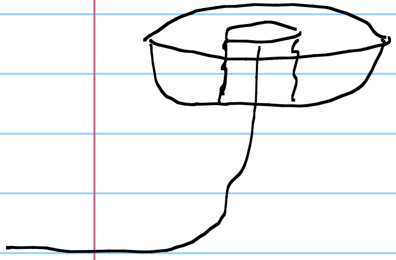


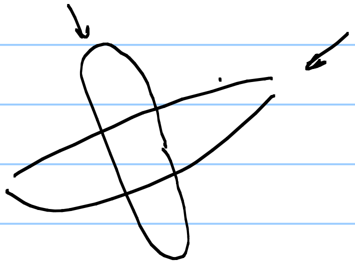


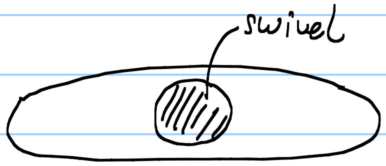
FPSO

high storage (3 E06 stb)





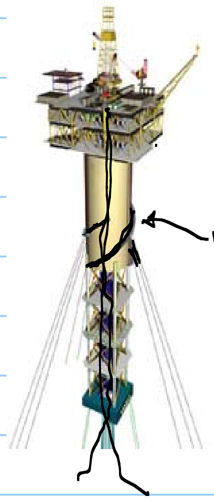


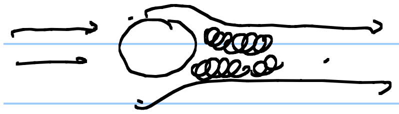


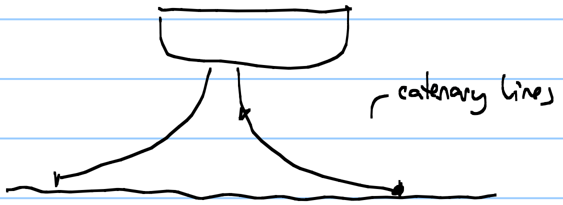
FPSO Sevan

Semi submersible
(they are used for drilling subsea)

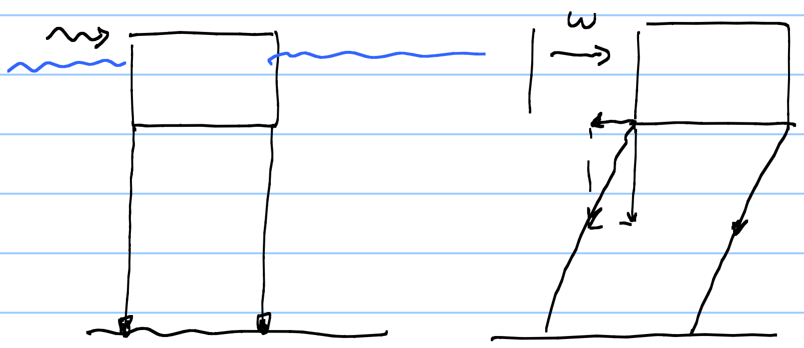
SPAR

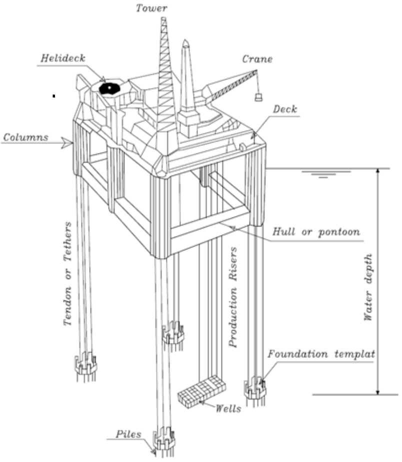






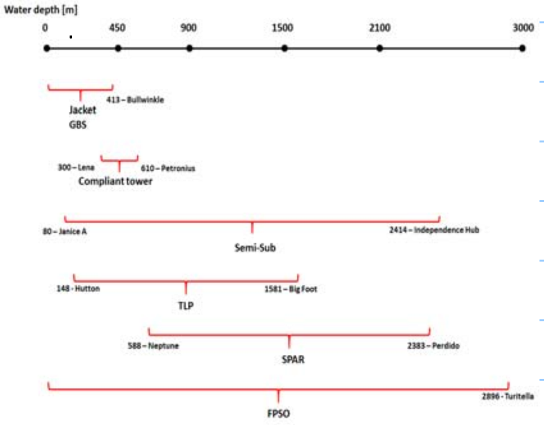
Positively bougant structure (Tension leg platform)





How do we select offshore structures?

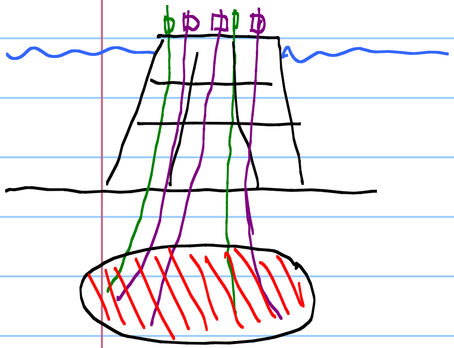
technical reasons
- 1: water depth — <600 m bottom supported structures; >600m floating structure
- 2: location of X-mas tree
- 3: oil storage
- 4: marine loads

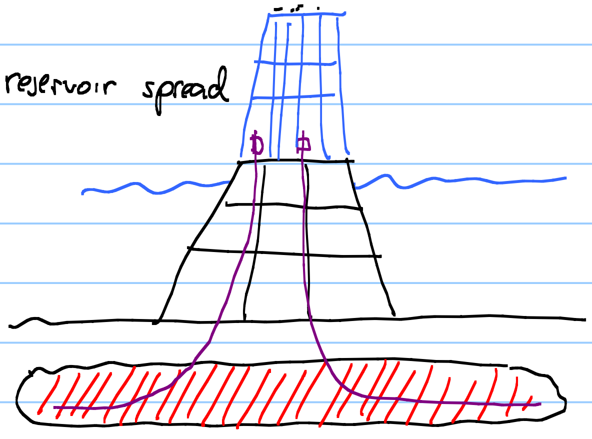


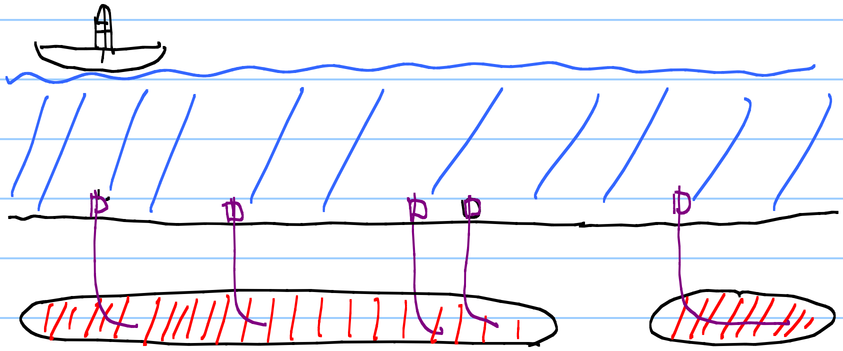
7- location of X-mas tree → under the sea
→ above the sea level

- water depth: only bottom-supported structures, TLP, SPARS allow for dry x-mas trees
  the current limit is 1500 m

- reservoir spread







- well intervention needs → tubing replacement
  → completion modification
  → artificial lift
  ESP lifetime 6month – 2 years
  no pump 5 years +

If frequent intervention is needed → dry X-mas trees
If " " is not needed → wet x-mas trees

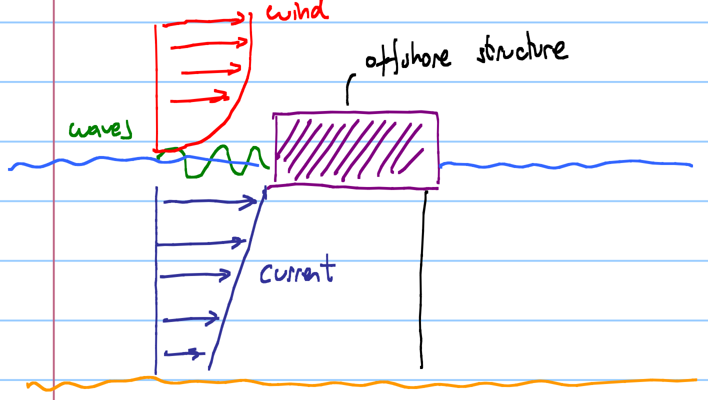
- infill drilling? → yes subsea well might be more suitable. (limited space in platform)

③ oil storage? → remoteness
→ weather conditions → yes!

Structures with storage are GBS, FPSO

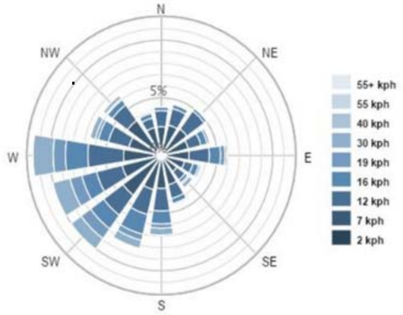
SPAR ~ 150000 stb

- marine loads

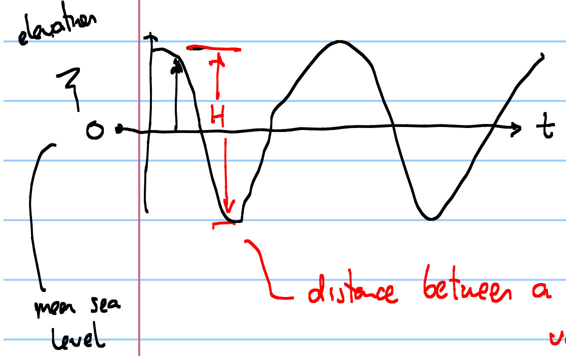


- wind a fixed value is used for design

  it's important to look at orientation



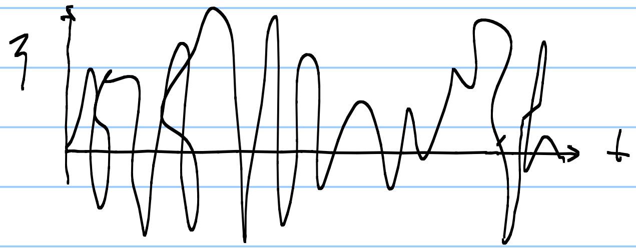
- waves



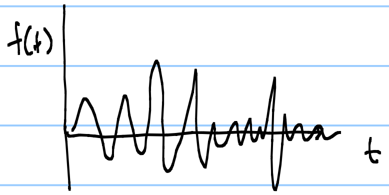
distance between a consequtive peak and valley

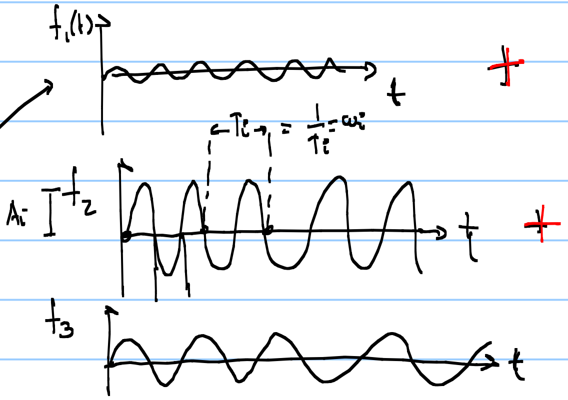
- currents: typically a constant value is used

  it is important to look at variation with depth

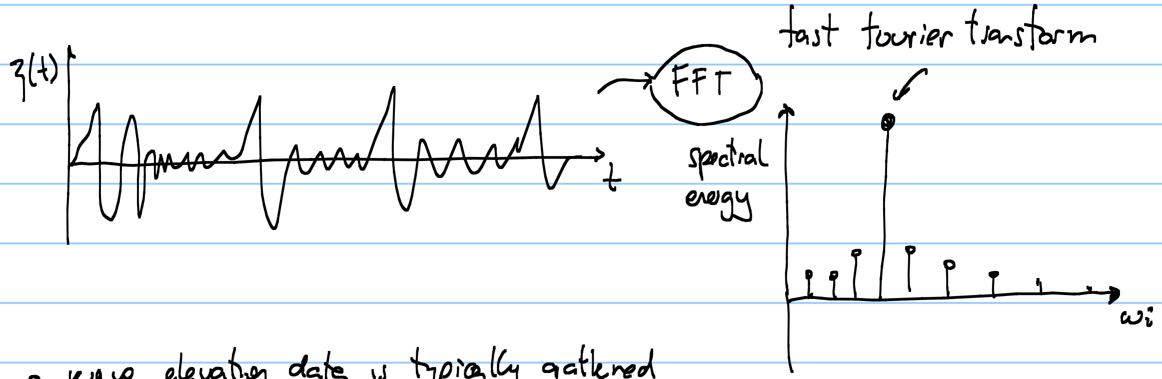


Fourier (french mathematician)

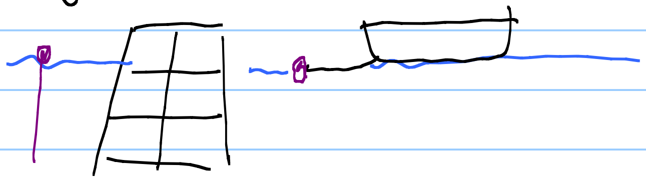


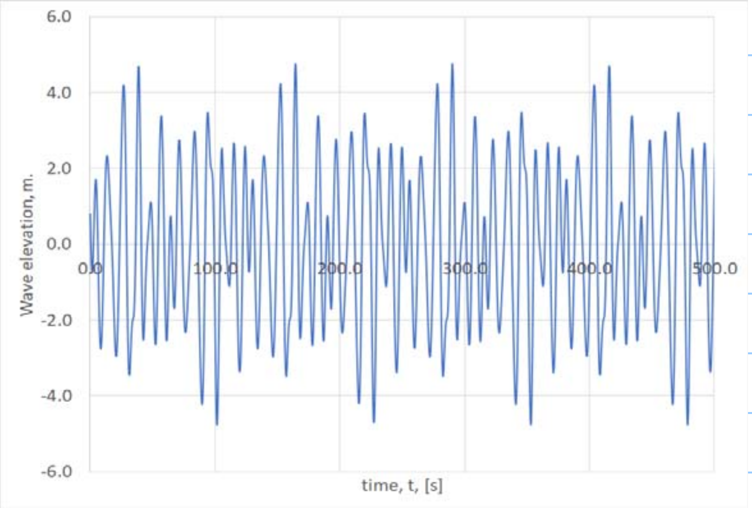


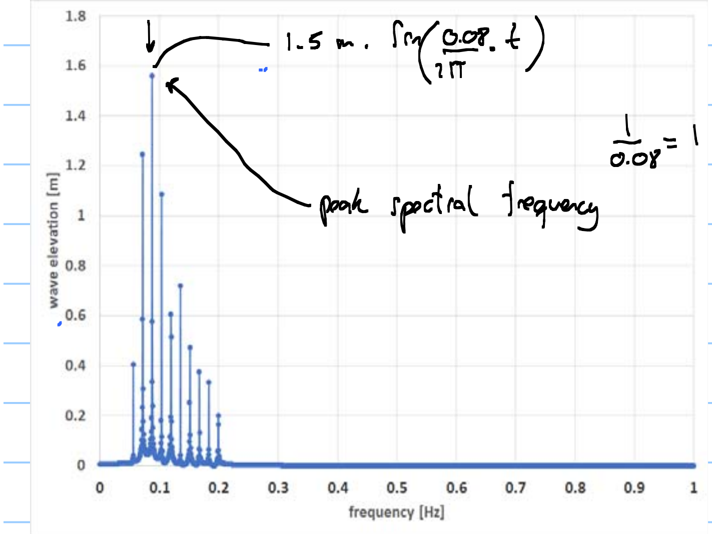
$$f(t) = \sum_{i=1}^{\infty} A_i \sin(\omega_i t - \delta_i)$$



- wave elevation data is typically gathered with bouys

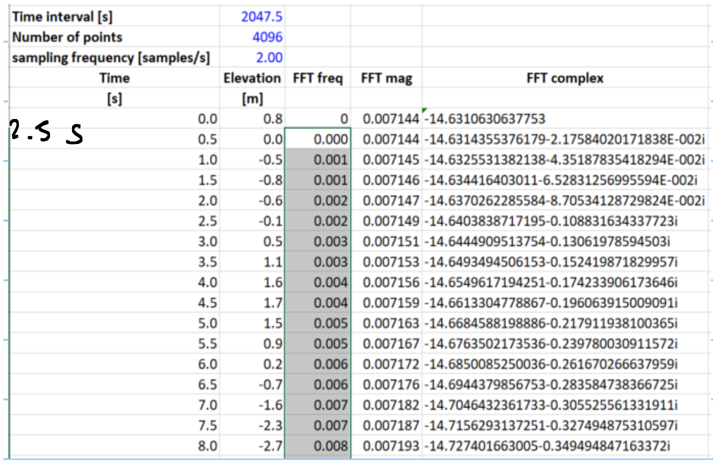






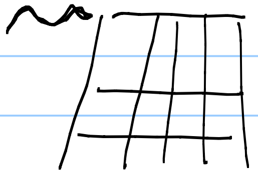
$1.5\ \mathrm{m}\cdot\sin\left(\frac{0.08}{2\pi}\cdot t\right)$

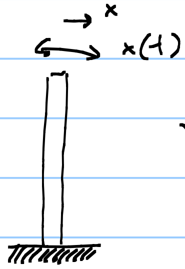
$\frac{1}{0.08} = 12.5\ \mathrm{s}$

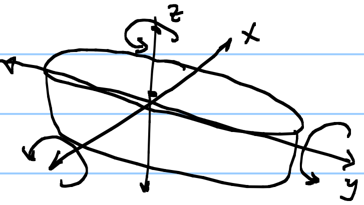


Time interval [s]	2047.5			
Number of points	4096			
sampling frequency [samples/s]	2.00			
Time [s]	Elevation [m]	FFT freq	FFT mag	FFT complex
0.0	0.8	0	0.007144	-14.6310630637753
0.5	0.0	0.000	0.007144	-14.6314355376179-2.17584020171838E-002i
1.0	-0.5	0.001	0.007145	-14.6325531382138-4.35187835418294E-002i
1.5	-0.8	0.001	0.007146	-14.634416403011-6.52831256995594E-002i
2.0	-0.6	0.002	0.007147	-14.6370262285584-8.70534128729824E-002i
2.5	-0.1	0.002	0.007149	-14.6403838717195-0.108831634337723i
3.0	0.5	0.003	0.007151	-14.6444909513754-0.13061978594503i
3.5	1.1	0.003	0.007153	-14.6493494506153-0.152419871829957i
4.0	1.6	0.004	0.007156	-14.6549617194251-0.174233906173646i
4.5	1.7	0.004	0.007159	-14.6613304778867-0.196063915009091i
5.0	1.5	0.005	0.007163	-14.6684588198886-0.217911938100365i
5.5	0.9	0.005	0.007167	-14.6763502173536-0.239780030911572i
6.0	0.2	0.006	0.007172	-14.6850085250036-0.261670266637959i
6.5	-0.7	0.006	0.007176	-14.6944379856753-0.283584738366725i
7.0	-1.6	0.007	0.007182	-14.7046432361733-0.305525561331911i
7.5	-2.3	0.007	0.007187	-14.7156293137251-0.327494875310597i
8.0	-2.7	0.008	0.007193	-14.727401663005-0.349494847163372i

offshore structures move in different ways

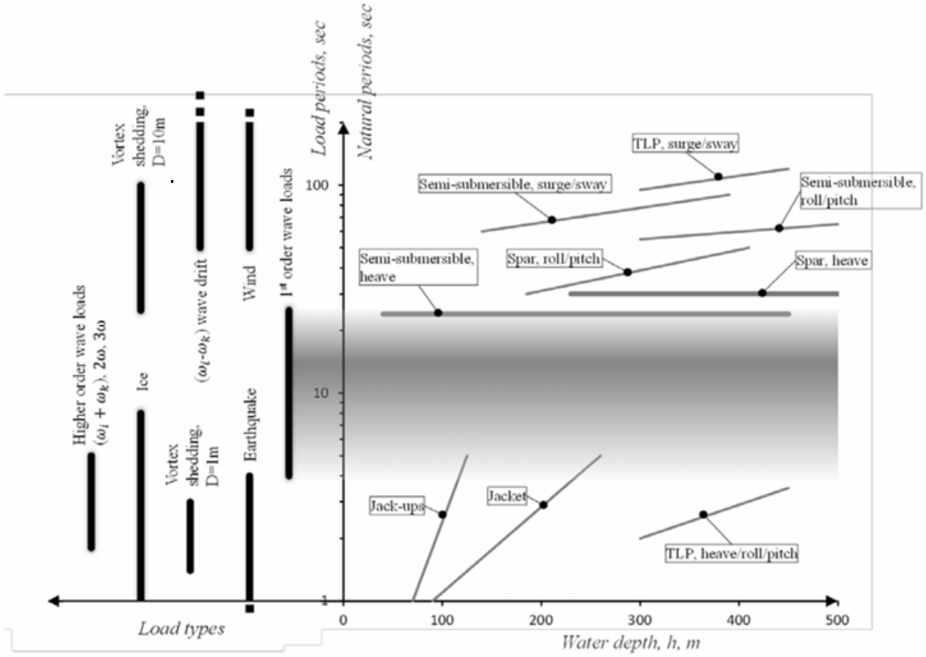






natural frequency

if wave frequency is close to the natural frequency of structure then movement will be maximum, stress will also be maximum ~> high risk of failure



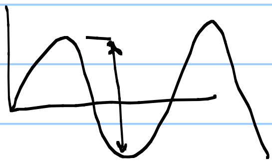
$$T = \frac{1}{\omega}$$

1 assumption to gathe wave data: sea state is a period of (3hrs) time when the spectral period doesn't change much

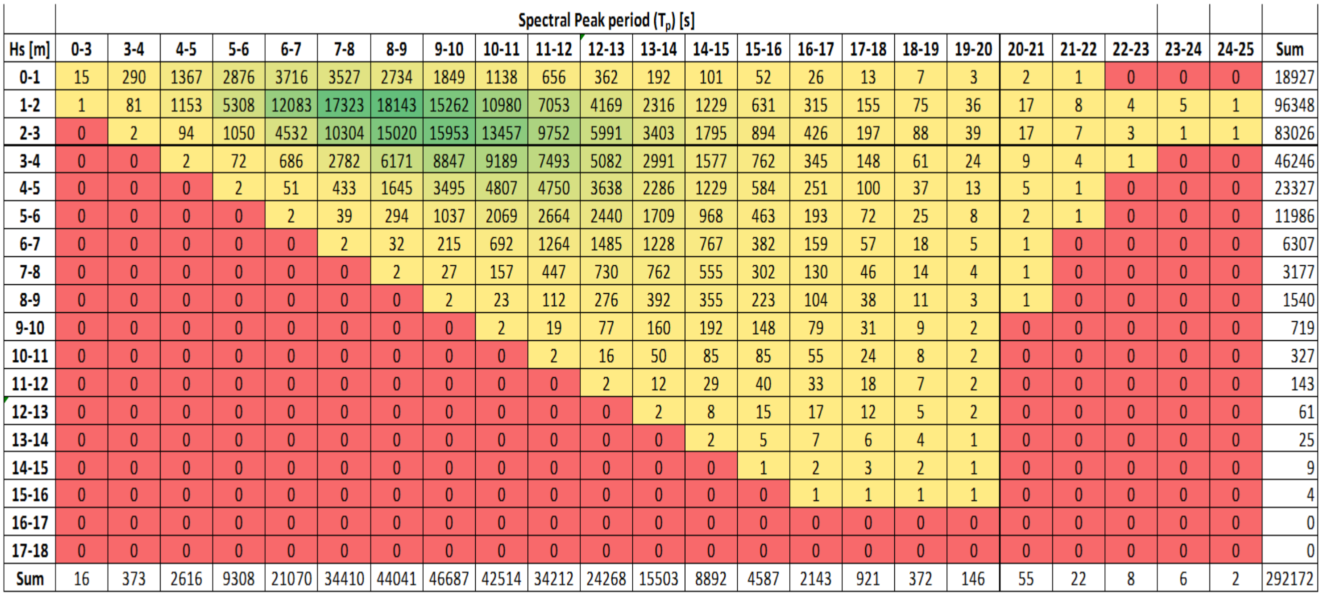
peak spectral period

period of time	tp	Hs
1	12,5	( )
2	9	( )
3	2	( )
4		
5		
100.000		

significant wave height



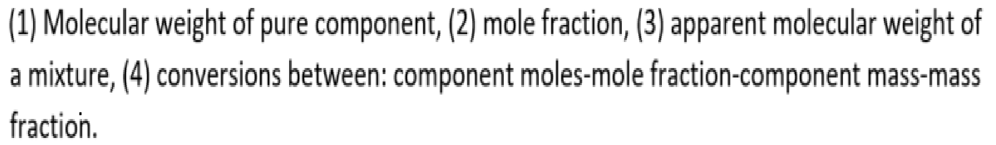
- visualize sea-state data



	Spectral Peak period (T_p) [s]																							
Hs [m]	**0-3**	**3-4**	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-24**	**24-25**	**Sum**
0-1	15	290	1367	2876	3716	3527	2734	1849	1138	656	362	192	101	52	26	13	7	3	2	1	0	0	0	18927
1-2	1	81	1153	5308	12083	17323	18143	15262	10980	7053	4169	2316	1229	631	315	155	75	36	17	8	4	5	1	96348
2-3	0	2	94	1050	4532	10304	15020	15953	13457	9752	5991	3403	1795	894	426	197	88	39	17	7	3	1	1	83026
3-4	0	0	2	72	686	2782	6171	8847	9189	7493	5082	2991	1577	762	345	148	61	24	9	4	1	0	0	46246
4-5	0	0	0	2	51	433	1645	3495	4807	4750	3638	2286	1229	584	251	100	37	13	5	1	0	0	0	23327
5-6	0	0	0	0	2	39	294	1037	2069	2664	2440	1709	968	463	193	72	25	8	2	1	0	0	0	11986
6-7	0	0	0	0	0	2	32	215	692	1264	1485	1228	767	382	159	57	18	5	1	0	0	0	0	6307
7-8	0	0	0	0	0	0	2	27	157	447	730	762	555	302	130	46	14	4	1	0	0	0	0	3177
8-9	0	0	0	0	0	0	0	2	23	112	276	392	355	223	104	38	11	3	1	0	0	0	0	1540
9-10	0	0	0	0	0	0	0	0	2	19	77	160	192	148	79	31	9	2	0	0	0	0	0	719
10-11	0	0	0	0	0	0	0	0	0	2	16	50	85	85	55	24	8	2	0	0	0	0	0	327
11-12	0	0	0	0	0	0	0	0	0	0	2	12	29	40	33	18	7	2	0	0	0	0	0	143
12-13	0	0	0	0	0	0	0	0	0	0	0	2	8	15	17	12	5	2	0	0	0	0	0	61
13-14	0	0	0	0	0	0	0	0	0	0	0	0	2	5	7	6	4	1	0	0	0	0	0	25
14-15	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	3	2	1	0	0	0	0	0	9
15-16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	4
16-17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17-18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sum	16	373	2616	9308	21070	34410	44041	46687	42514	34212	24268	15503	8892	4587	2143	921	372	146	55	22	8	6	2	292172

I have to select an offshore structure which natural period is NOT the most fequent spectral peak period in this chart !

Michael Golan refreshment of concepts



(1) Molecular weight of pure component, (2) mole fraction, (3) apparent molecular weight of a mixture, (4) conversions between: component moles-mole fraction-component mass-mass fraction.

$$\overset{2+16}{H_2O} \qquad Mw = 18 \ \frac{kg}{kmol} \ \frac{g}{mol}$$

exercise : air : 18 mol O_2

78 mol N_2

4 mol CO_2

$$x_{O_2} = \frac{18}{18+78+4}$$

$x_{O_2} = 0.18$

$x_{N_2} = 0.78$

$x_{CO_2} = 0.04$

O_2 → $Mw=32$

N_2 → $Mw=28$

CO_2 → $Mw = 48$

Mwair ? $Mwair = Mw_{O_2} \cdot x_{O_2} + MW_{N_2} \cdot x_{N_2} + MW_{CO_2} \cdot x_{CO_2}$

$Mwair = 32 \cdot 0.18 + 28 \cdot 0.78 + 48 \cdot 0.04$

$Mwair = 29.52$

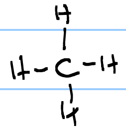
$Mwair = 28.97$ in petroleum

for gases $\gamma_g = \frac{MW_{gas}}{MW_{air}}$ $\gamma_g = 0.8$ $MW_{gas} = ?$

specific gas gravity

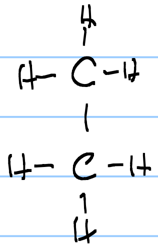
$MW_{gas} = 0.8 \cdot 28.97$

$MW_{gas} = 23.176$



$MW_{methane} = 16$

$MW_{ethane} = 30$



mol $\frac{kg}{kmol}$ $\frac{g}{mol}$

mass fraction? [y]

$$y_{O_2} = \frac{m_{O_2}}{m_T} = \frac{(n_{O_2} \cdot MW_{O_2})}{n_T \cdot MW_{air}} =$$

mas fraction $y_{O_2} = x_{O_2} \cdot \left(\frac{Mw_{O_2}}{Mw_{air}}\right)$

mole fraction

$$y_{O_2} = \frac{18 \quad 32}{100 \text{ moles} \cdot 29.52} = 0.195$$

the end