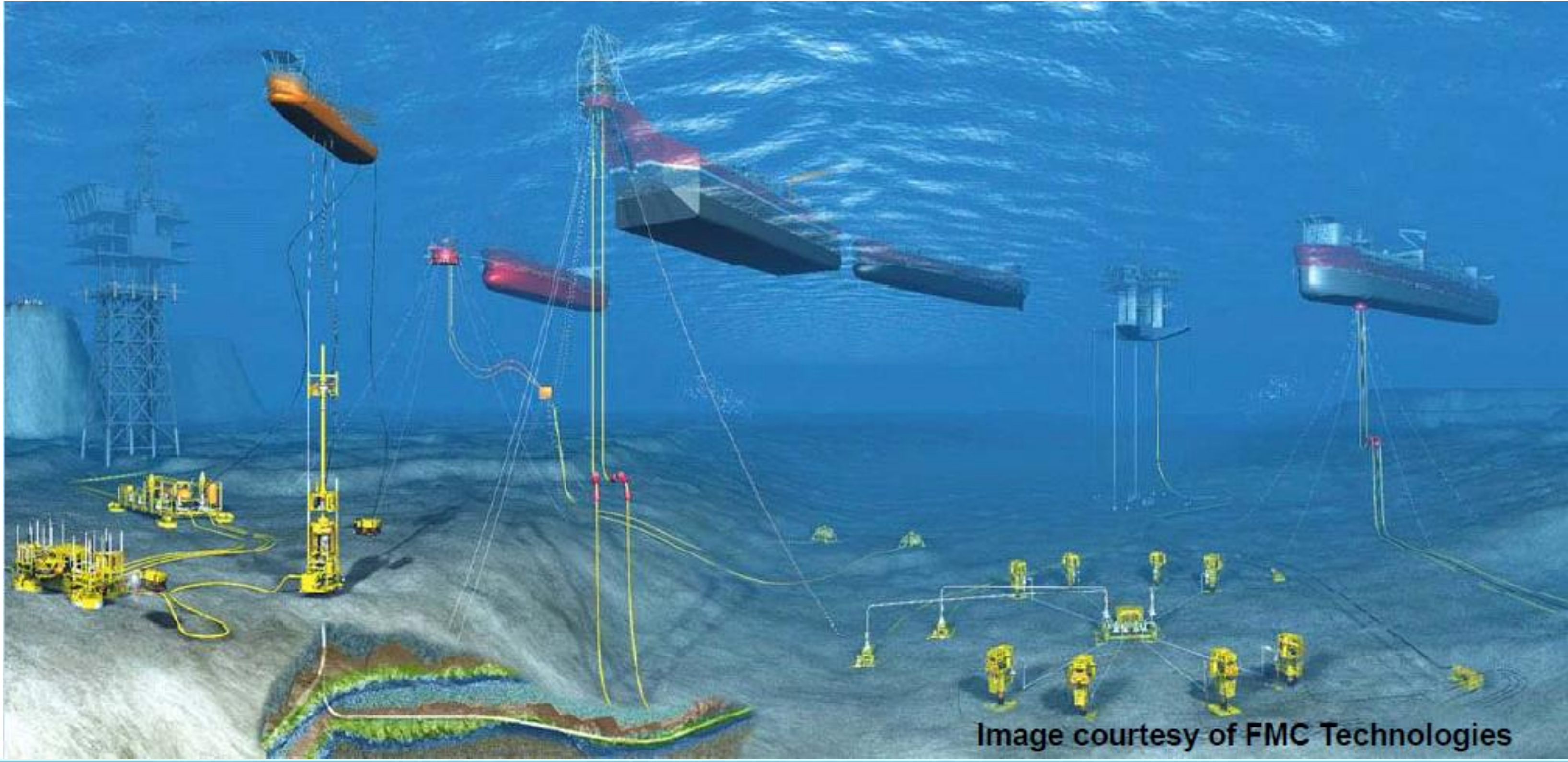


Flow Assurance

서유택

Petroleum Industry

- Upstream: Exploration and Production
- Midstream: Transportation (Field to Refinery)
- Downstream: Refining and Marketing

Upstream

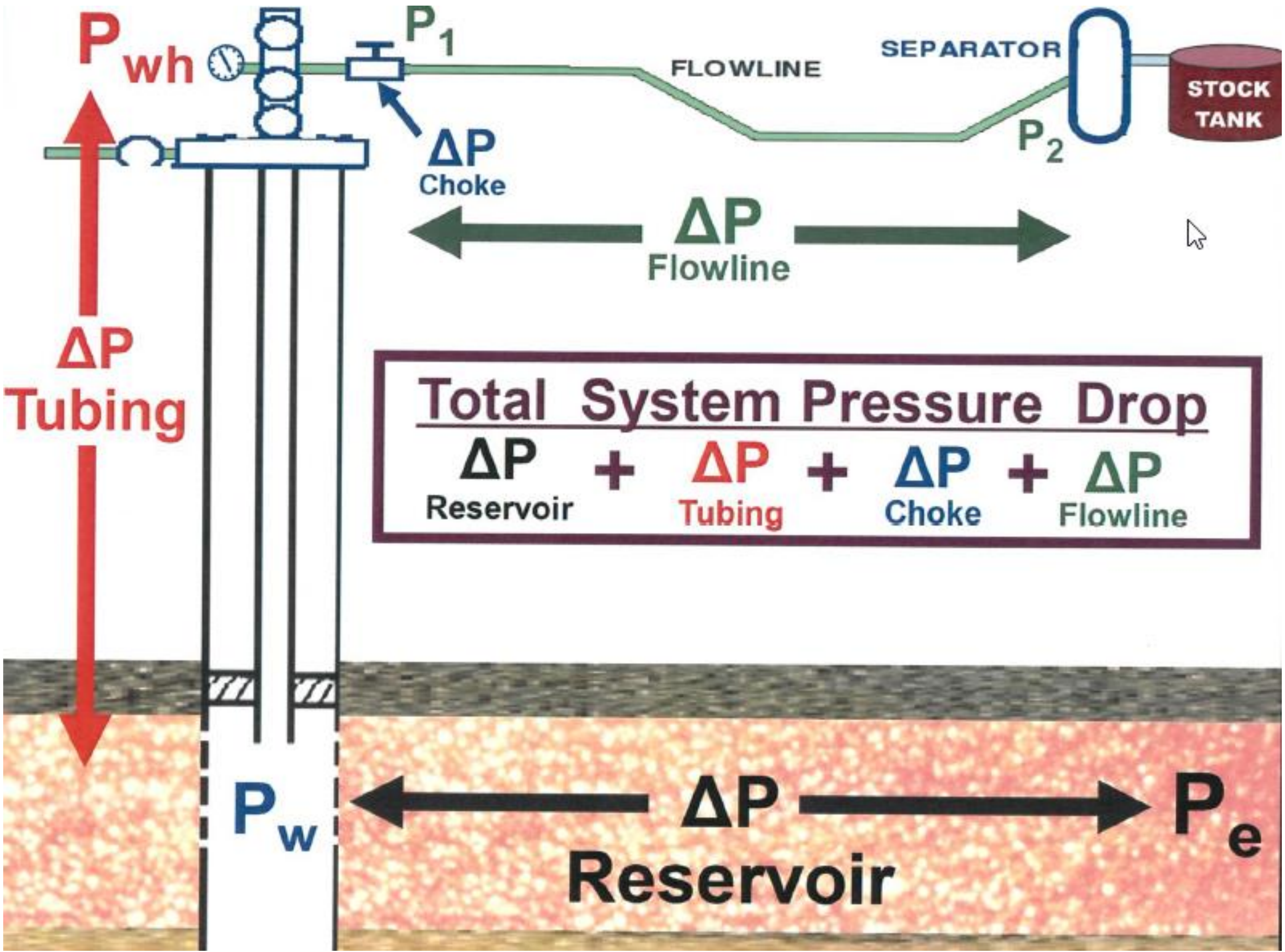
- Three major oil/gas flow systems

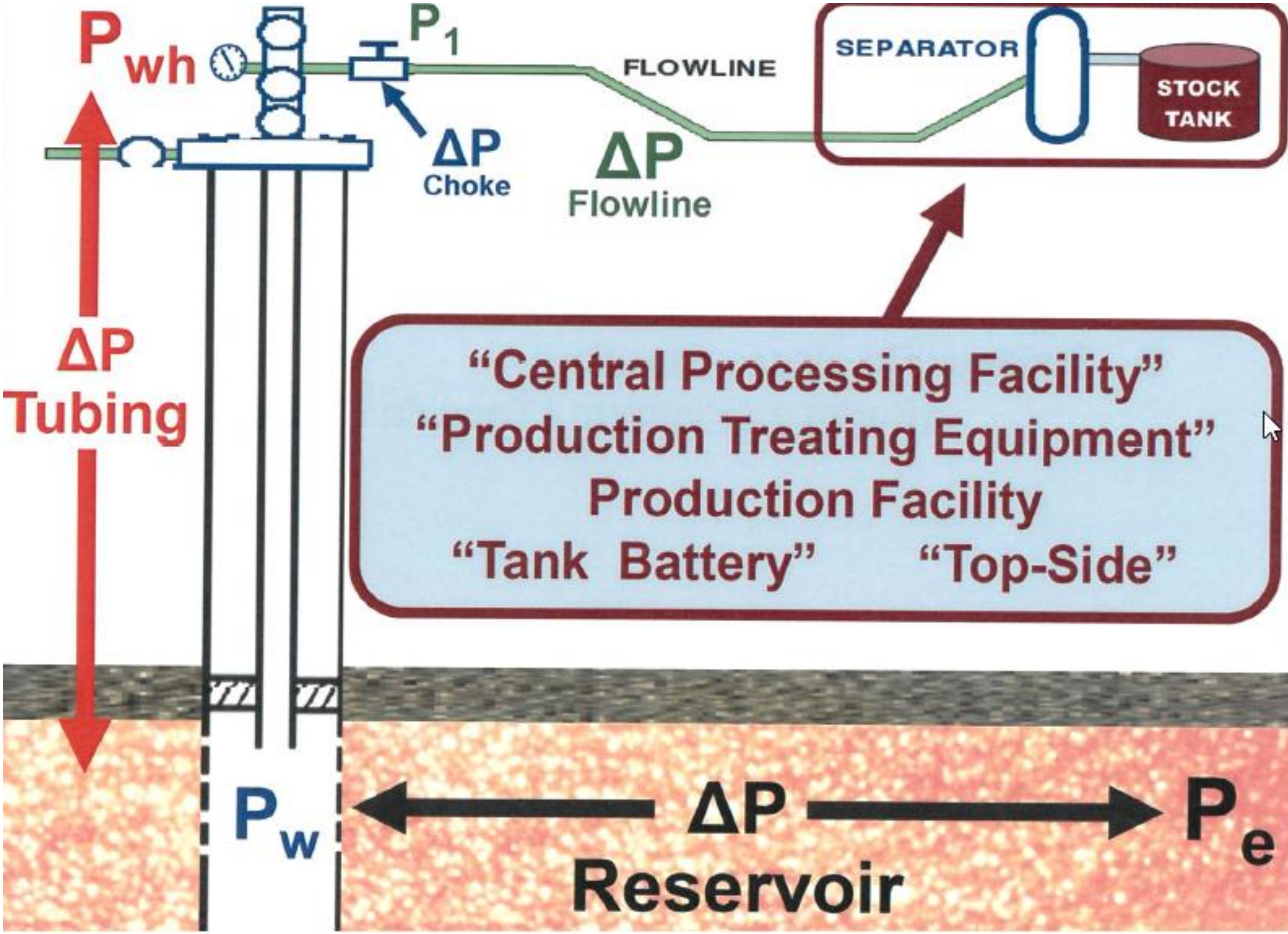
1. Reservoir

2. Wellbore (Casing/Tubing)

3. Surface (Flowline/Treating)
   (Surface/Platform/Topside/Ocean floor)

Pressure drop in flow systems

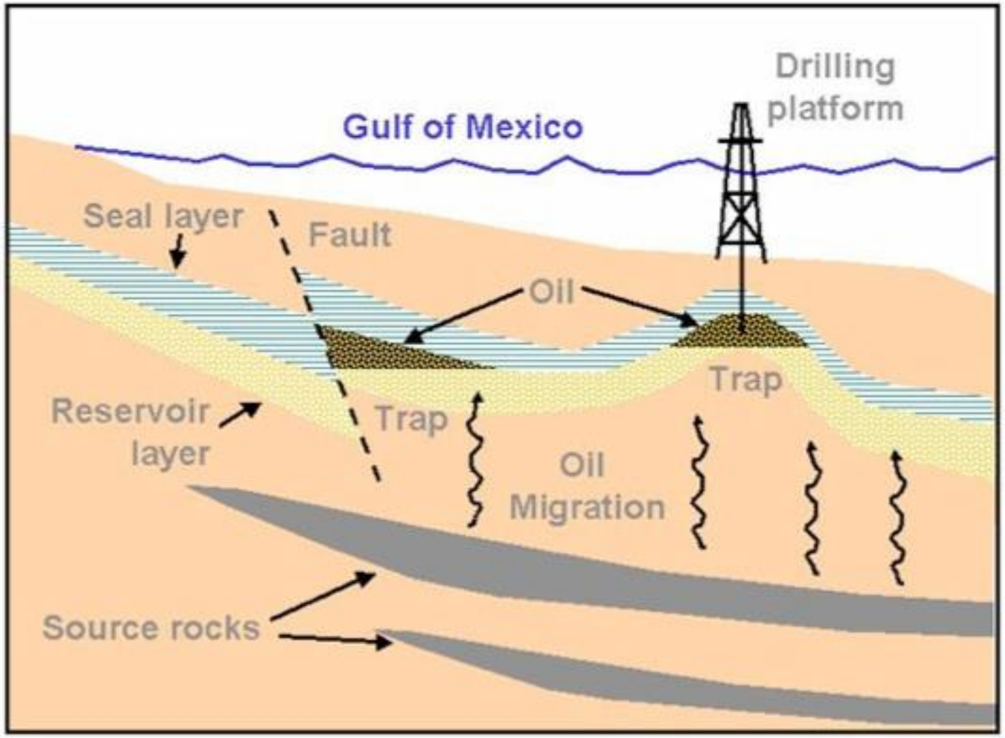




P_{wh}
P_1
FLOWLINE
SEPARATOR
STOCK TANK
ΔP Choke
ΔP Flowline
ΔP Tubing
"Central Processing Facility"
"Production Treating Equipment"
Production Facility
"Tank Battery"
"Top-Side"
P_w
ΔP Reservoir
P_e

Reservoirs

- Accumulation of hydrocarbons
  - Oil and/or Gas plus initial saturated water
  - Contaminants
  - Free water
- Trapped underground within porous and permeable rock

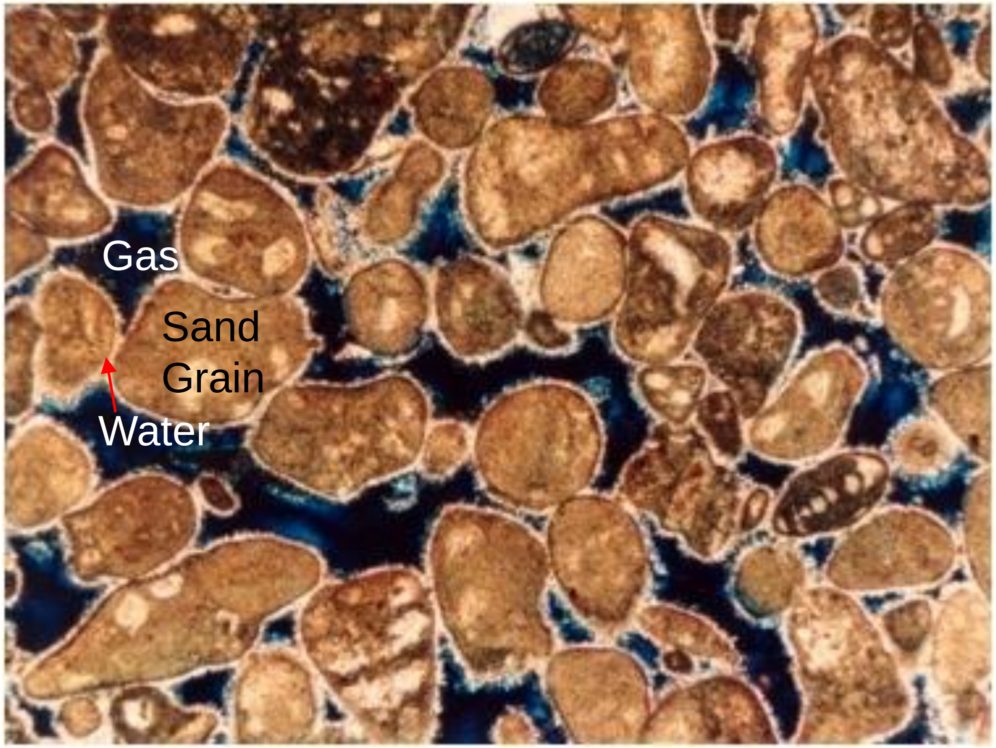


Reservoir

- Trap rock retains the hydrocarbons in the reservoir rock. Without a seal rock, hydrocarbons cannot be retained. The hydrocarbons will flow until they reach another reservoir with a trap and seal rock.
- Seal rock is impermeable and made up of fine grains or salt such as shale, anhydrite and gypsum. Its impermeability prevents the migration of hydrocarbons and retains the hydrocarbon in a reservoir under a trap.
- Reservoirs exist anywhere from the land surface to 30,000 ft (9,000 m) below the surface and are in a variety of shapes, sizes and ages. The hydrocarbons will stay in the reservoir until they are discovered, extracted and processed into oil and gas products

Reservoir rock

- Rock – Water – Reservoir fluids
- Gas in the reservoir is saturated with water vapor at reservoir condition
- For an oil reservoir to form, porous rock needs to be covered by a non-porous layer such as salt, shale, chalk or mud rock that does not allow hydrocarbons to leak from the structure.



Reservoir fluids

- Hydrocarbons: Oil and Gas

- Water
  - Irreducible
  - Mobile

- Contaminants

Reservoir fluids

- Hydrocarbon vapour – Natural gas (Gas)

- Hydrocarbon liquid
  - Oil (If liquid when in reservoir)
  - Condensate (If vapour when in reservoir)

- Fluid
  - Liquid or Vapor

  oil / condensate / water

Petroleum fluids

- Large number of petroleum compounds mixed together

- Individual molecules
  - "Hydro" or hydrogen
  - "Carbon" or carbon

- Classification:
  - Open chain vs Cyclic chain (Ring)
  - Single or Multiple carbon bonding

    : Single = saturated

    : Multiple = unsaturated

Petroleum fluids

Note:
Paraffin wax= 20<n<40

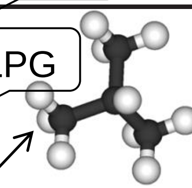
Paraffin = Alkane (C_nH_{2n+2})

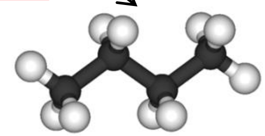
Naphthene = Cycloalkane

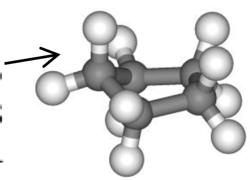
Component	Formula	Boiling Temperature at 1 atm (°C)	Density at 1 atm and 15°C (g/cm^3)
		Paraffins	
Methane	CH_4	−161.5	–
Ethane	C_2H_6	−88.3	–
Propane	C_3H_6	−42.2	–
i-Butone	C_4H_{10}	−10.2	–
n-Butane	C_4H_{10}	−0.6	—
n-Pentane	C_5H_{12}	36.2	0.626
n-Hexane	C_6H_{14}	69.0	0.659
i-Octane	C_8H_{18}	99.3	0.692
n-Decane	$C_{10}H_{22}$	174.0	0.730
Naphthenes			
Cyclopentane	C_5H_{10}	49.5	0.745
Methyl cyclo-pentane	$CH_3C_5H_{10}$	71.8	0.754
Cyclohexane	C_6H_{12}	81.4	0.779
Aromatics			
Benzene	C_6H_6	80.1	0.885
Toluene	C_7H_8	110.6	0.867
o-Xylene	C_8H_{10}	144.4	0.880
Naphthalene	$C_{10}H_8$	217.9	0.971
Others			
Nitrogen	N_2	−195.8	—
Carbon dioxide	CO_2	−78.4	—
Hydrogen sulfide	H_2S	−60.3	—

LNG

LPG





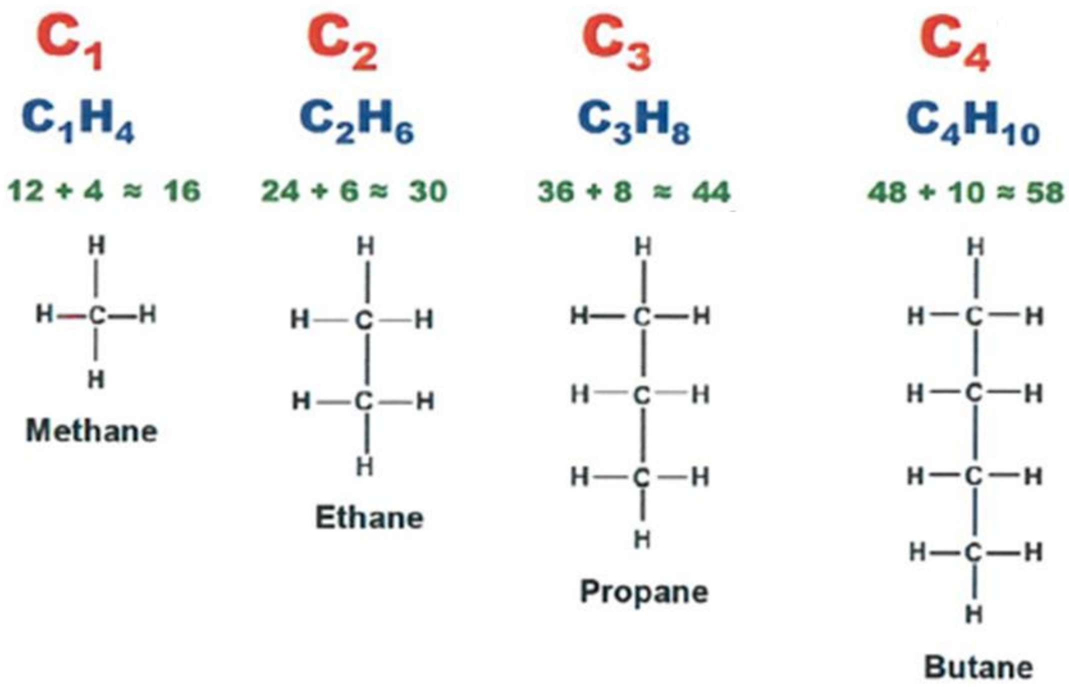


Sweet corrosion

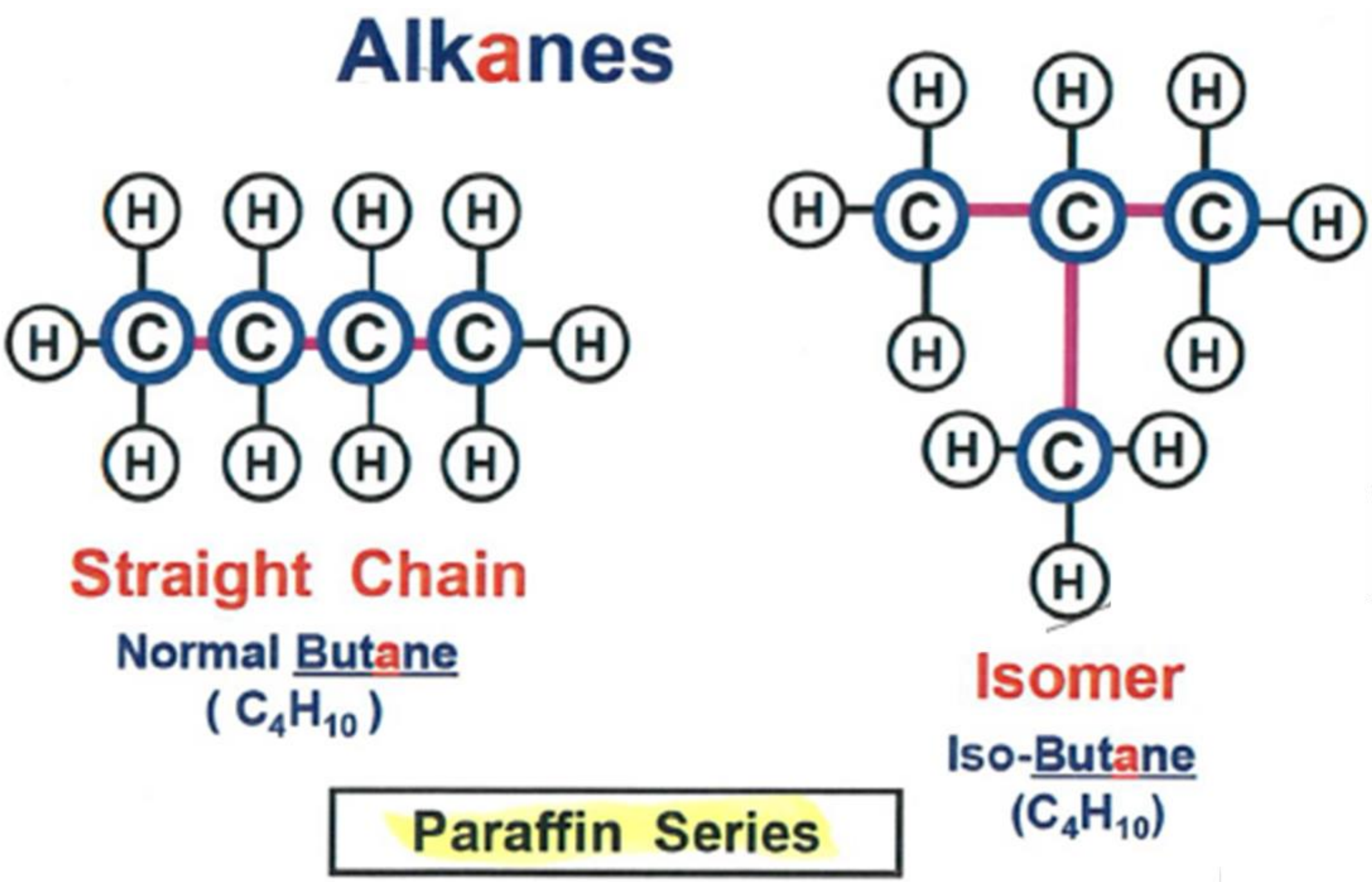
Sour corrosion

Hydrocarbon molecules

- More than C3, getting closer to the properties of liquid hydrocarbon



Open chains – Single bonds

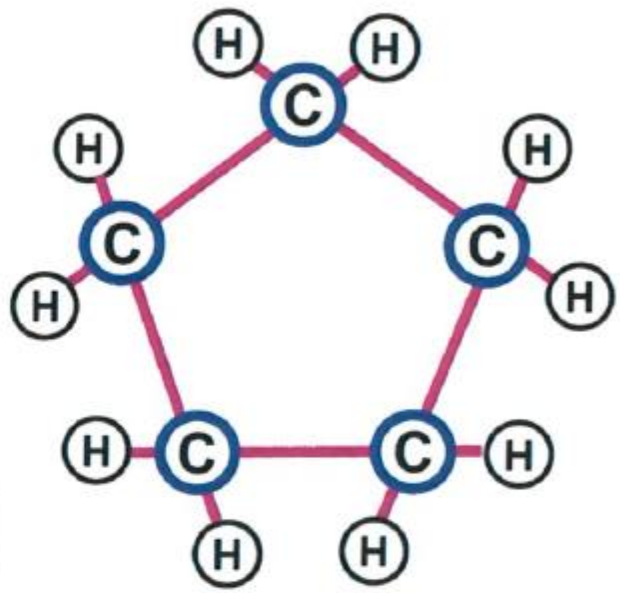


Paraffin build-up in flowline

Ring chain – Single bonds

CycloAlkanes

CycloPentane
(C_5H_{10})

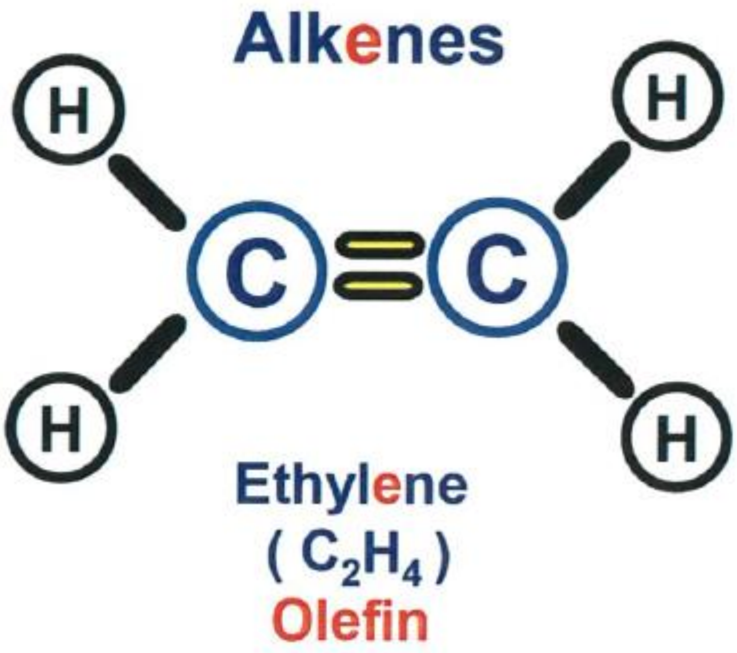


Asphaltene Series

Asphaltenes

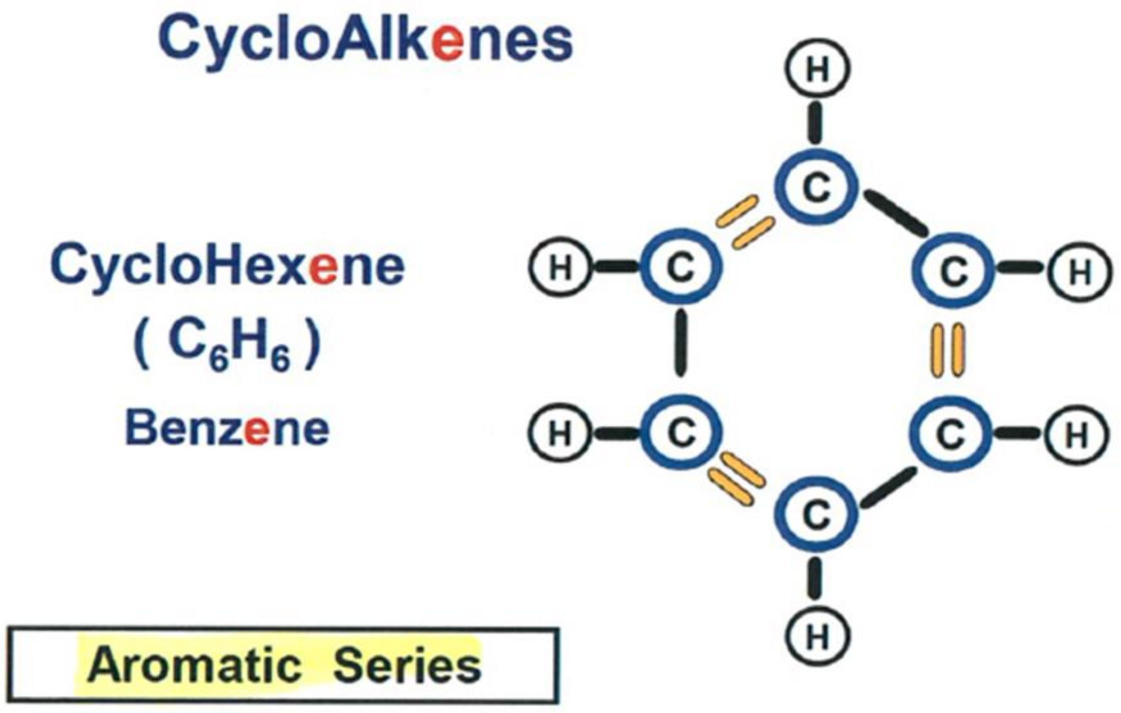
Open chain – Double bond

- Very small fraction in the reservoir



Ring chain – Double bonds

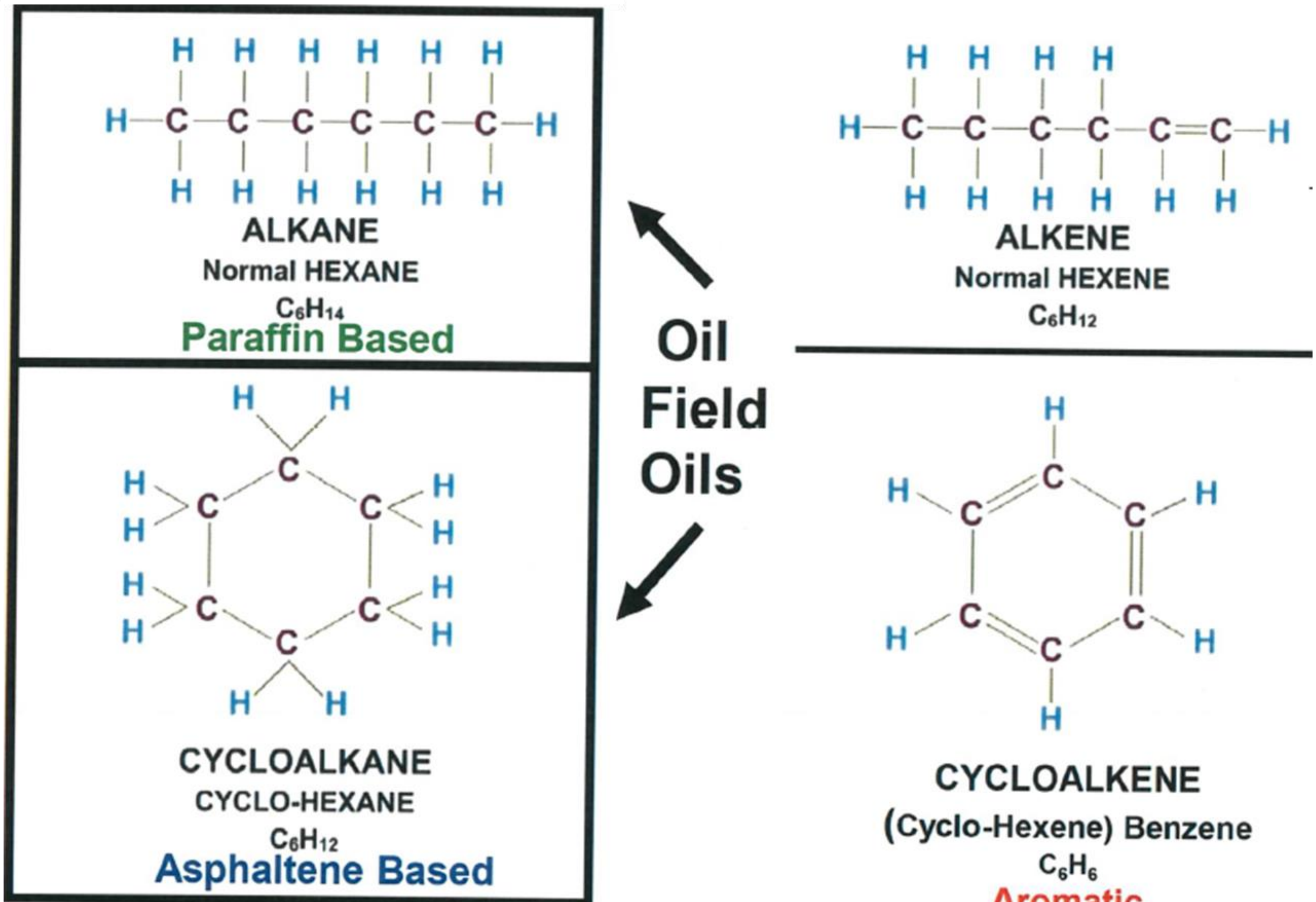
- Aromatic components: Benzene, Toluene, Ethylbenzene, Xylene (BTEX)
- Hazardous!! → must track the composition in every stream



Hydrocarbon classification

Alkane (Paraffin Series)	Open Chain	Saturated (all Single Bonds)
Alkene (Olefin Series)	Open Chain	Unsaturated (1+ Double Bond)
Cycloalkane (Asphaltene Series)	Ring Chain Cyclic	Saturated (all Single Bonds)
Cycloalkenes (Aromatic Series)	Ring Chain Cyclic	Unsaturated (1+ Double Bond)

Four H-C Series: C6



Natural Gas

- Mixture of mainly smaller sized hydrocarbons
  - Light hydrocarbons C1 – C4
  - Intermediates C5 – C9

- Described by

1. Chemical composition
   (C1, C2, C3, C4, ………….., C7+)

2. Gas specific gravity

Gas sample – chemical composition

Tech Services
2401 W. Blue Mound Rd. Haslet, TX 76052
(817) 439-0140

Source:	XYZ Oil & Gas	Report Date:	11/18/2005
Station #:	95095-2748	Sample Date:	11/18/05
Station Name:	Baker Ranch	Flowing Pressure:	243 psig
Field:	Denton/Wise Co	Flowing Temp.:	90 F

Gas Analysis by Chromatograph

NAME	MOLE % Component Molecular Fraction - %	BTU Heating Value (BTU / scf)	GPM Liquids Recovery (gals per Thousands scf)
Nitrogen	0.402	0.000	
Methane	79.643	801.876	
CO2	0.891	0.000	
Ethane	11.471	202.367	3.049
Propane	4.366	109.513	1.196
i-Butane	0.812	26.324	0.264
n-Butane	1.114	36.229	0.349
i-Pentane	0.375	14.956	0.136
n-Pentane	0.355	14.186	0.128
Hexanes+	0.571	27.072	0.233

Gas sample – chemical composition

Condensate Yield of this GAS = 5.355 Gals Per Mscf

$$\frac{5.355 \text{ Gals Per Mscf} \times 1000}{42 \text{ Gals / Bbl}} = 127.5 \text{ Bbls / MMscf}$$

Gas Analysis by Chromatograph

NAME	MOLE % Component Molecular Fraction - %	BTU Heating Value (BTU / scf)	GPM Liquids Recovery (gals per Thousands scf)
Nitrogen	0.402	0.000	
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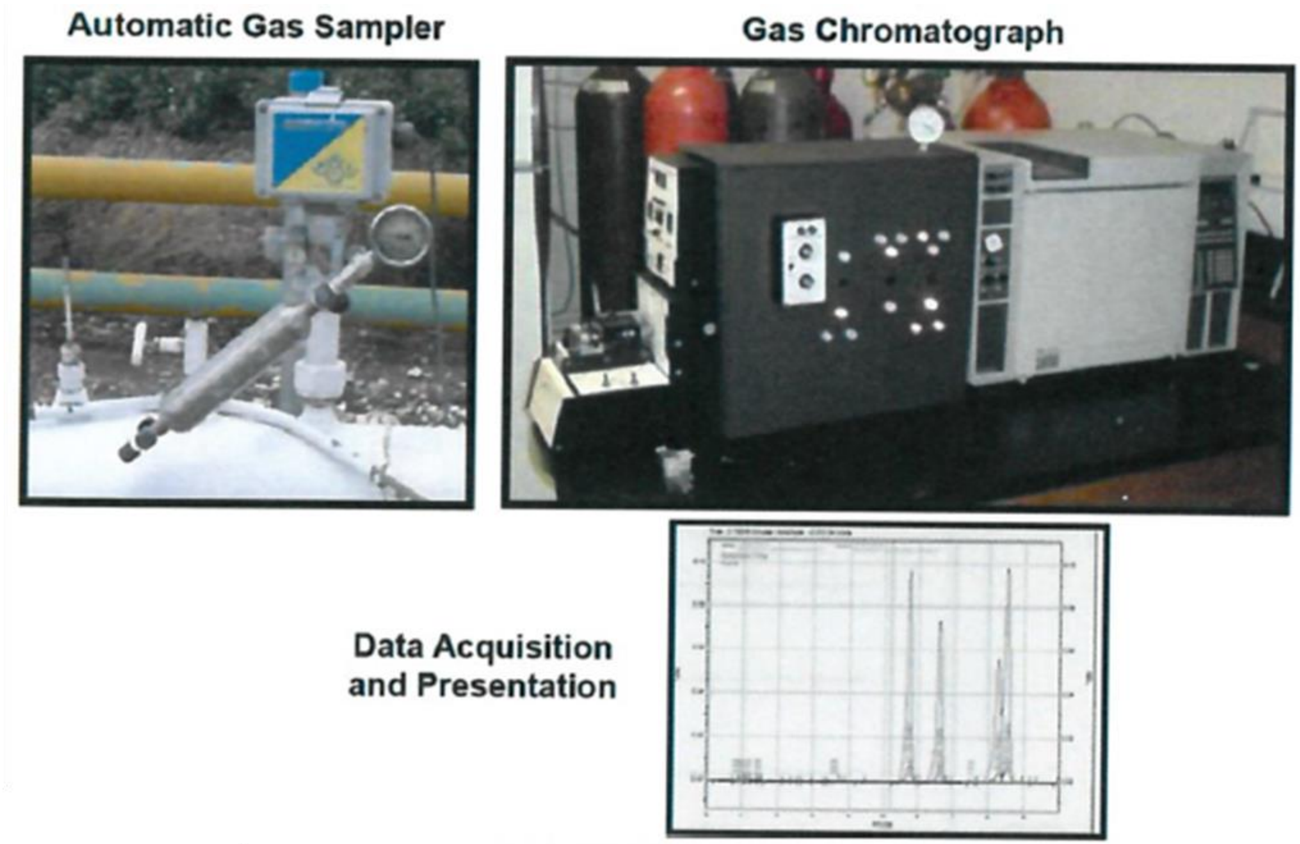
i-Pentane	0.375	14.956	0.136
n-Pentane	0.355	14.186	0.128
Hexanes+	0.571	27.072	0.233
			5.355

Gas composition – Fractional analysis



Natural Gas

- Mixture of mainly smaller sized hydrocarbons
  - Light hydrocarbons C1 – C4
  - Intermediates C5 – C9

- Described by

1. Chemical composition
   (C1, C2, C3, C4, ………….., C7+)

2. Gas specific gravity: SG_g

Gas specific gravity

$$SG_g = \frac{\text{Density of a Gas}}{\text{Density of Air}}$$

$$SG_g = \frac{\text{Molecular Weight of a Gas}}{\text{Molecular Weight of Air}}$$

Natural Gas Compositions

Component	Pluto (mol %)	NWS (mol %)	Gorgon (vol. %)	Jansz (vol. %)	Browse (mol %)	Ichthys (mol %)
N_2	8.1	0.8	2.0	2.3	0.5	0.4
CO_2	1.9	3.0	14.0	0.3	9.8	8.5
CH_4	83.0	85.3	76.7	91.5	79.3	70.0
C_2H_6	3.9	5.8	3.2	3.8	5.6	10.3
C_3H_8	1.4	2.2	0.9	1.1	2.1	4.2
C_4H_{10}	0.7	1.0	0.3	0.4	0.9	1.9
C_5+	1.4	1.9	0.1	0.6	1.8	4.4

Crude oil

- Mixture of large range of H-C (includes "Heavies")

- Described by
  1. Liquid specific gravity

$$SG_{liquid} = \frac{\text{Density of a Liquid}}{\text{Density of Fresh Water}}$$

$$\mathbf{SG_{liquid}} \rightarrow \mathbf{SG_L}$$

  2. °API (American Petroleum Institute: First standards issued in 1924)

$$°API = \frac{141.5}{SG_L} - 131.5$$

$$SG_L = \frac{141.5}{°API + 131.5}$$

Single component hydrocarbon at standard conditions

- C1 – C4: Vapor phase
- C6 – C17: Liquid phase
- C18 – + : Solid phase (paraffin, asphaltene)

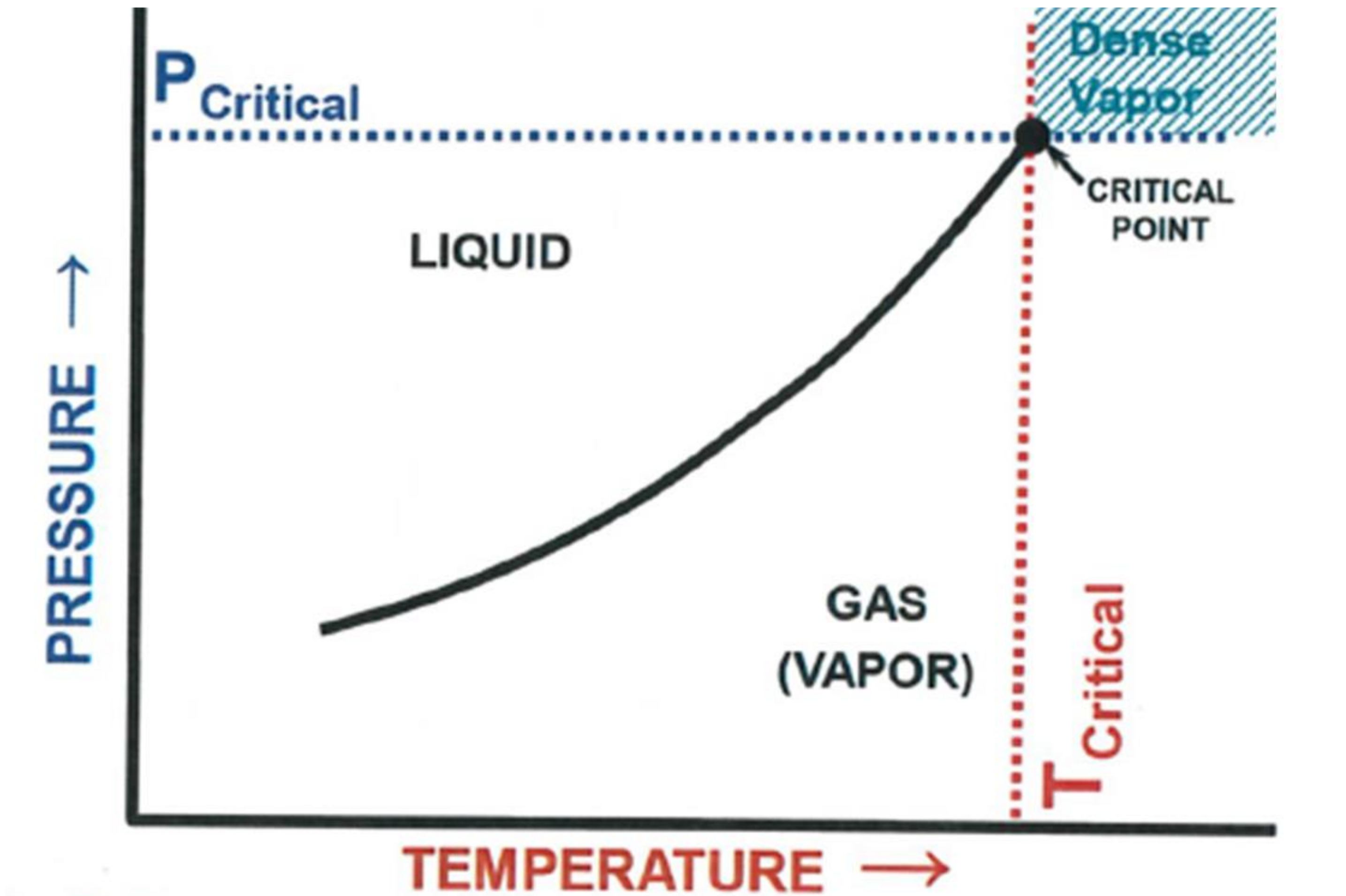
Typical oil field composition

Produced Gas		C1 – C5
Natural Fuel Gas		C1, C2, some C3
Liquefied Petroleum Gas		C3 – C5
Refined Gasoline		C7 – C10
Lubricating Oils		C15 – C30
Lubricating Greases		C40 – C80
Paving Asphalt		C100+
60+ API	Crude	C4 – C12
40+ API	Crude	C10 – C40
20+ API	Crude	C20 – C60+
10+ API	Crude	C80+

Different crude oil sample

Different crude oil samples

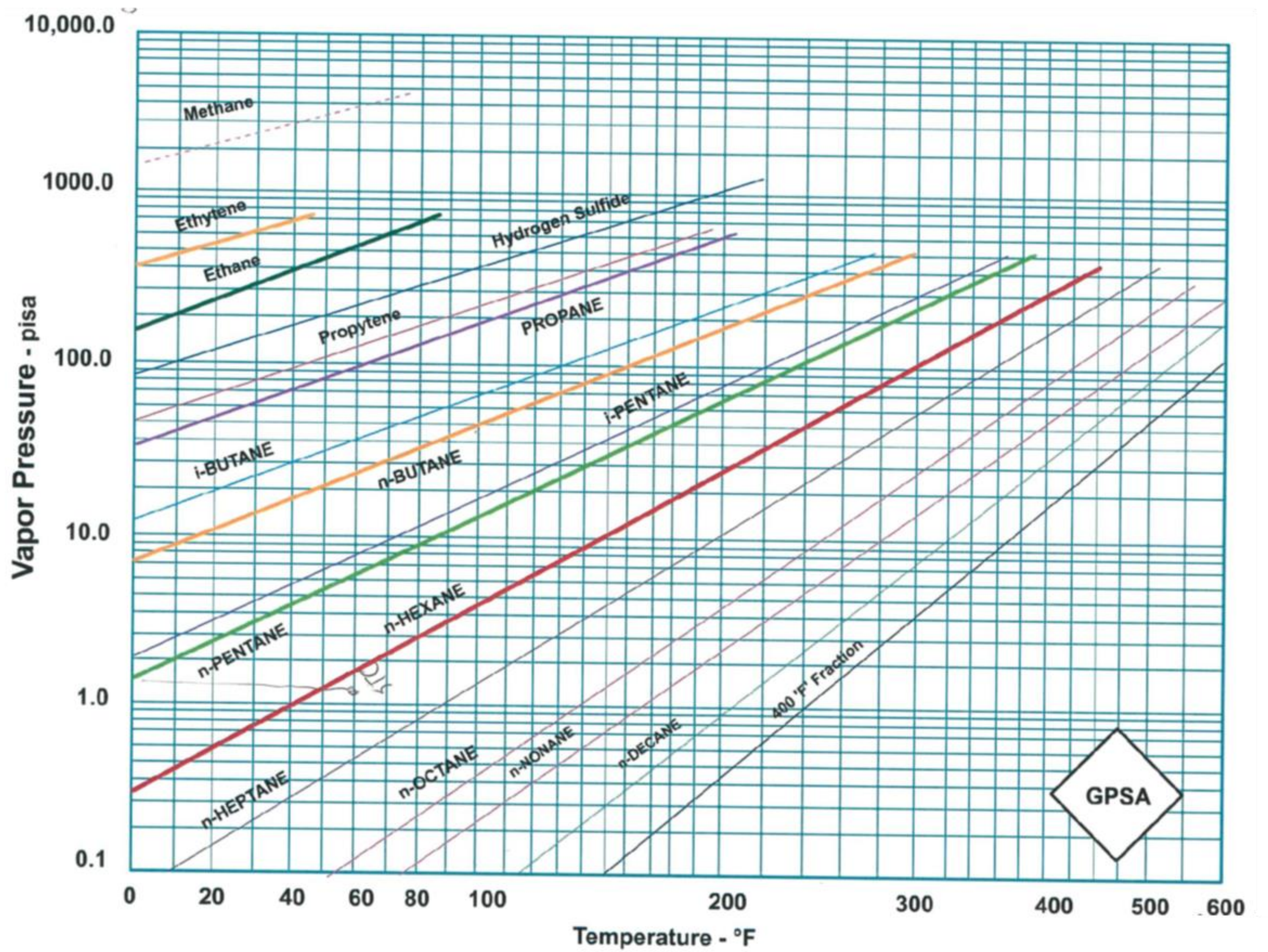
Phase behavior – Single component



Changes in Petroleum Phases

GAS (VAPOR)	OIL (LIQUID)
LOW PRESSURE	HIGH PRESSURE
LIGHT MOLECULES *(LOW ATTRACTION)*	HEAVY MOLECULES *(HIGH ATTRACTION)*
HIGH TEMPERATURE (*High KINETIC Energy*)	LOW TEMPERATURE (*Low KINETIC Energy*)

Vapor pressure for light hydrocarbons



Physical properties of hydrocarbons

Component	Formula	Mole Weight	Critical Constants		SG $_L$ (water)	Liquid Density	SG $_G$ (air)	Vapor Density	Heating Value
			Press psia	Temp °F		lbm / gal		ft³ / lb*	BTU/ ft³
Methane	CH_4	16.043	667.0	(-117)	0.3000	2.5000	0.5539	23.654	909.4
Ethane	C_2H_6	30.070	707.8	90	0.3562	2.9696	1.0382	12.620	1618.7
Propane	C_3H_8	44.097	615.0	206	0.5070	4.2268	1.5226	8.606	2314.9
IsoButane	C_4H_{10}	58.123	527.9	274	0.5629	4.6927	2.0068	6.529	3000.4
n-Butane	C_4H_{10}	58.123	548.8	306	0.5840	4.8691	2.0068	6.529	3010.8
i-Pentane	C_5H_{12}	72.150	490.4	369	0.6244	5.2058	2.4912	5.260	3699.0
n-Pentane	C_5H_{12}	72.150	488.1	386	0.6311	5.2614	2.4912	5.260	3706.9
n-Hexane	C_6H_{14}	86.177	439.5	452	0.6640	5.5363	2.9755	4.404	4403.9
n-Heptane	C_7H_{16}	100.204	397.4	511	0.6881	5.7364	3.4598	3.787	5100.0
n-Octane	C_8H_{18}	114.231	361.1	564	0.7069	5.8926	3.9441	3.322	5796.1
n-Nonane	C_9H_{20}	128.258	330.7	611	0.7219	6.0189	4.4284	2.959	6493.2
n-Decane	$C_{10}H_{22}$	142.285	304.6	652	0.7342	6.1210	4.9127	2.667	7189.6
WATER	H_2O	18.015	3200.1	705	1.0000	8.3372	0.6220	21.065	
AIR	mixture	28.963	546.9	(-221)	0.8748	7.2930	1.0000	13.103	
Carbon Dioxide	CO_2	44.010	1069.5	88	0.8180	6.8199	1.5196	8.623	
Hydrogen Sulfide	H_2S	34.080	1300.0	212	0.8104	6.6817	1.1767	11.135	586.8
Hydrogen	H_2	2.016	187.5	(-400)	0.0711	0.5925	0.0696	188.250	273.8
Oxygen	O_2	31.999	731.4	(-181)	1.1421	9.5221	1.1048	11.859	
Nitrogen	N_2	28.013	492.8	(-233)	0.8094	6.7481	0.9672	13.54	

Hydrostatic head: Fresh water

- 8.3372 lbm/gal (= ppg, pound per gallon)

= 8.3372 lb / 0.13368 ft^3 = 62.37 lb/ft^3

- Transform the density to pressure

psi = pounds per square inch

62.37 lb / (12 inch * 12 inch) = 0.433 psi

→ 1 foot depth of fresh water exerts 0.433 psi pressure

: Hydrostatic head

Q. How much pressure does a 10 foot column of liquid C10 exert at its base?

A. $P = 0.433 * SG_L * H$

Component	Formula	Mole Weight	Critical Constants		SG_L (water)	Liquid Density	SG_G (air)	Vapor Density	Heating Value
			Press psia	Temp °F		lbm / gal		ft³ / lb*	BTU/ ft³
Methane	CH_4	16.043	667.0	(-117)	0.3000	2.5000	0.5539	23.654	909.4
Ethane	C_2H_6	30.070	707.8	90	0.3562	2.9696	1.0382	12.620	1618.7
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IsoButane	C_4H_{10}	58.123	527.9	274	0.5629	4.6927	2.0068	6.529	3000.4
n-Butane	C_4H_{10}	58.123	548.8	306	0.5840	4.8691	2.0068	6.529	3010.8
i-Pentane	C_5H_{12}	72.150	490.4	369	0.6244	5.2058	2.4912	5.260	3699.0
n-Pentane	C_5H_{12}	72.150	488.1	386	0.6311	5.2614	2.4912	5.260	3706.9
n-Hexane	C_6H_{14}	86.177	439.5	452	0.6640	5.5363	2.9755	4.404	4403.9
n-Heptane	C_7H_{16}	100.204	397.4	511	0.6881	5.7364	3.4598	3.787	5100.0
n-Octane	C_8H_{18}	114.231	361.1	564	0.7069	5.8926	3.9441	3.322	5796.1
n-Nonane	C_9H_{20}	128.258	330.7	611	0.7219	6.0189	4.4284	2.959	6493.2
n-Decane	$C_{10}H_{22}$	142.285	304.6	652	0.7342	6.1210	4.9127	2.667	7189.6
WATER	H_2O	18.015	3200.1	705	1.0000	8.3372	0.6220	21.065	

Fluid viscosity

- Symbol: μ
  - Internal resistance of a fluid to flow against itself
  - Usually measured in centipoise

- Absolute viscosity: μ
  - Greek letter mu
  - Units: Centipoise

$$\nu = \frac{\mu}{SG_L}$$

- Kinematic viscosity: v
  - Greek letter nu
  - Units: Centistrokes

Absolute (μ) and Kinematic (v) viscosity

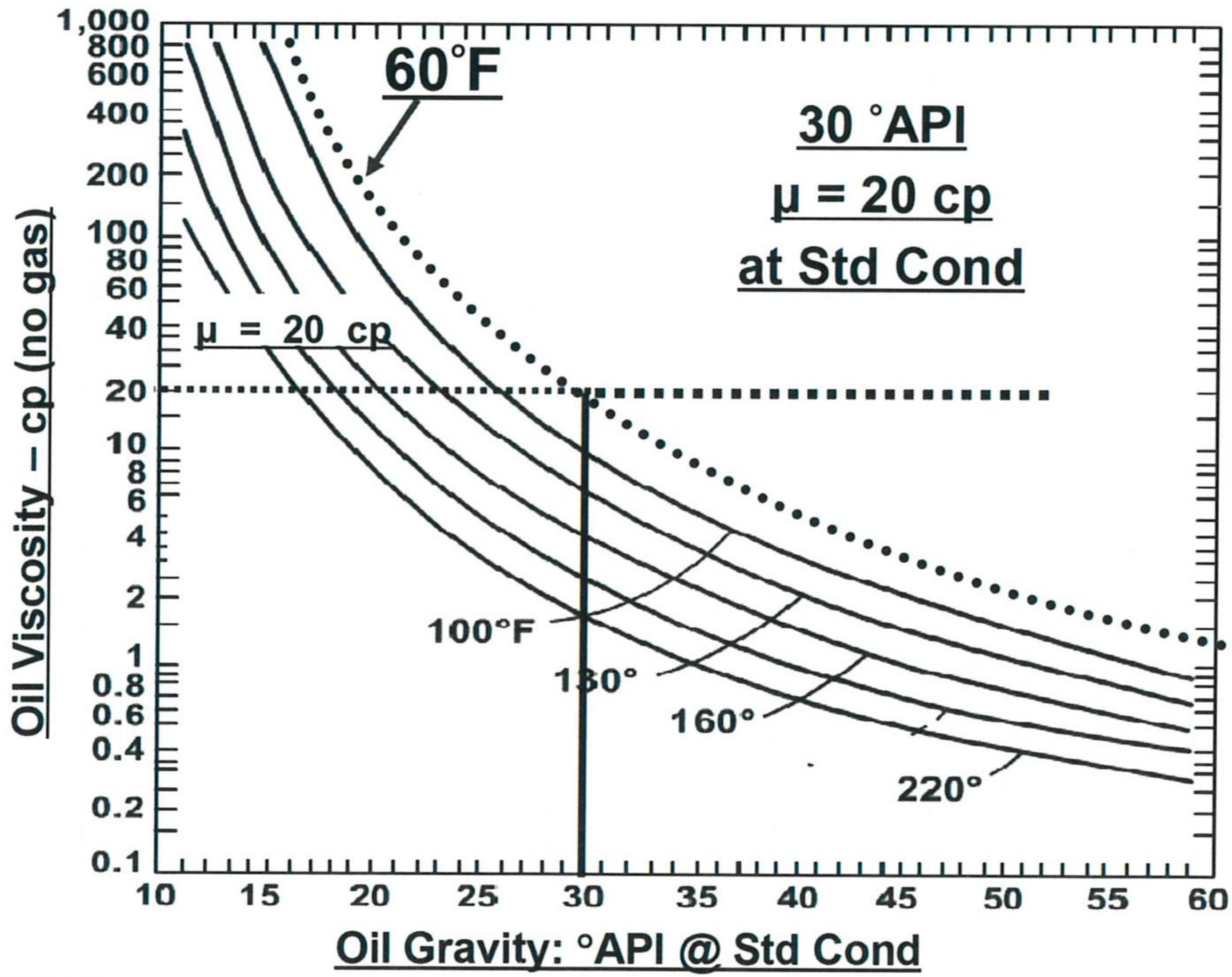
$$\nu_{Kinematic} = \frac{\mu_{Absolute}}{\rho}$$

For Liquids:

$$\nu_{Centistokes} = \frac{\mu_{Cp}}{SG_L}$$

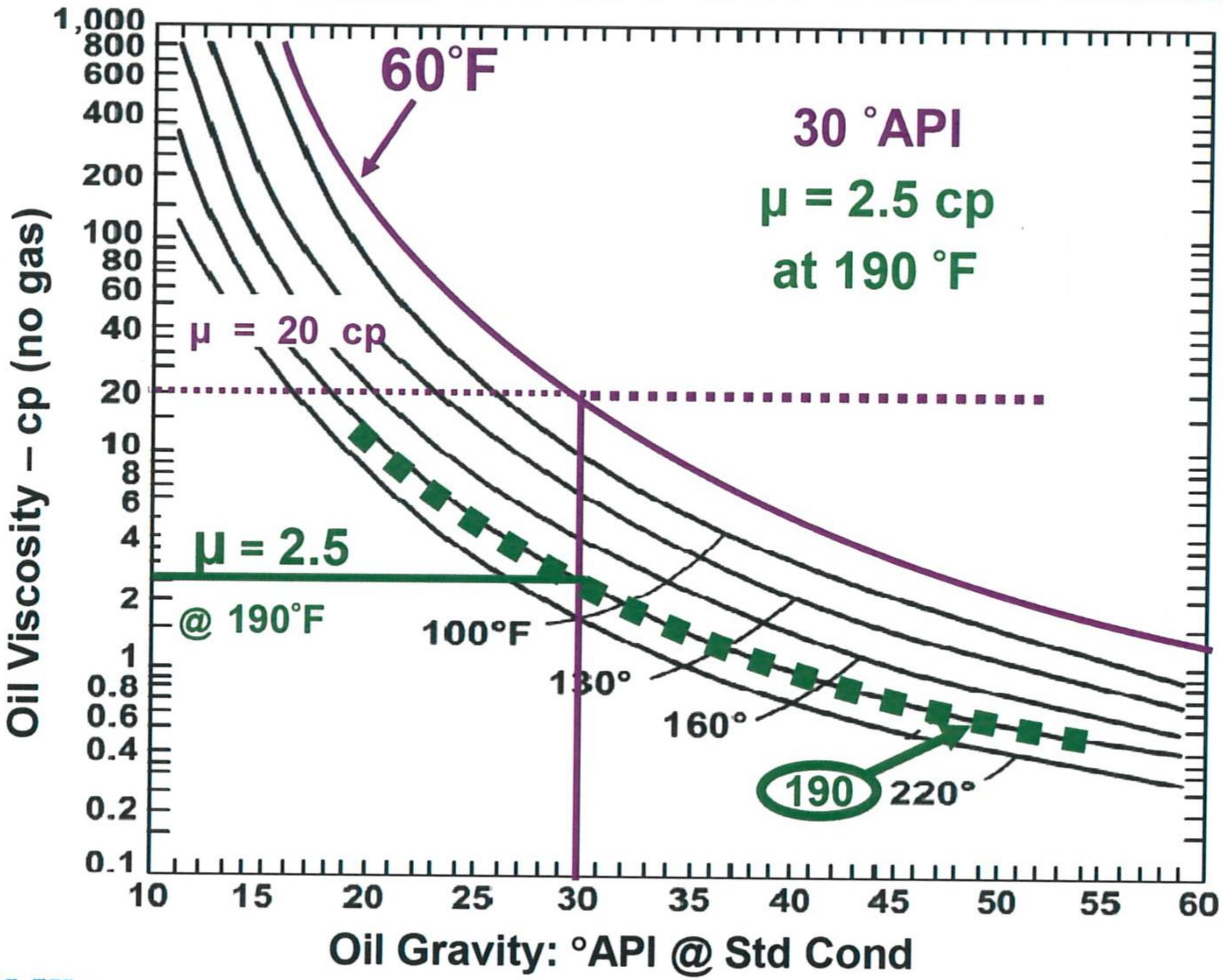
Stock Tank Oil
(Measured at Standard Conditions)

Oil viscosity vs. Temperature



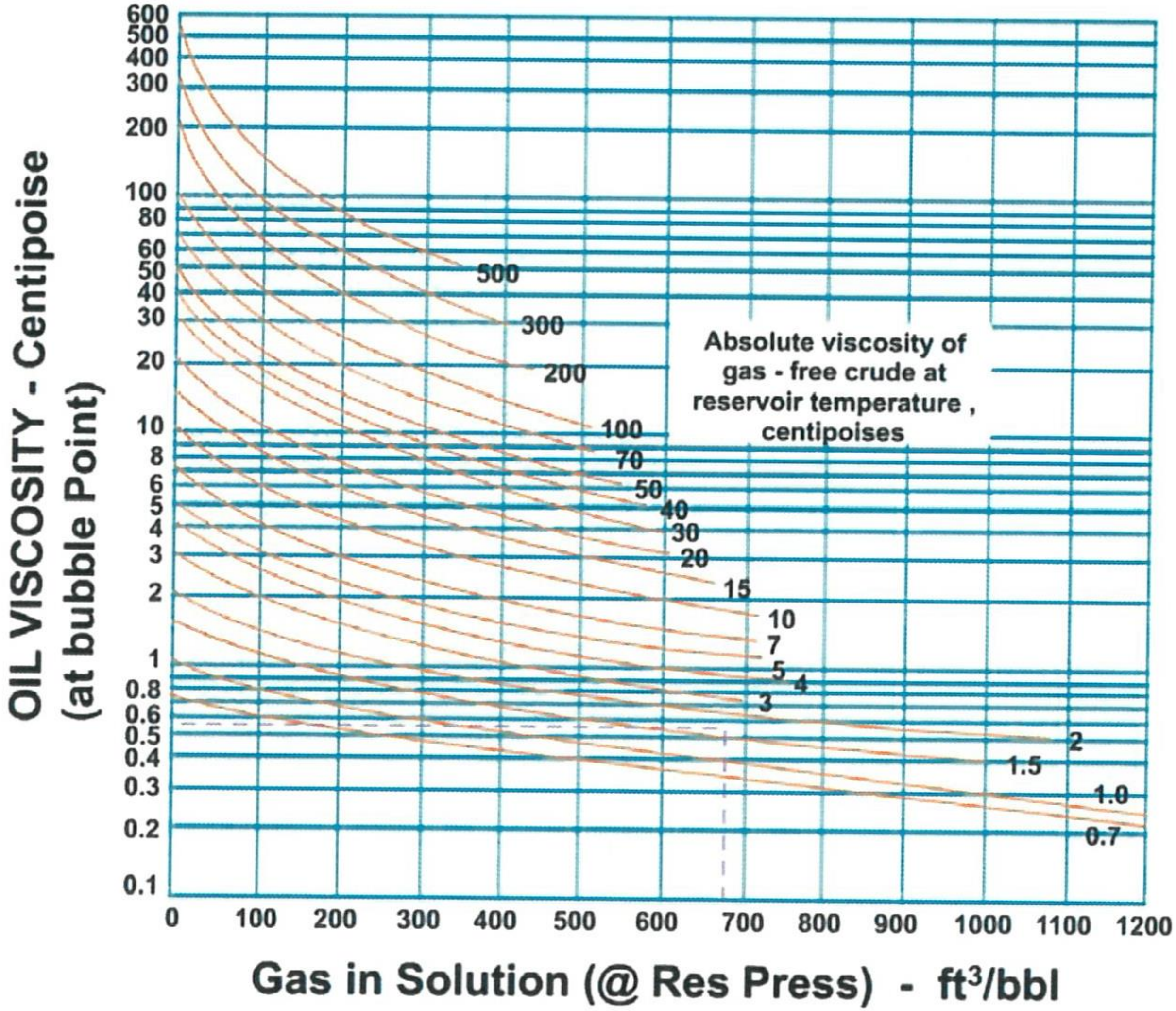
Oil viscosity vs. Temperature

- Dominant effect by temperature

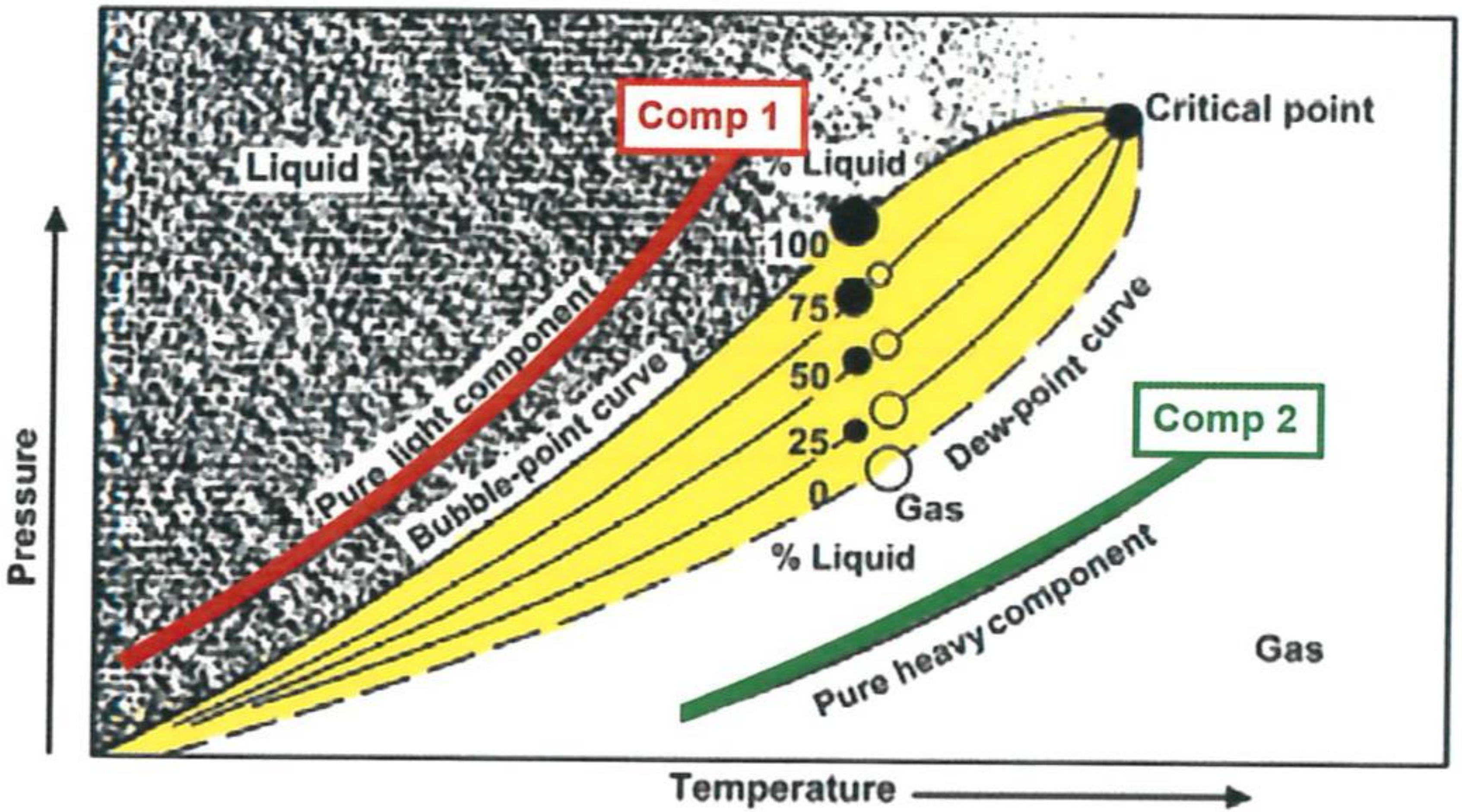


Effect of solution gas on oil viscosity

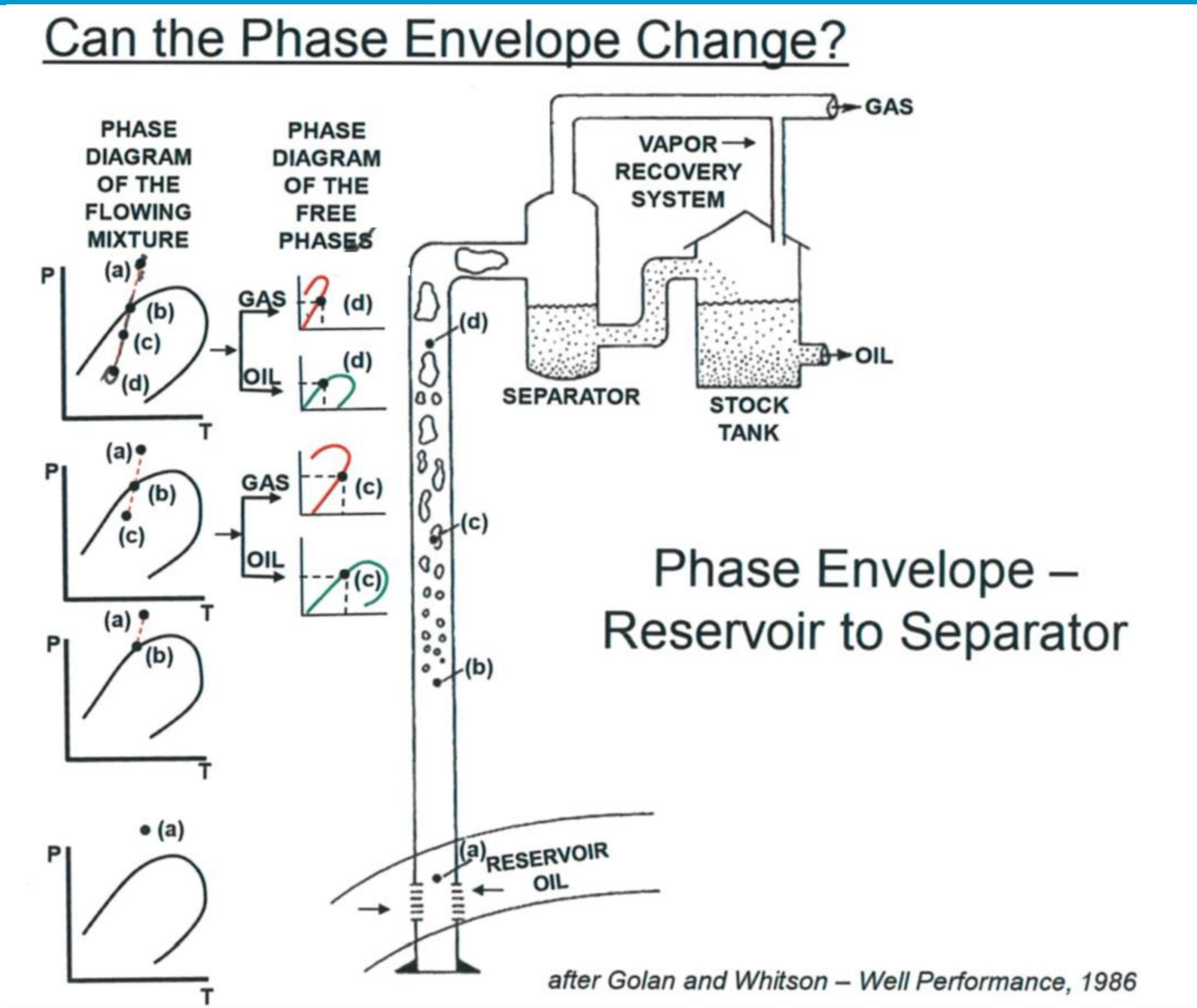
- Gas dissolution reduces viscosity



Phase diagram: Two components

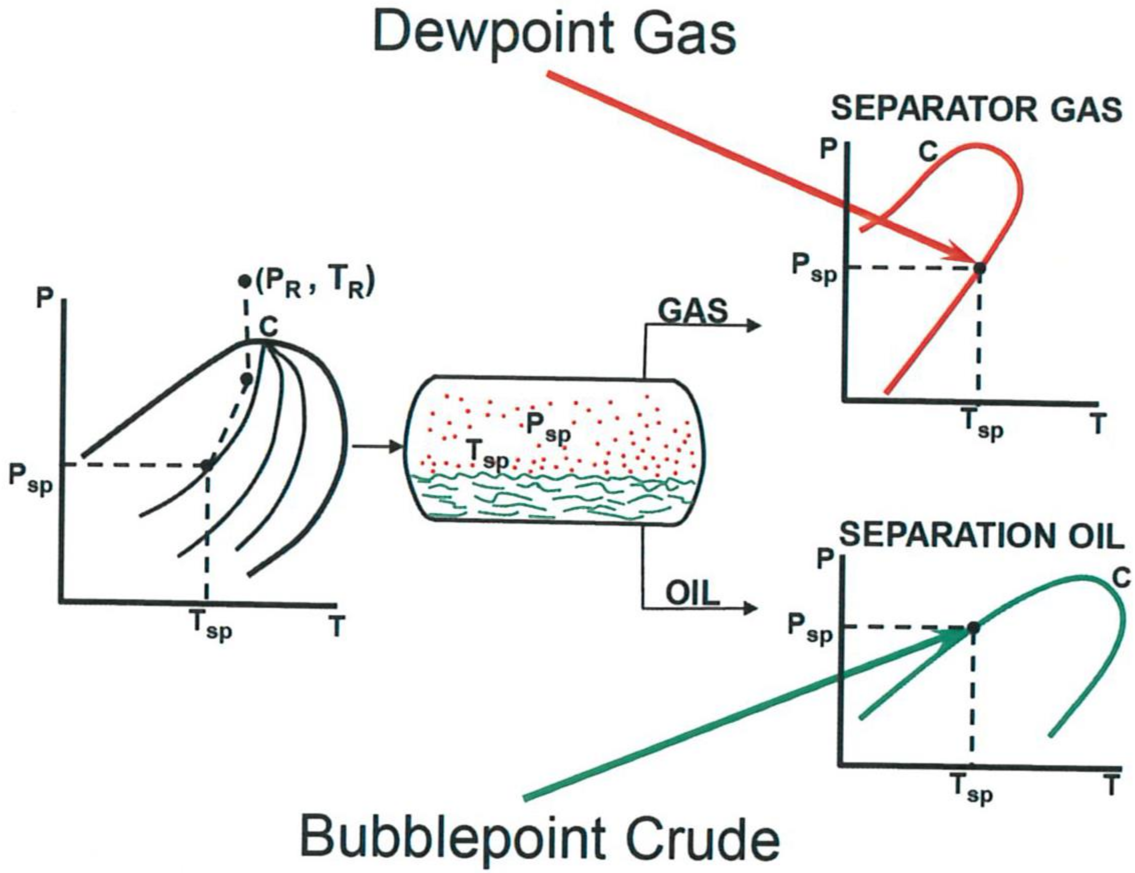


Phase behavior



Phase behavior

Can the Phase Envelope Change?

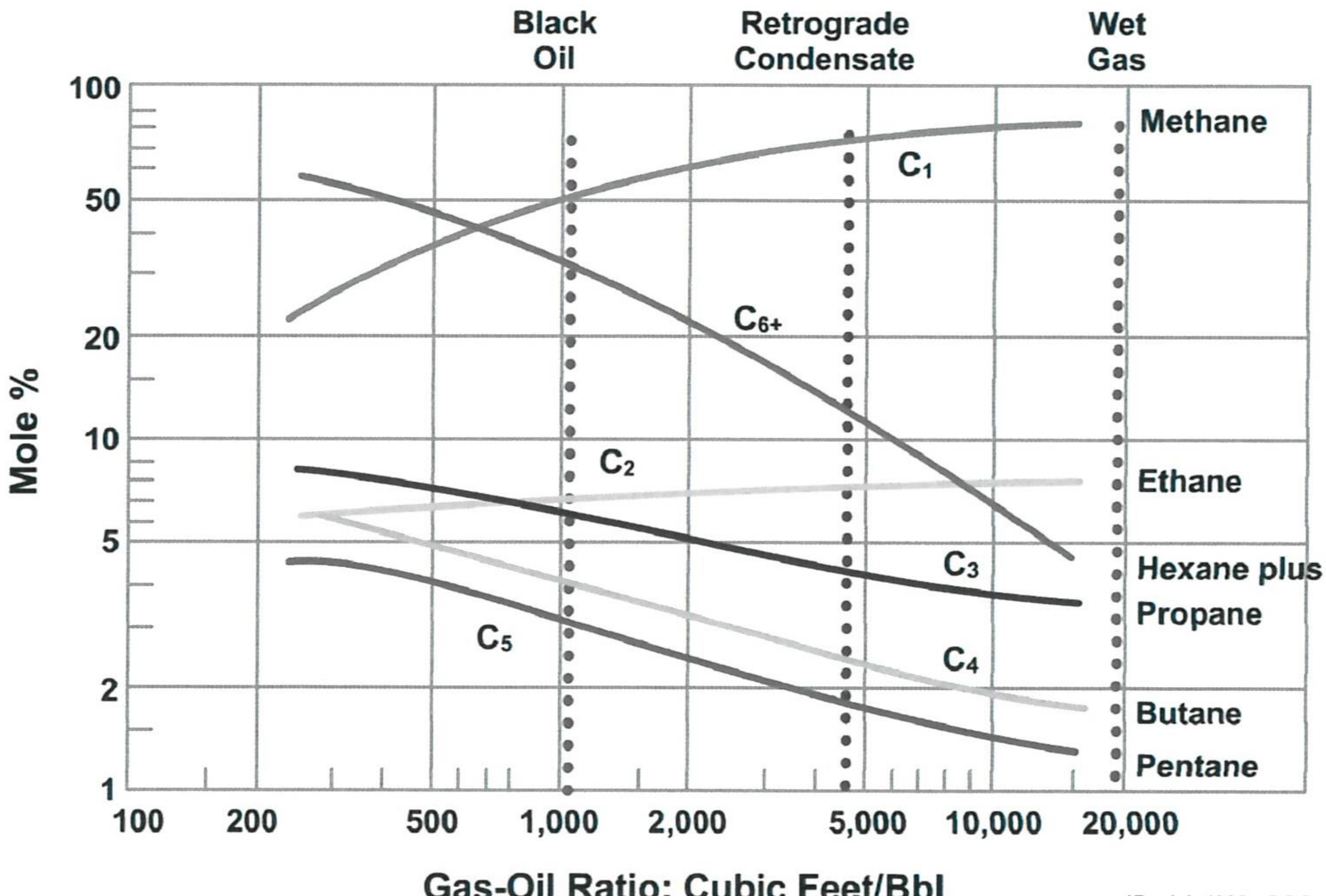


Composition change = Phase Envelope change

Petroleum fluid classification

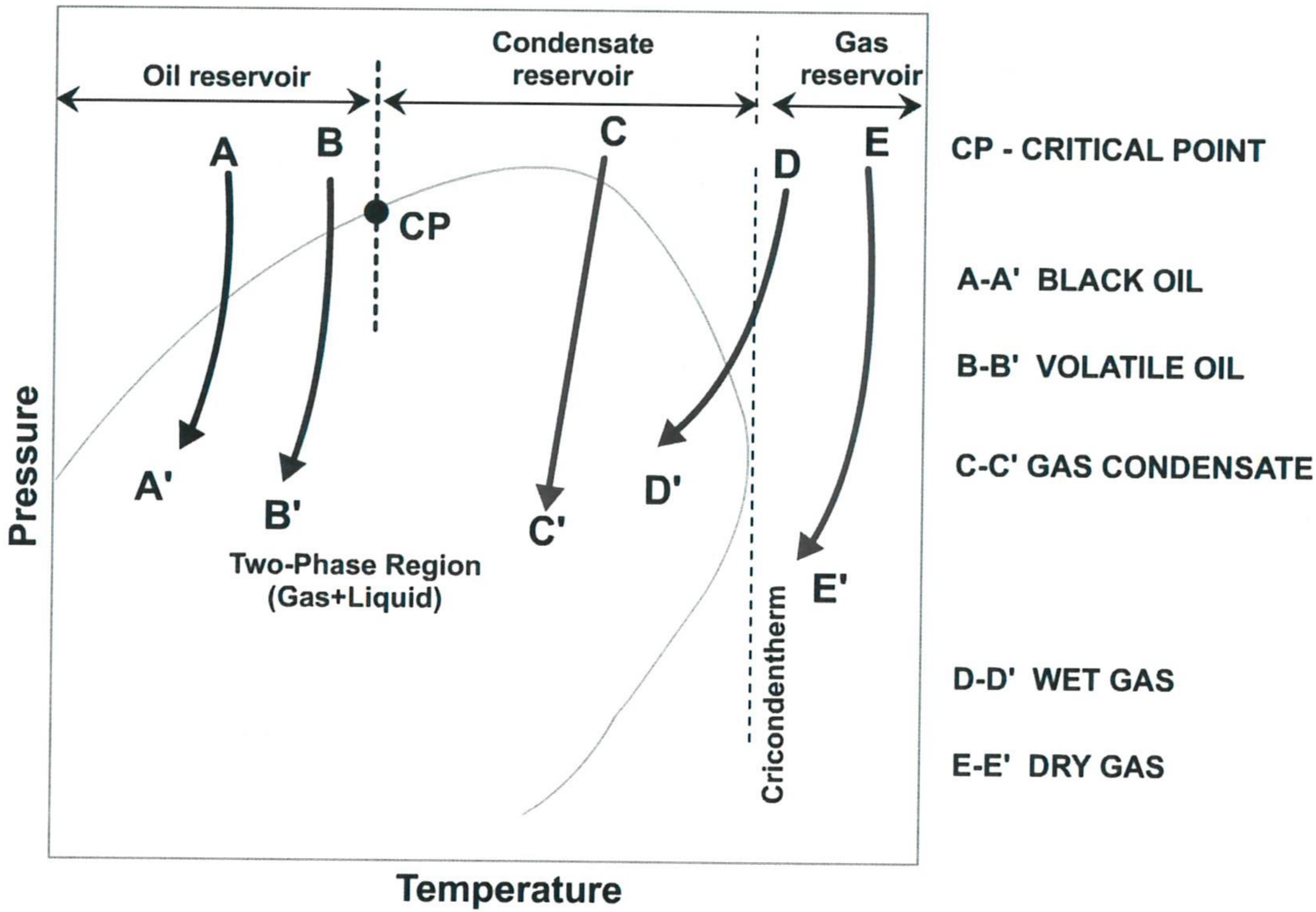
Fluid	Shrinkage STBO/Res Bbl	GOR Scf/STBO	API	Color	Yield STBO/MMscf
Low-Shrinkage Oil (Low GOR)	> 0.5	< 2,000	< 45	Very Dark Often Black	> 500
High-Shrinkage Oil (High GOR)	< 0.5	2,000 - 3,300	> 45	Colored Usually Brown	> 500
Retrograde Condensation	> 0.35	3,300 - 50,000	50-60	Light Clear	20 - 300
Wet Gas	-	> 50,000	> 50	Clear	1 - 20
Dry Gas	-	-	-	-	< 1

Reservoir composition vs. GOR



(*Penick 1983 - OGJ*)

Reservoir classification



Critical pressure and critical temperature

1. **Gas Mixture**

COMP 1	MOL FRAC 2	COMP P_c 3	Stream Ppc 4 = 2 x 3	COMP T_c 5	Stream Tpc 6 = 2 x 5
C_1	0.681	666	454	-117 (343)	(234)
C_2	0.126	706	89	90 (550)	(69)
C_3	0.052	616	32	206 (666)	(35)
iC_4	0.042	528	22	274 (734)	(31)
nC_4	0.025	551	14	306 (766)	(19)
iC_5	0.026	490	13	369 (829)	(22)
nC_5	0.018	489	9	386 (846)	(15)
nC_6	0.015	437	6	454 (914)	(14)
C_7	0.015	397	6	512 (972)	(15)
Total	1.000		645		-6 (454)

Exercise 1.

- Calculate P_{pc} and T_{pc} for a gas mixture composed of

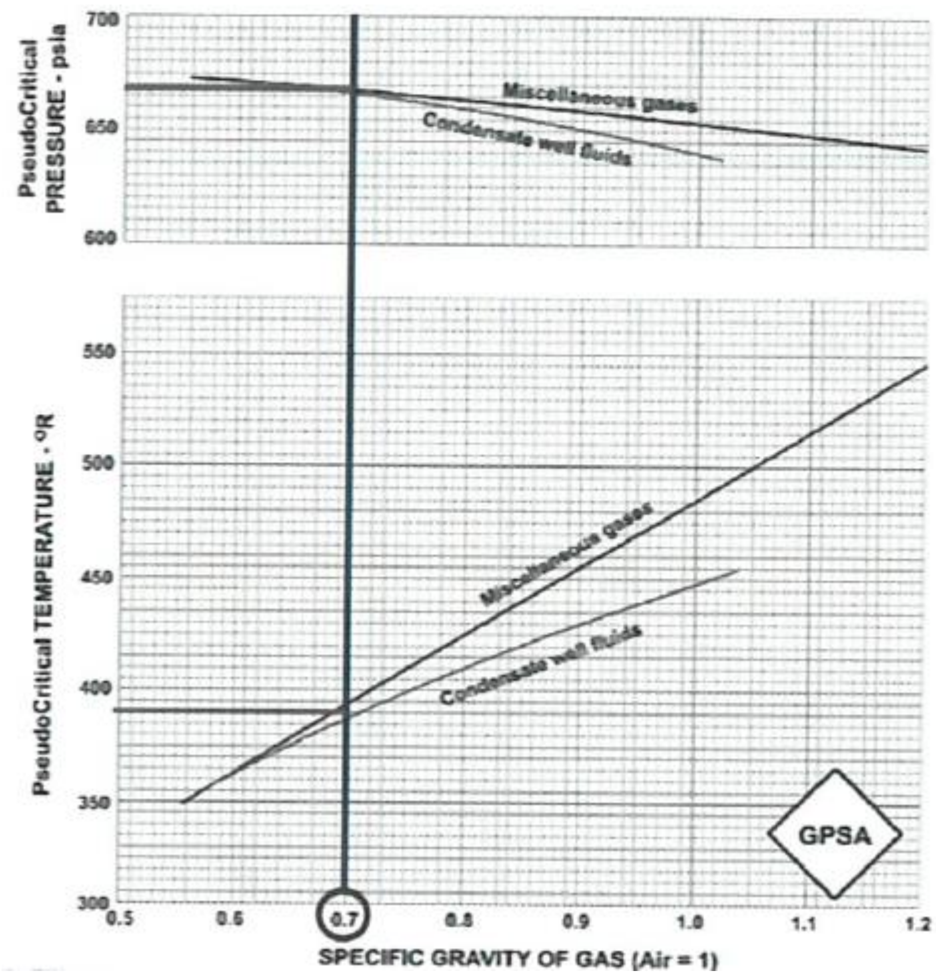
COMP	Pc	x%	Tc	x%
70% C_1	666		343	
20% C_2	706		550	
10% C_3	616		666	

Ppc	Tpc

Critical P_c & T_c of a Mixture is referred to as

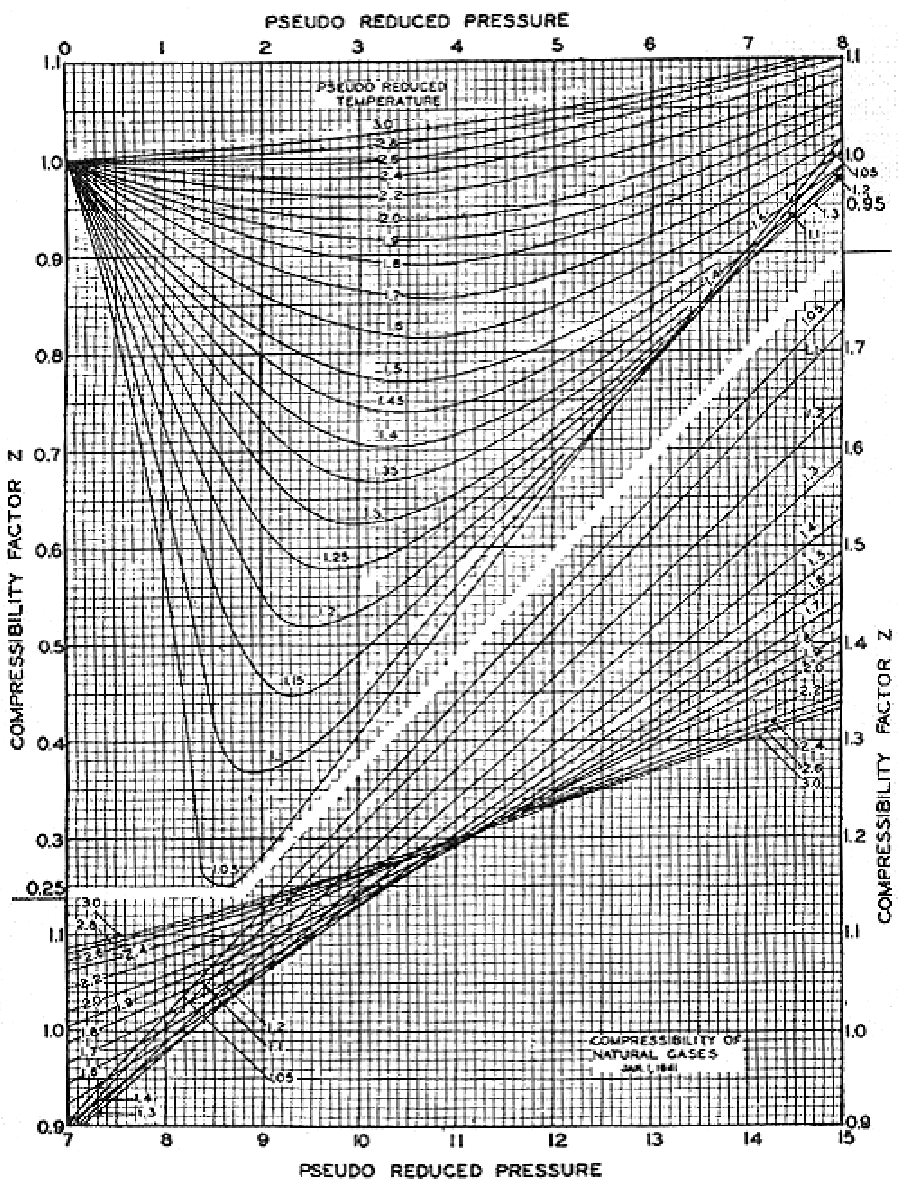
$$\frac{\text{Psuedo - Critical Pressure}}{P_{pc}} \ \& \ \frac{\text{Pseudo - Critical Temperature}}{T_{pc}}$$

Tc, Pc from SG



FIND P_{pc} and T_{pc} of a GAS with SG_g = .7

Compressibility Factor: Z



Find Z

Exercise

P = 3000 psia

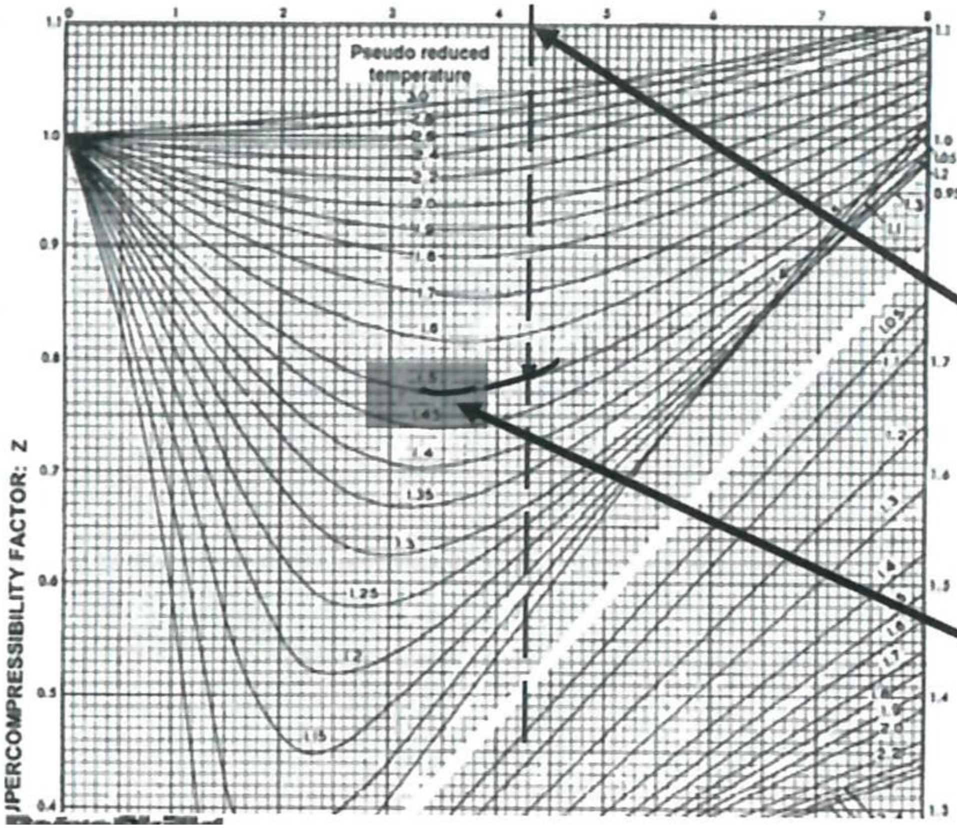
T = 120°F = 580°R

SG = .7 ∴

P_{pc} = 666 psia

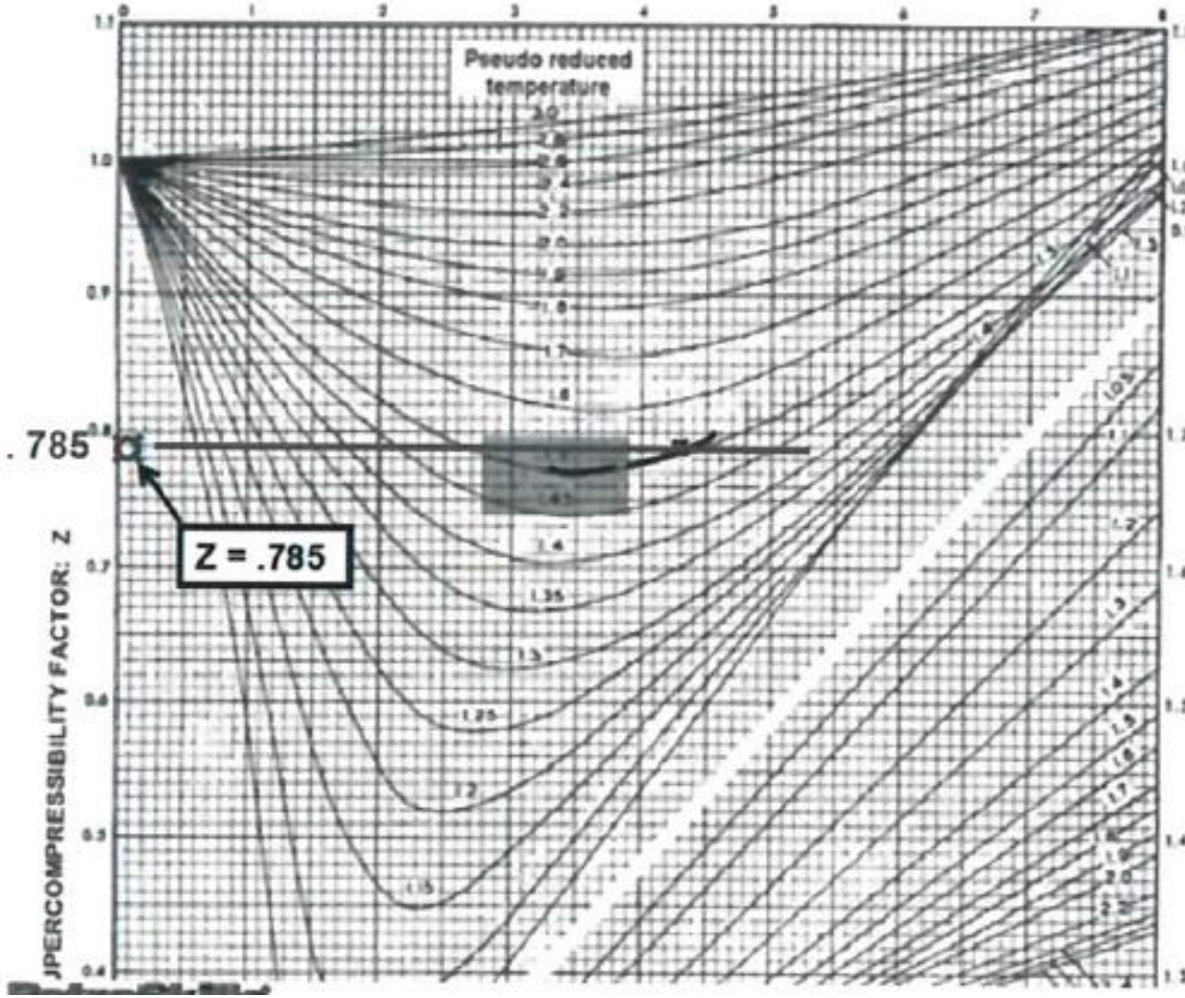
T_{pc} = 390 °R

Compressibility Factor: Z



$$P_R = \frac{3000}{666} = 4.5$$

$$T_R = \frac{580}{390} = 1.49$$



$$P_R = \frac{3000}{666} = \mathbf{4.5}$$

$$T_R = \frac{580}{390} = \mathbf{1.49}$$

Exercise 2.

- **How much Space would 1 Cubic Foot of Gas at Pipeline Conditions Occupy at Standard Conditions?**
  - **Standard Pressure is 15 psia,**
  - **Standard Temp is 60°F (460 + 60 = 520°R),**
  - **Gas Deviation Factor (Z) at the surface is 1.0**
  - **Pipeline Pressure is 3000 psia,**
  - **Pipeline Temp is 180°F (640°R)**
  - **Z Factor is .785**

$$\left[\frac{PV}{TZ}\right]_{Cond\,1} = \left[\frac{PV}{TZ}\right]_{Cond\,2}$$

Standard Conditions   Pipeline Conditions

Thank you