

Image courtesy of FMC Technologies

Flow Assurance

서유택

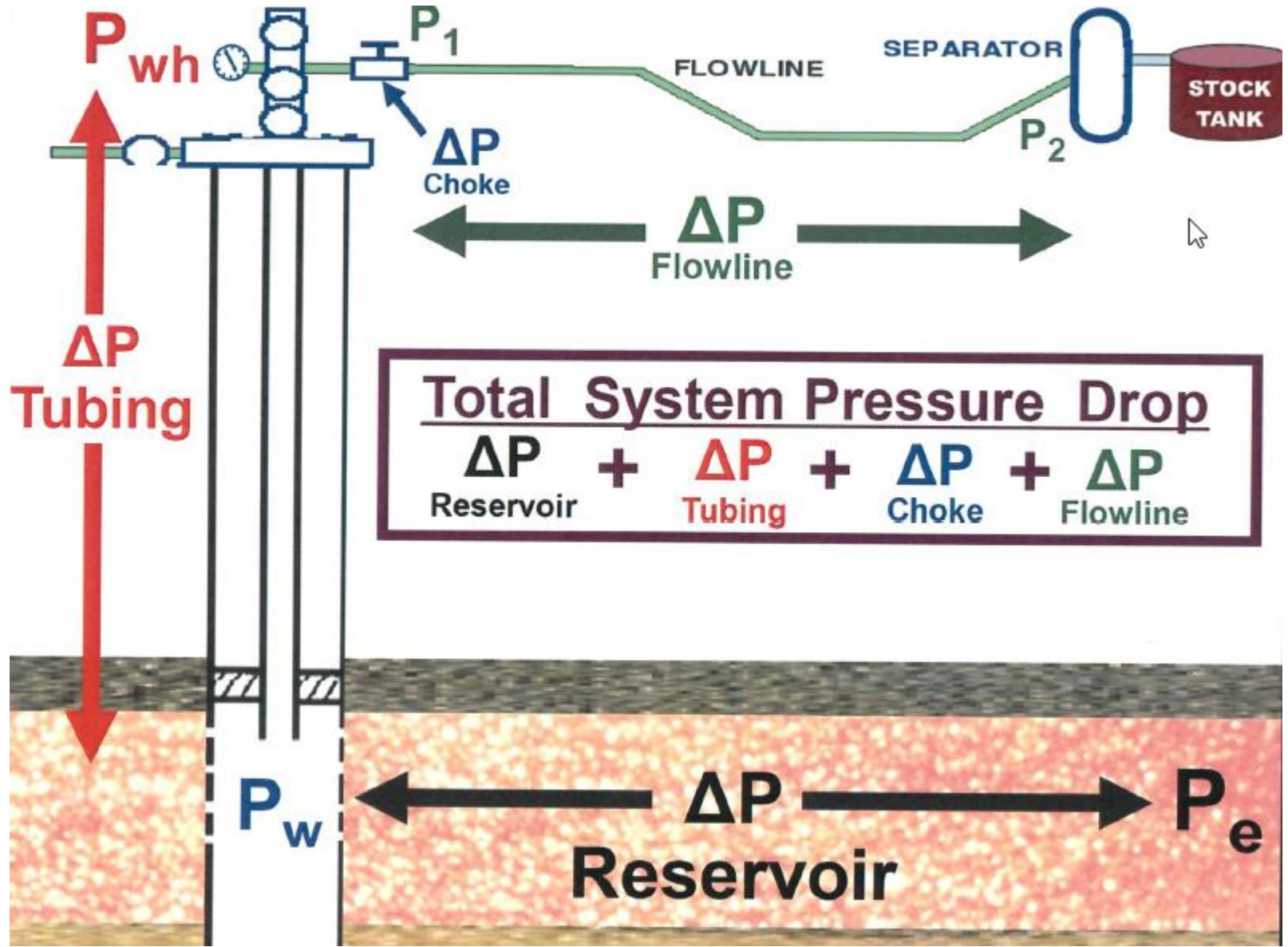
Petroleum Industry

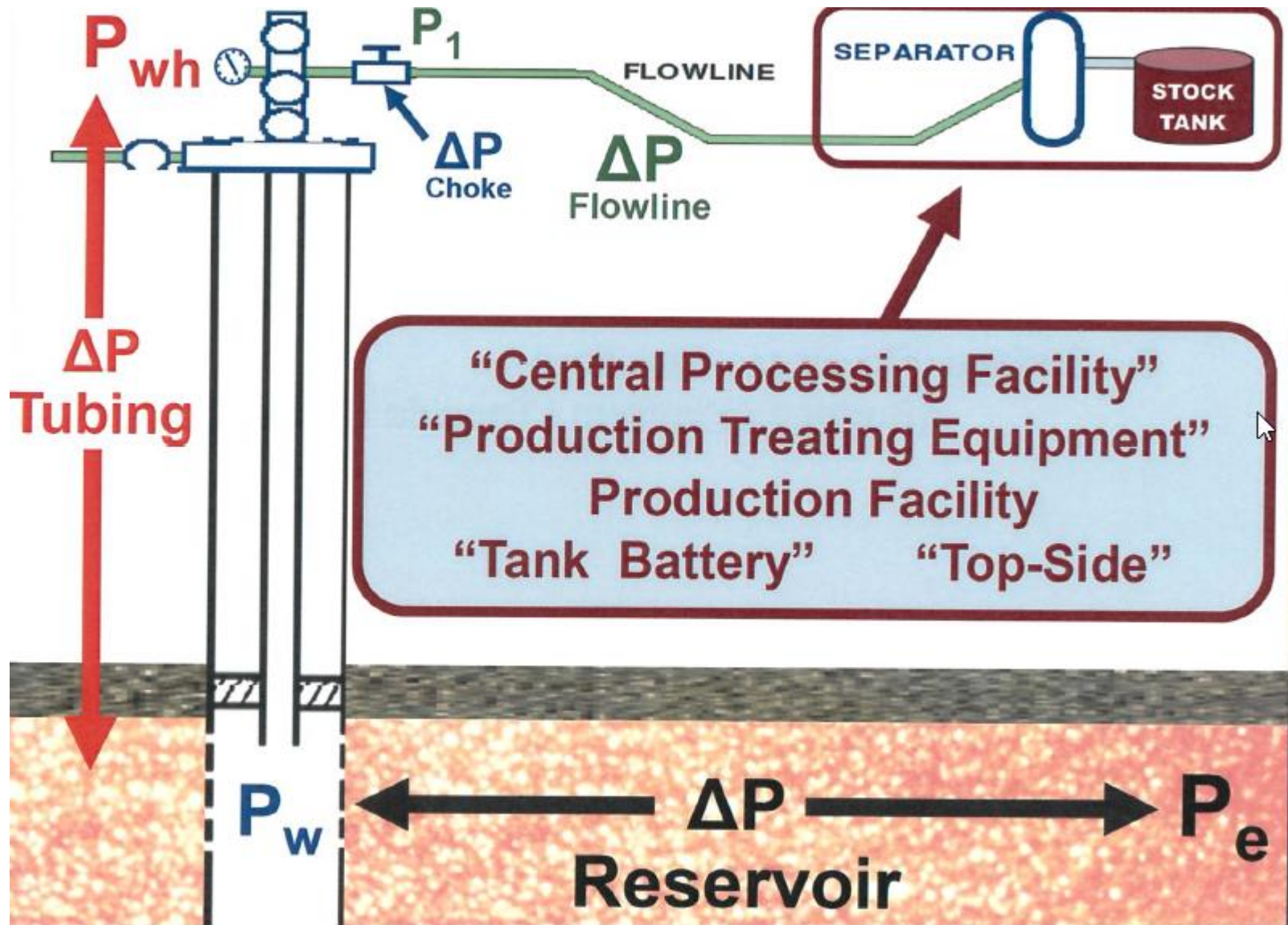
- Upstream: Exploration and Production
- Midstream: Transportation (Field to Refinery)
- Downstream: Refining and Marketing

Upstream

- Three major oil/gas flow systems
 1. Reservoir
 2. Wellbore (Casing/Tubing)
 3. Surface (Flowline/Treating)
(Surface/Platform/Topside/Ocean floor)

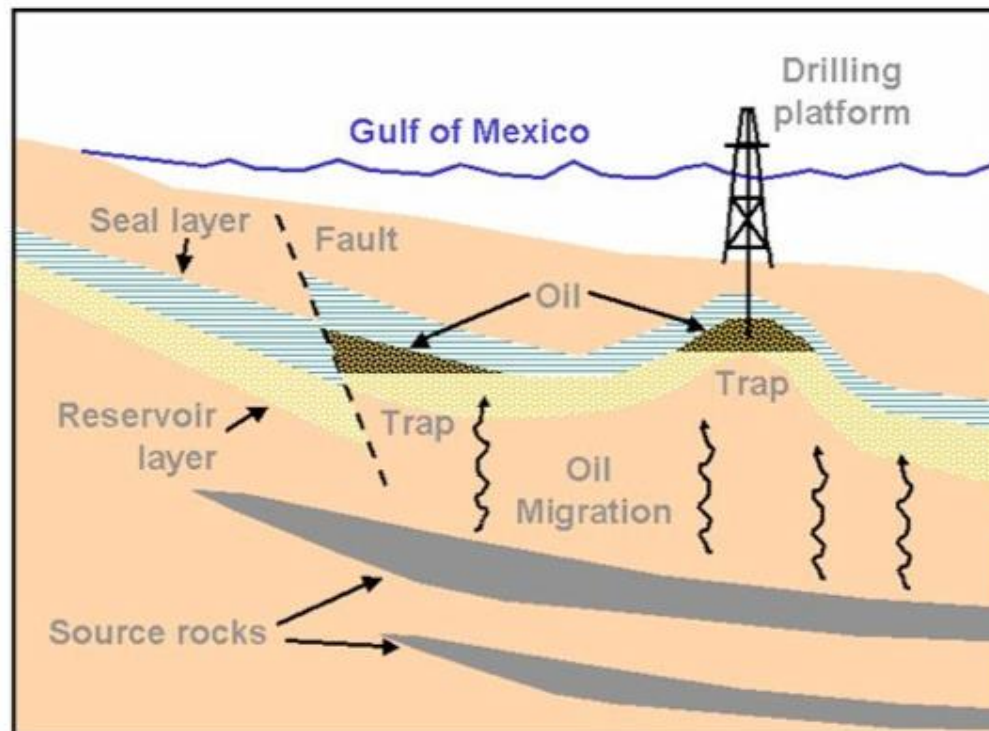
Pressure drop in flow systems





Reservoirs

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

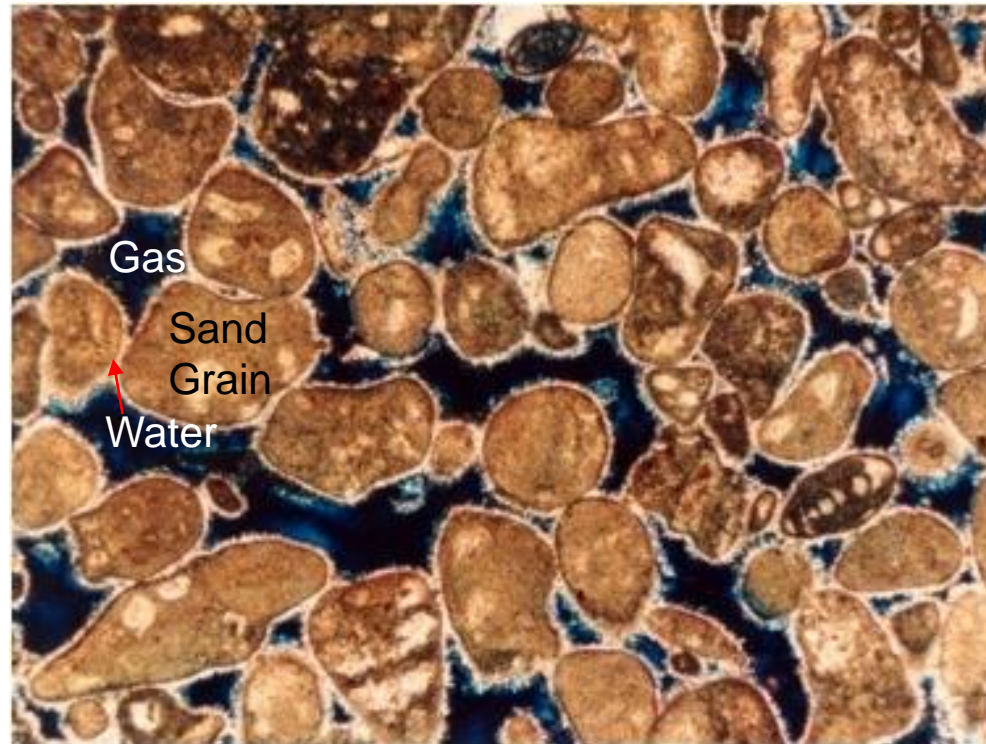


Reservoir

- 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

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 ₂ H ₆	-88.3	—
Propane	C ₃ H ₈	-42.2	—
<i>i</i> -Butane	C ₄ H ₁₀	-10.2	—
<i>n</i> -Butane	C ₄ H ₁₀	-0.6	—
<i>n</i> -Pentane	C ₅ H ₁₂	36.2	0.626
<i>n</i> -Hexane	C ₆ H ₁₄	69.0	0.659
<i>i</i> -Octane	C ₈ H ₁₈	99.3	0.692
<i>n</i> -Decane	C ₁₀ H ₂₂	174.0	0.730
		Naphthenes	
Cyclopentane	C ₅ H ₁₀	49.5	0.745
Methyl cyclo-pentane	CH ₃ C ₅ H ₁₀	71.8	0.754
Cyclohexane	C ₆ H ₁₂	81.4	0.779
		Aromatics	
Benzene	C ₆ H ₆	80.1	0.885
Toluene	C ₇ H ₈	110.6	0.867
<i>o</i> -Xylene	C ₈ H ₁₀	144.4	0.880
Naphthalene	C ₁₀ H ₈	217.9	0.971
		Others	
Nitrogen	N ₂	-195.8	—
<u>Carbon dioxide</u>	CO ₂	-78.4	—
<u>Hydrogen sulfide</u>	H ₂ S	-60.3	—

Note:
Paraffin wax= 20<n<40

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

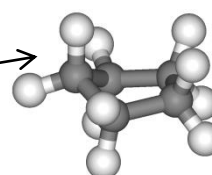
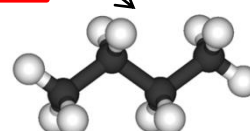
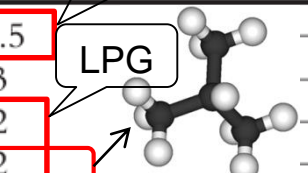
Naphthene
= Cycloalkane

Sweet corrosion

Sour corrosion

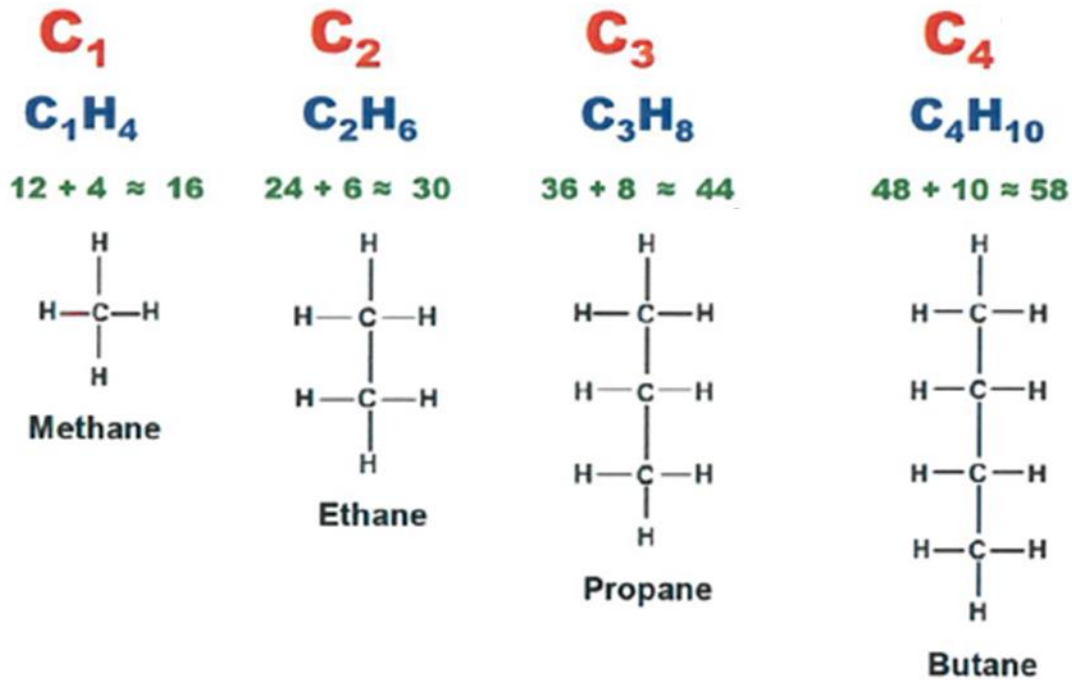
LNG

LPG



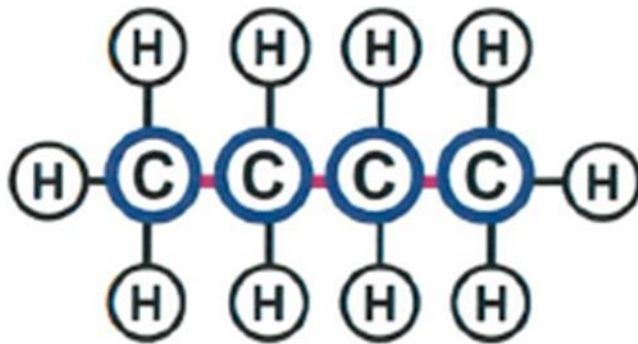
Hydrocarbon molecules

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



Open chains – Single bonds

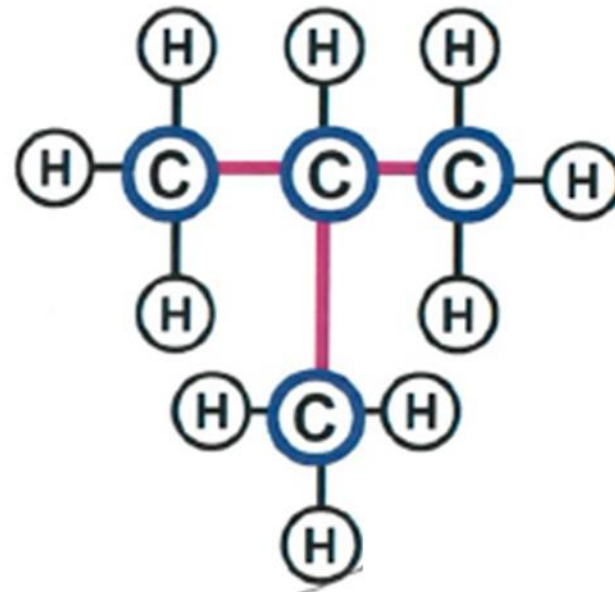
Alkanes



Straight Chain

Normal Butane
(C₄H₁₀)

Paraffin Series



Isomer

Iso-Butane
(C₄H₁₀)

Paraffin build-up in flowline

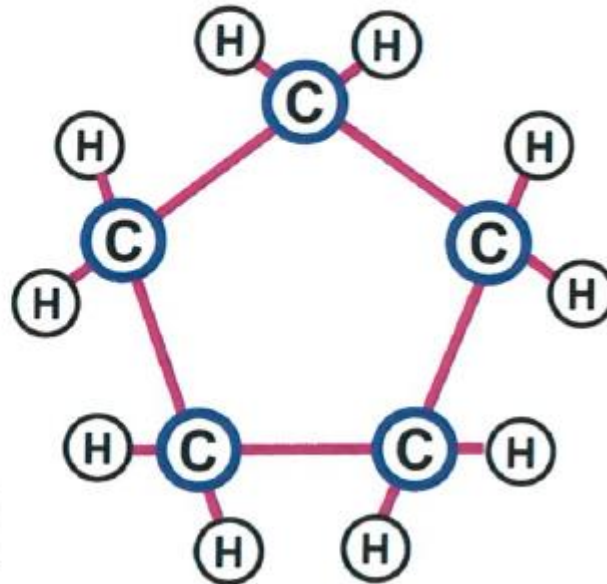


Ring chain – Single bonds

CycloAlkanes

CycloPentane
(C_5H_{10})

Asphaltene Series

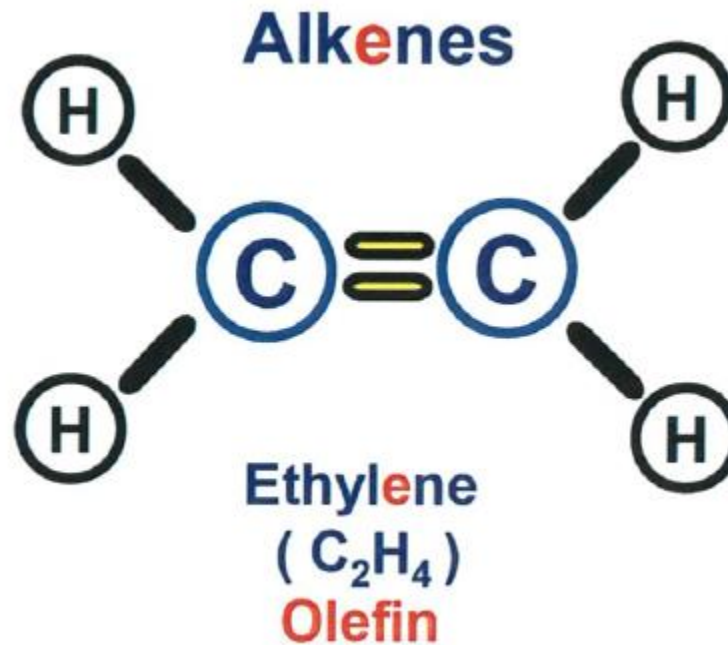


Asphaltenes



Open chain – Double bond

- Very small fraction in the reservoir

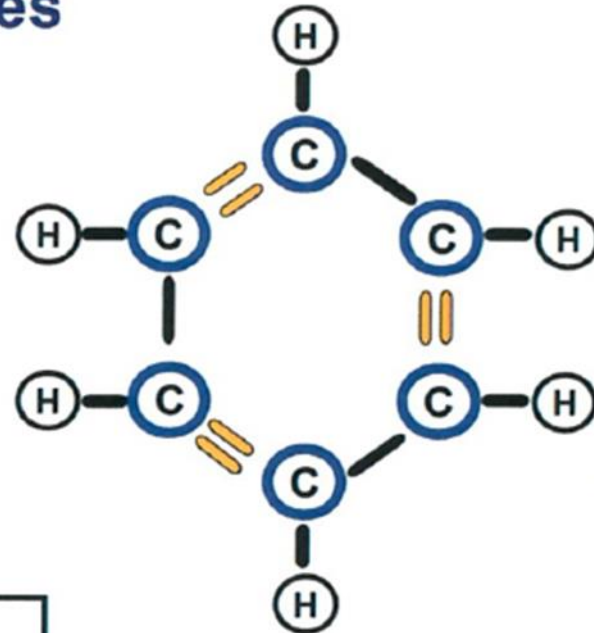


Ring chain – Double bonds

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

CycloAlkenes

CycloHexene
(C_6H_6)
Benzene

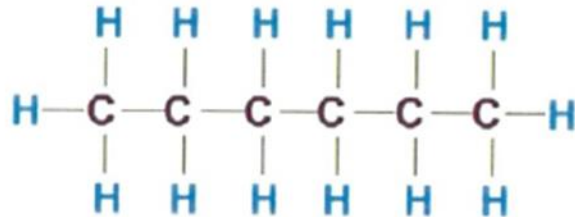


Aromatic Series

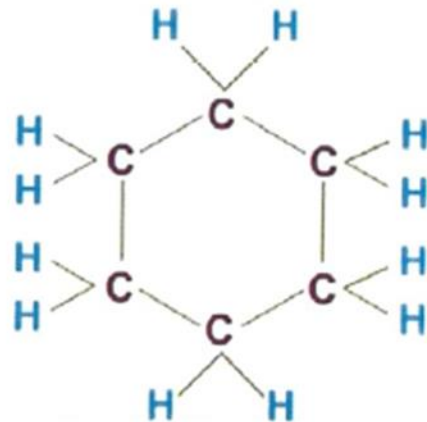
Hydrocarbon classification

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

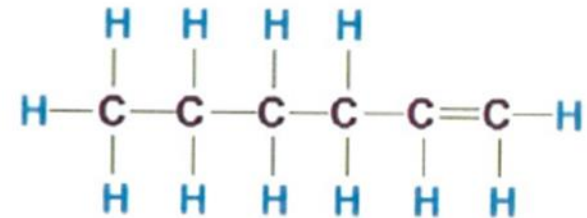
Four H-C Series: C6



ALKANE
Normal HEXANE
 C_6H_{14}
Paraffin Based

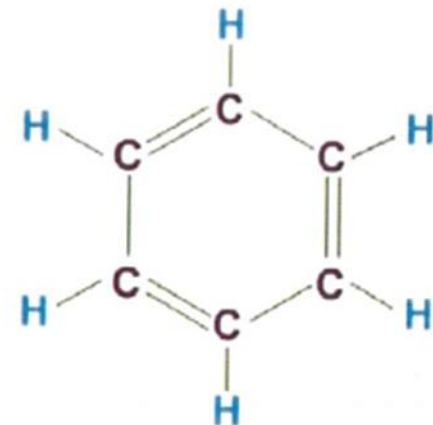


CYCLOALKANE
CYCLO-HEXANE
 C_6H_{12}
Asphaltene Based



ALKENE
Normal HEXENE
 C_6H_{12}

Oil
Field
Oils



CYCLOALKENE
(Cyclo-Hexene) Benzene
 C_6H_6
Aromatic

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
Station #: 95095-2748
Station Name: Baker Ranch
Field: Denton/Wise Co

Report Date: 11/18/2005
Sample Date: 11/18/05
Flowing Pressure: 243 psig
Flowing Temp.: 90 F

Gas Analysis by Chromatograph

<u>NAME</u>	<u>MOLE %</u> Component Molecular Fraction - %	<u>BTU</u> Heating Value (BTU / scf)	<u>GPM</u> 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

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

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5.355

Gas composition – Fractional analysis

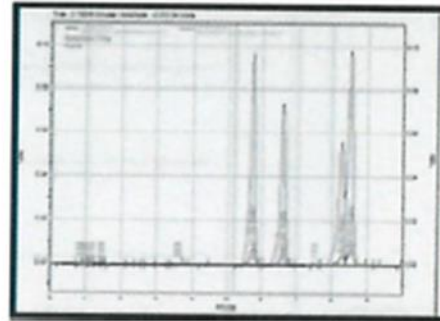
Automatic Gas Sampler



Gas Chromatograph



**Data Acquisition
and Presentation**



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 ₂ H ₆	3.9	5.8	3.2	3.8	5.6	10.3
C ₃ H ₈	1.4	2.2	0.9	1.1	2.1	4.2
C ₄ H 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

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

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

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

$$^{\circ}\text{API} = \frac{141.5}{SG_L} - 131.5$$

$$SG_L = \frac{141.5}{^{\circ}\text{API} + 131.5}$$

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



SOURAKHANY
Caucasus – Azerbaijan
Clear / Light / Sweet
Used as Medicine

ARABIAN LIGHT
Middle East
Reference
Medium
Sulfur

Barrow Island
AUSTRALIA
Light Crude
Very Few
' Heavies '

BRENT
North Sea
Low Sulfur
Medium °API

PARENTIS
France
Light
Sweet

Different crude oil samples



ARABIAN HEAVY

Low °API
High Sulfur



PENNSYLVANIA

Very Pure
Lubricant
without
Refining



Santa Barbara

Offshore Calif
High Sulfur
Medium °API



BOSCAN

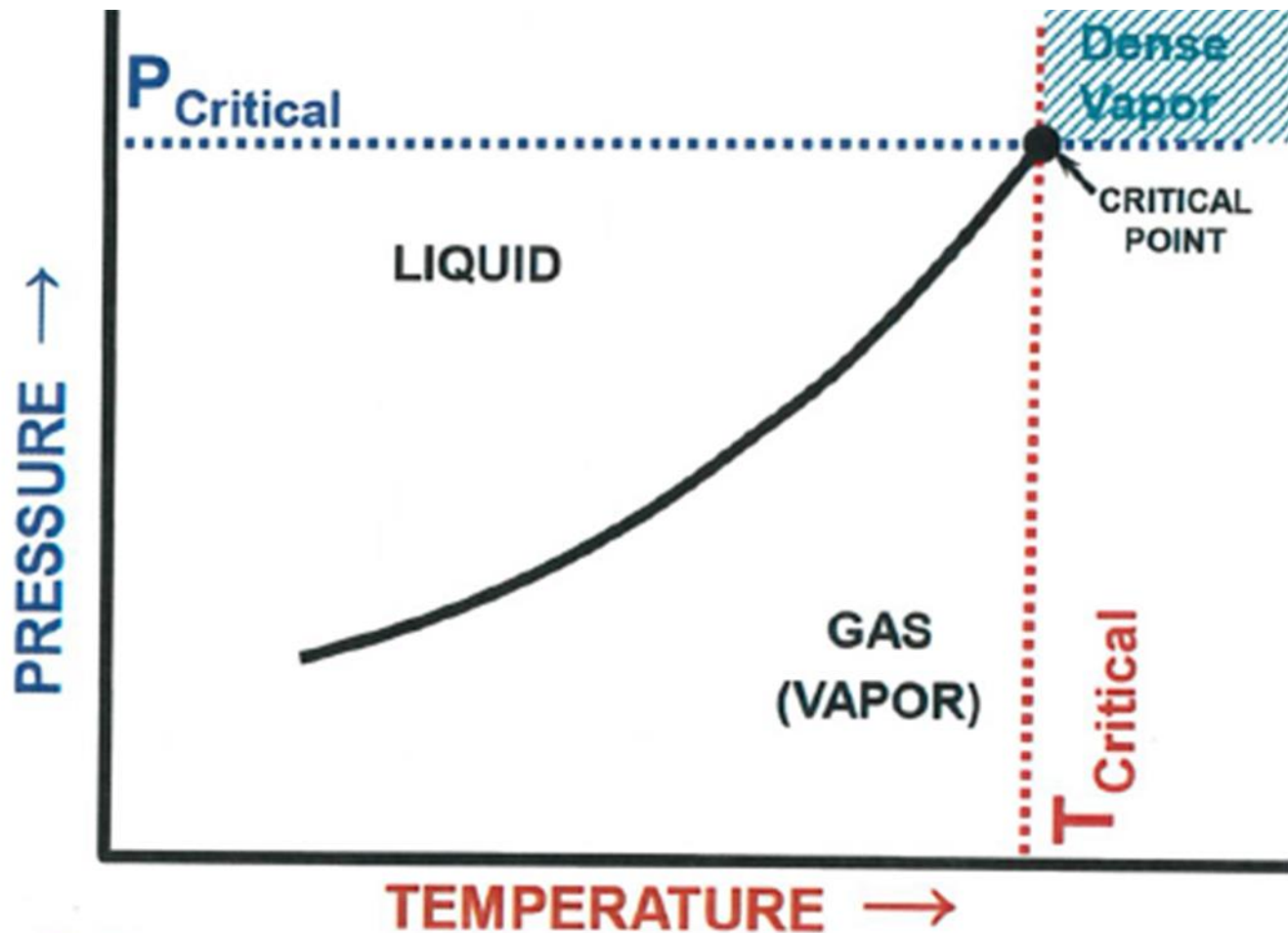
Venezuela
16.8 °API
2.4 % Sulfur
High Grade
Asphalts



ALTAMOUNT

UTAH
Highly
PARAFFINIC
Solid at
Std Conditions

Phase behavior – Single component



Changes in Petroleum Phases

GAS (VAPOR)

LOW PRESSURE

LIGHT MOLECULES
(*LOW ATTRACTION*)

HIGH TEMPERATURE
(*High KINETIC Energy*)

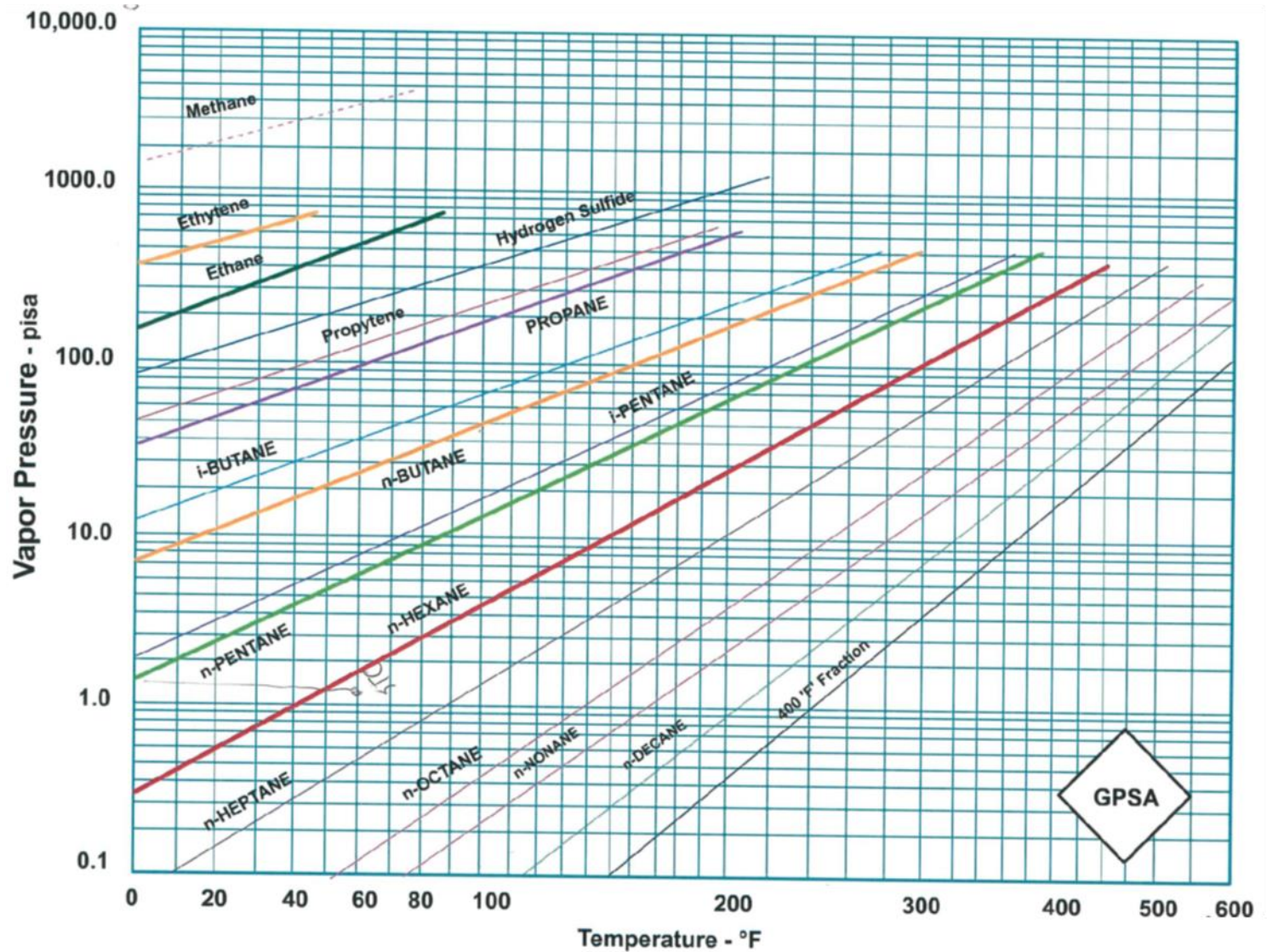
OIL (LIQUID)

HIGH PRESSURE

HEAVY MOLECULES
(*HIGH ATTRACTION*)

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 lbm / gal	SG _G (air)	Vapor Density ft ³ / lb*	Heating Value BTU/ ft ³
			Press psia	Temp °F					
Methane	CH ₄	16.043	667.0	(-117)	0.3000	2.5000	0.5539	23.654	909.4
Ethane	C ₂ H ₆	30.070	707.8	90	0.3562	2.9696	1.0382	12.620	1618.7
Propane	C ₃ H ₈	44.097	615.0	206	0.5070	4.2268	1.5226	8.606	2314.9
IsoButane	C ₄ H ₁₀	58.123	527.9	274	0.5629	4.6927	2.0068	6.529	3000.4
n-Butane	C ₄ H ₁₀	58.123	548.8	306	0.5840	4.8691	2.0068	6.529	3010.8
i-Pentane	C ₅ H ₁₂	72.150	490.4	369	0.6244	5.2058	2.4912	5.260	3699.0
n-Pentane	C ₅ H ₁₂	72.150	488.1	386	0.6311	5.2614	2.4912	5.260	3706.9
n-Hexane	C ₆ H ₁₄	86.177	439.5	452	0.6640	5.5363	2.9755	4.404	4403.9
n-Heptane	C ₇ H ₁₆	100.204	397.4	511	0.6881	5.7364	3.4598	3.787	5100.0
n-Octane	C ₈ H ₁₈	114.231	361.1	564	0.7069	5.8926	3.9441	3.322	5796.1
n-Nonane	C ₉ H 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 ₂ O	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 ₂ S	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)

$$= 8.3372 \text{ lb} / 0.13368 \text{ ft}^3 = 62.37 \text{ lb/ft}^3$$

- Transform the density to pressure

psi = pounds per square inch

$$62.37 \text{ lb} / (12 \text{ inch} * 12 \text{ inch}) = 0.433 \text{ psi}$$

→ 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 lbm / gal	SG _G (air)	Vapor Density ft ³ / lb*	Heating Value BTU / ft ³
			Press psia	Temp °F					
Methane	CH ₄	16.043	667.0	(-117)	0.3000	2.5000	0.5539	23.654	909.4
Ethane	C ₂ H ₆	30.070	707.8	90	0.3562	2.9696	1.0382	12.620	1618.7
Propane	C ₃ H ₈	44.097	615.0	206	0.5070	4.2268	1.5226	8.606	2314.9
IsoButane	C ₄ H ₁₀	58.123	527.9	274	0.5629	4.6927	2.0068	6.529	3000.4
n-Butane	C ₄ H ₁₀	58.123	548.8	306	0.5840	4.8691	2.0068	6.529	3010.8
i-Pentane	C ₅ H ₁₂	72.150	490.4	369	0.6244	5.2058	2.4912	5.260	3699.0
n-Pentane	C ₅ H ₁₂	72.150	488.1	386	0.6311	5.2614	2.4912	5.260	3706.9
n-Hexane	C ₆ H ₁₄	86.177	439.5	452	0.6640	5.5363	2.9755	4.404	4403.9
n-Heptane	C ₇ H ₁₆	100.204	397.4	511	0.6881	5.7364	3.4598	3.787	5100.0
n-Octane	C ₈ H ₁₈	114.231	361.1	564	0.7069	5.8926	3.9441	3.322	5796.1
n-Nonane	C ₉ H 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 ₂ O	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
- Kinematic viscosity: ν
 - Greek letter nu
 - Units: Centistokes

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

Absolute (μ) and Kinematic (ν) viscosity

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

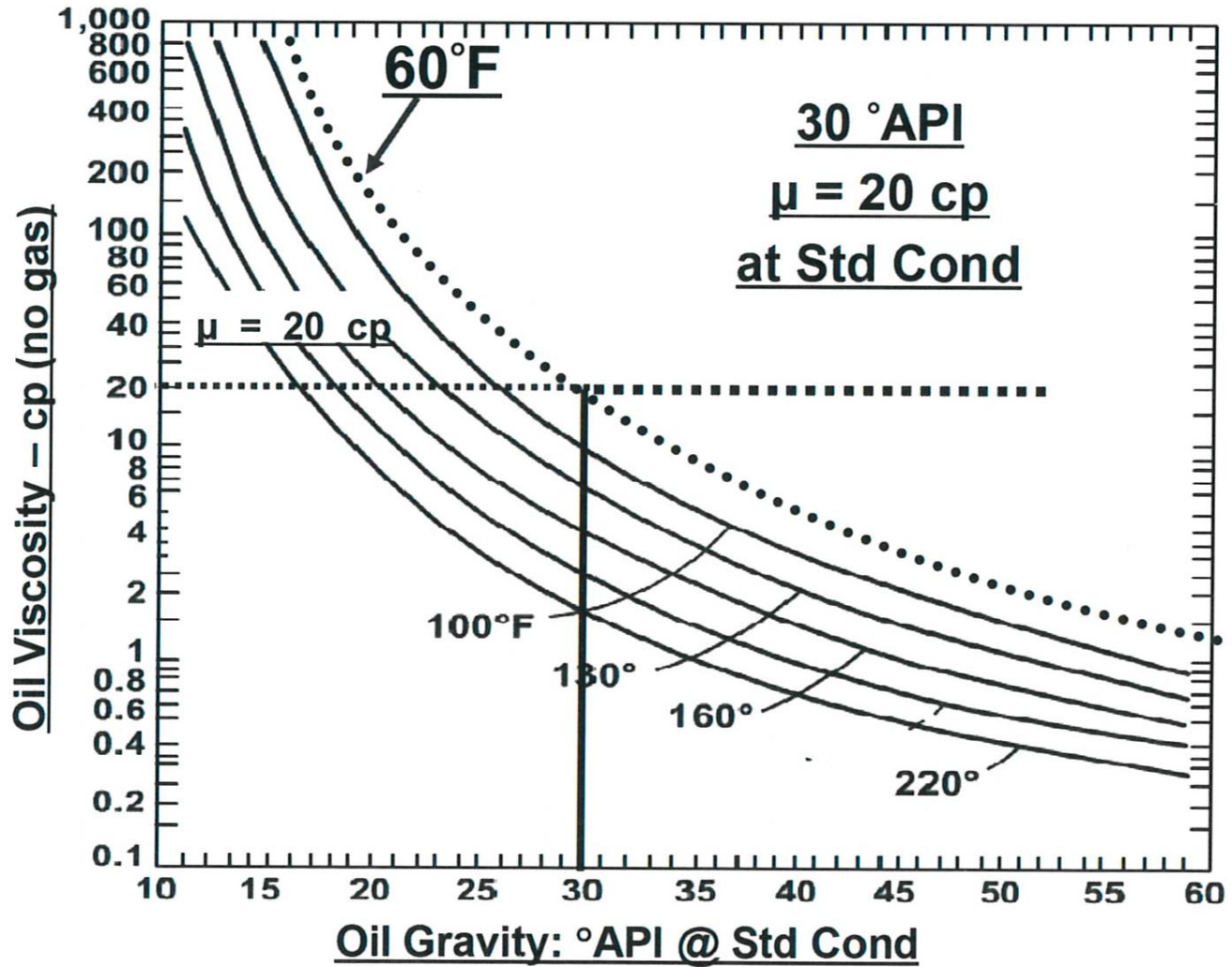
For Liquids:

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

Stock Tank Oil

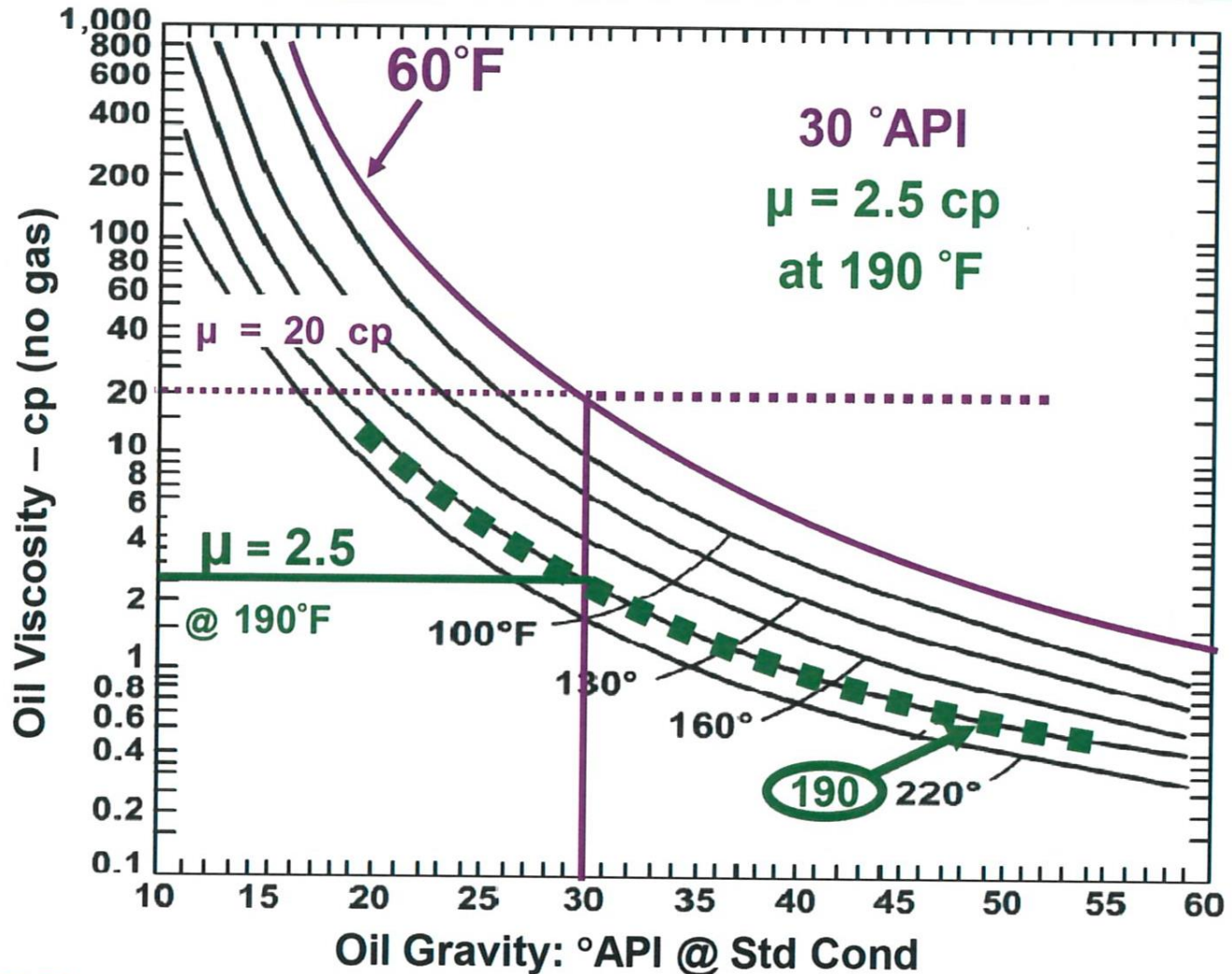
(Measured at Standard Conditions)

Oil viscosity vs. Temperature



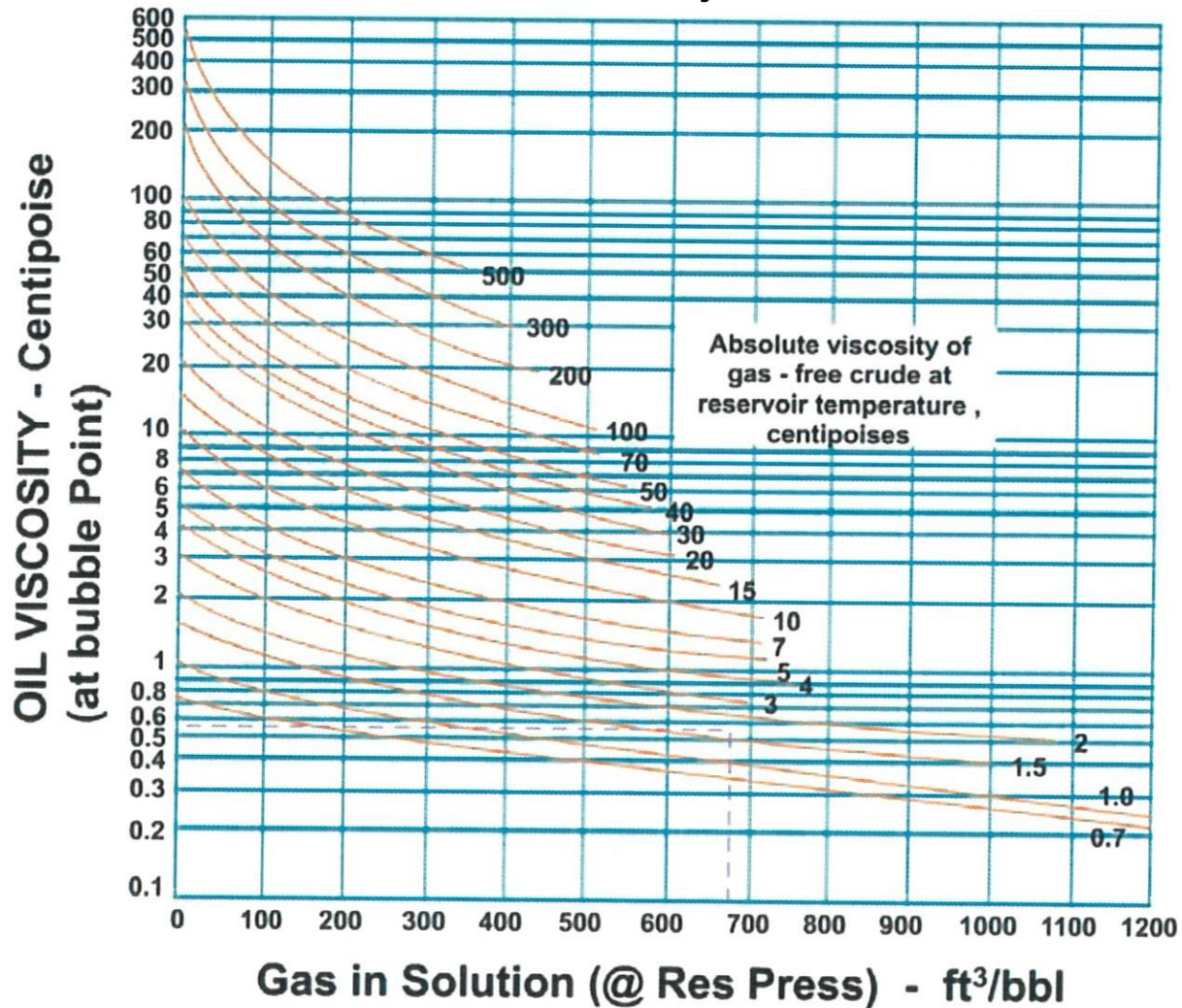
Oil viscosity vs. Temperature

- Dominant effect by temperature

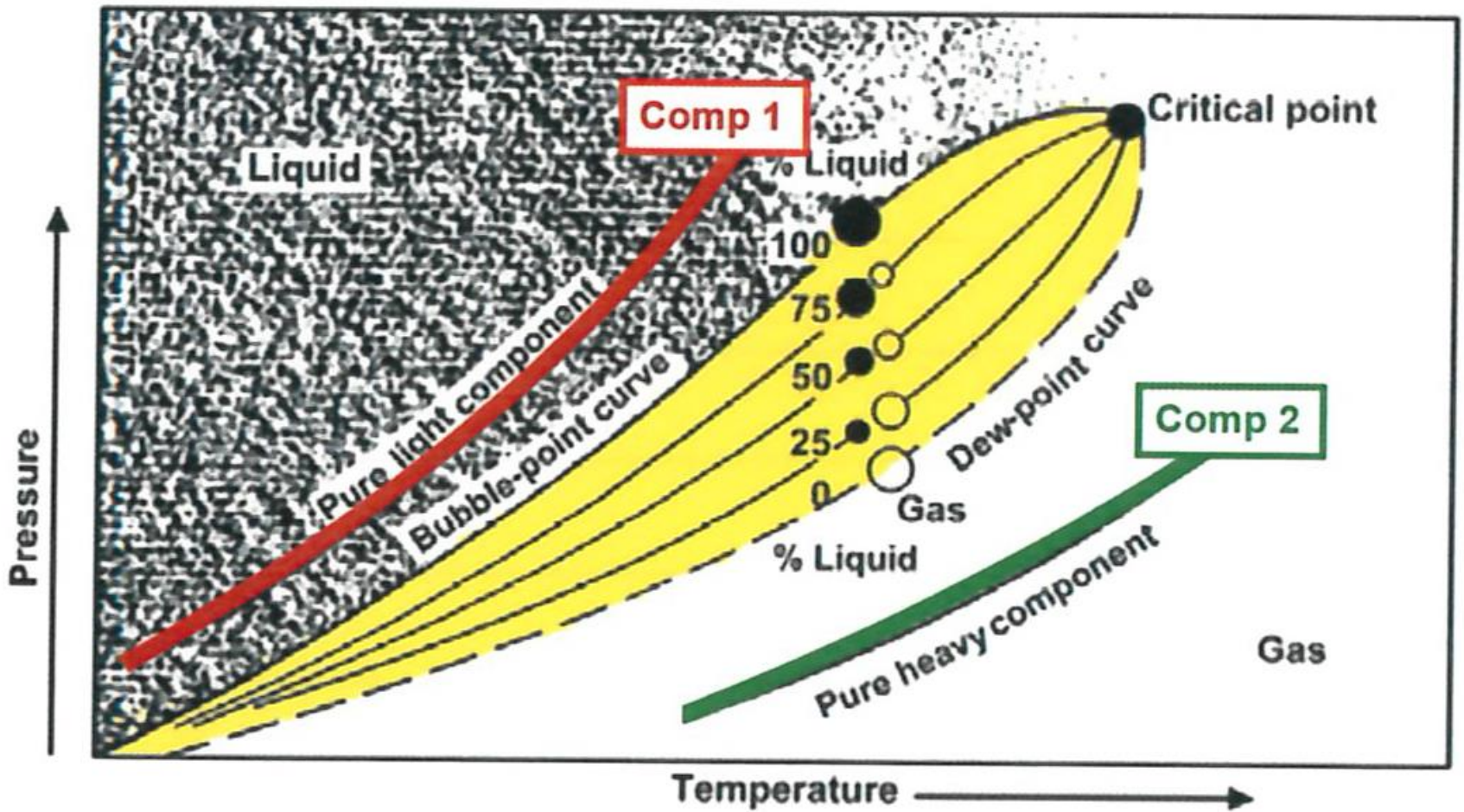


Effect of solution gas on oil viscosity

- Gas dissolution reduces viscosity

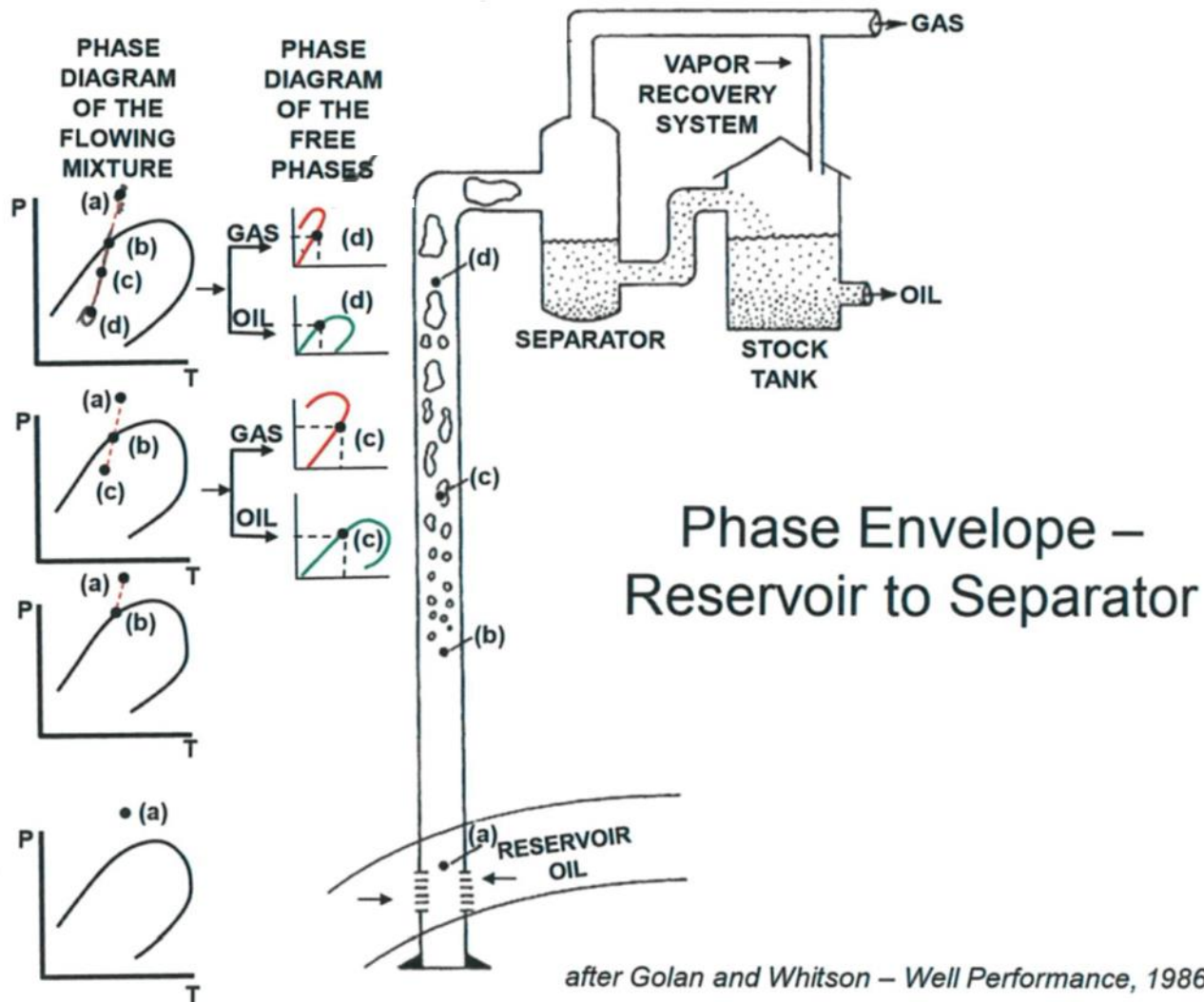


Phase diagram: Two components



Phase behavior

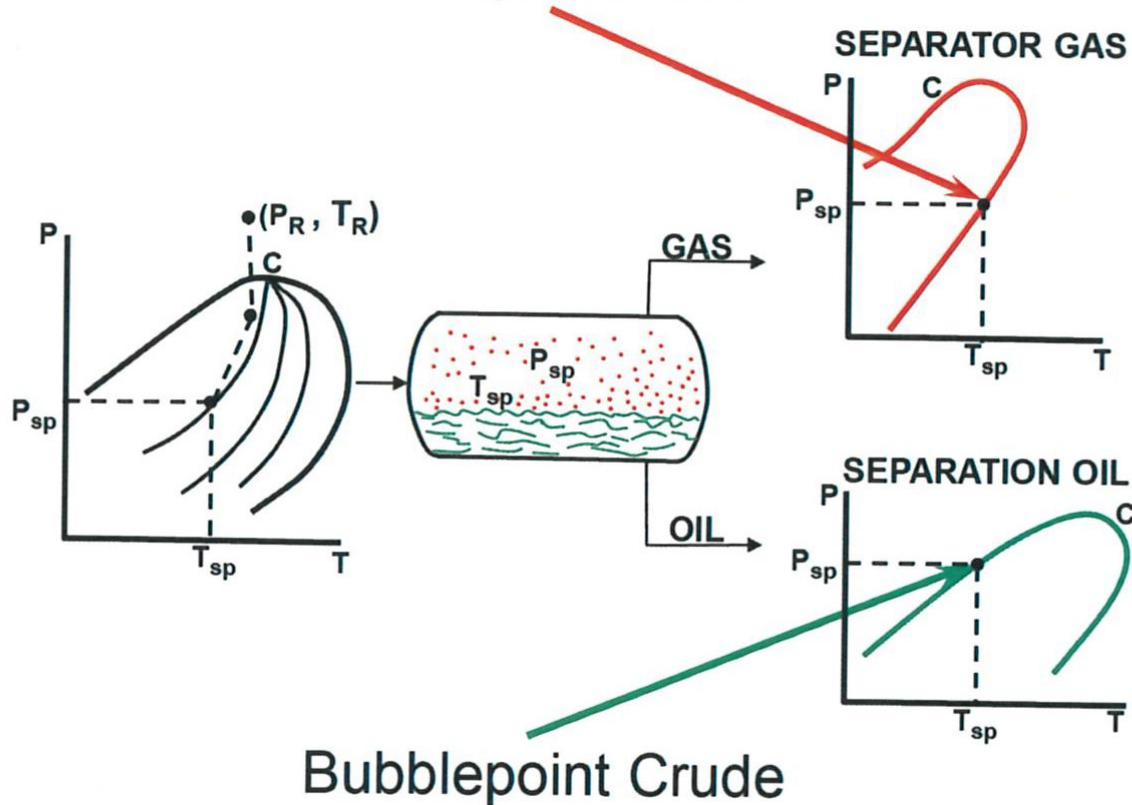
Can the Phase Envelope Change?



Phase behavior

Can the Phase Envelope Change?

Dewpoint Gas



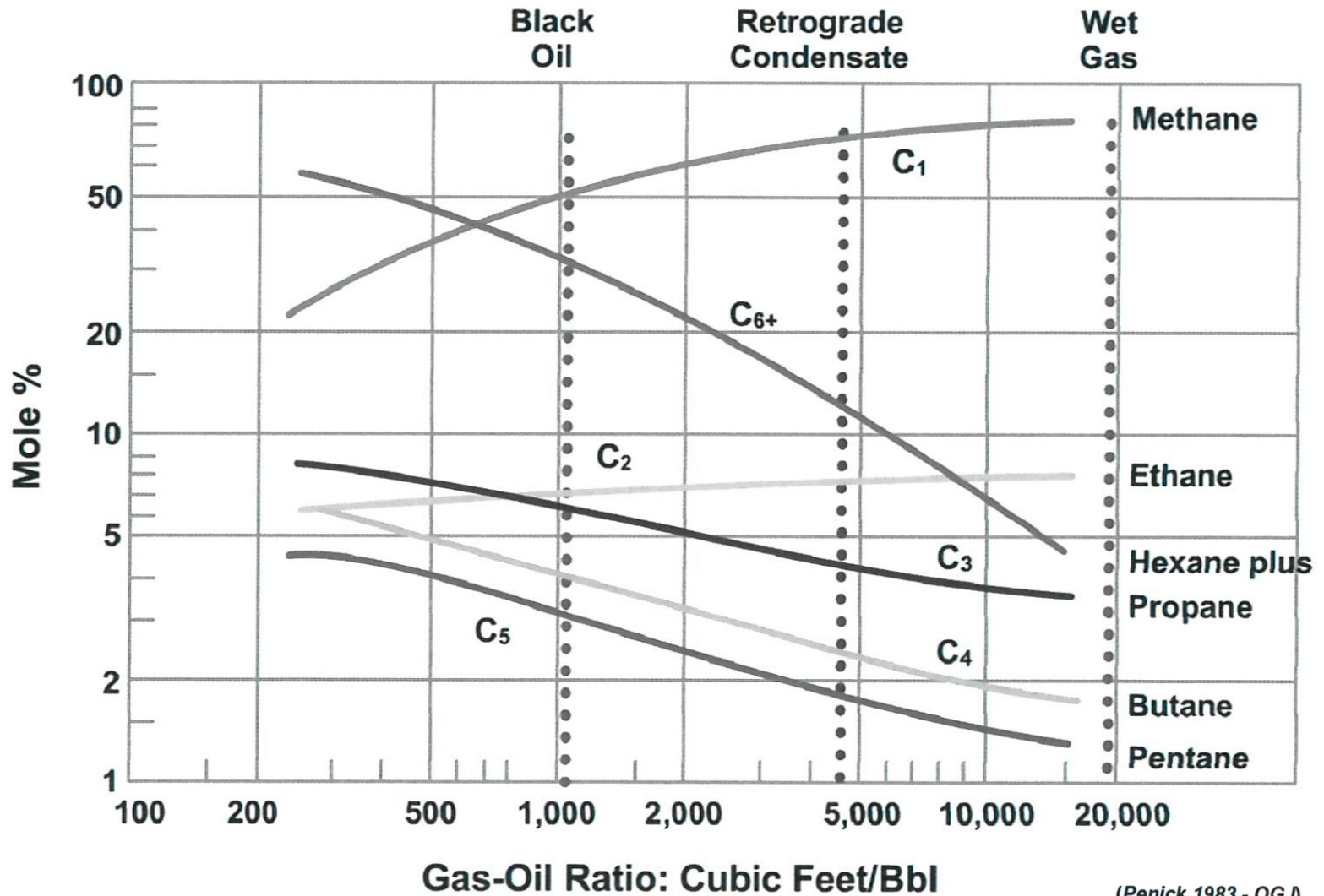
Bubblepoint Crude

Composition change = Phase Envelope change

Petroleum fluid classification

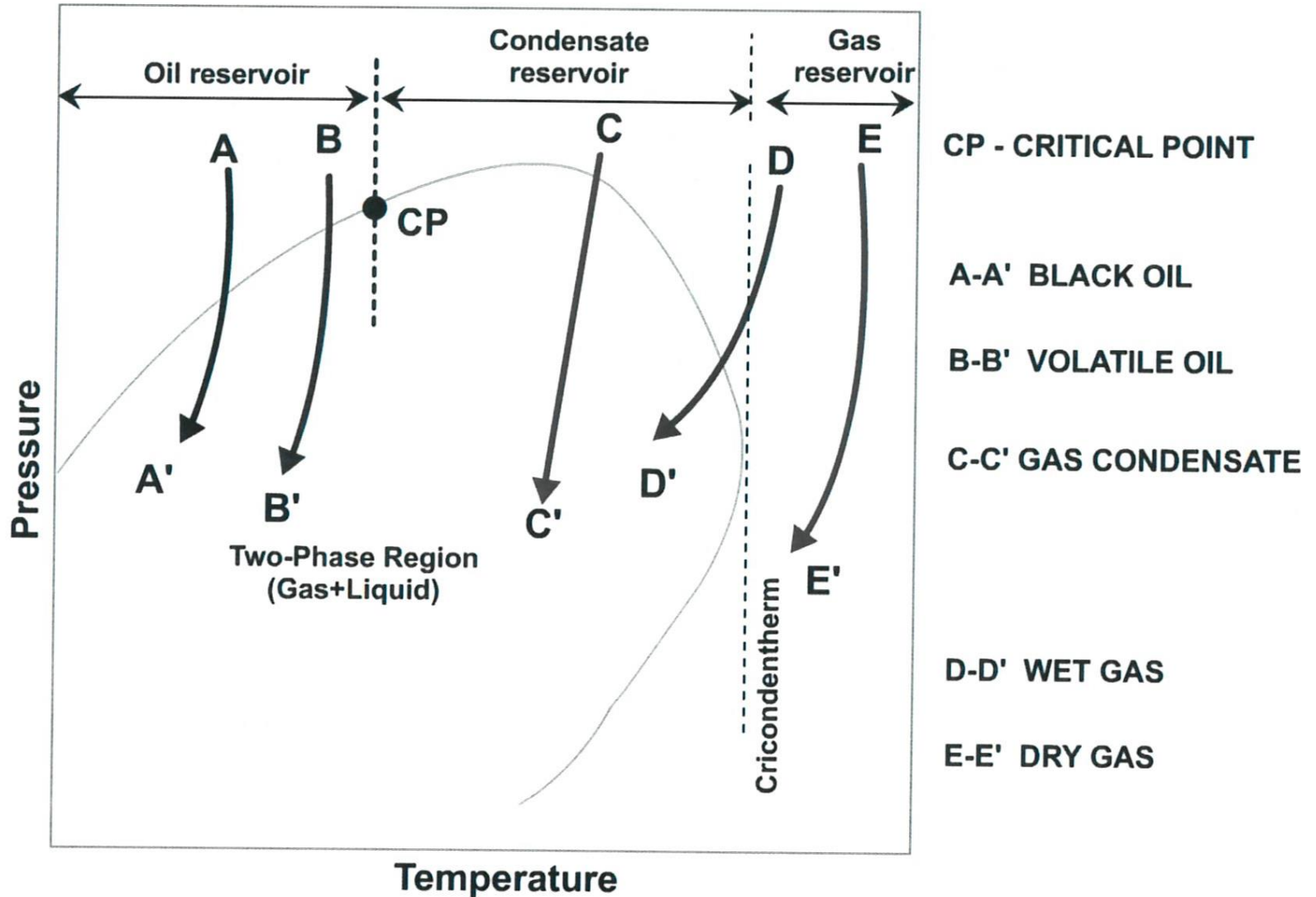
Fluid	Shrinkage STBO/Res Bbl	GOR Scf/STBO	API	Color	Yield STBO/MMscf
Low-Shrinkage Oil (Low GOR)	> 0.5	< 2,000	< 45	Very Dark Often Black	> 500
High-Shrinkage Oil (High GOR)	< 0.5	2,000 - 3,300	> 45	Colored Usually Brown	> 500
Retrograde Condensation	> 0.35	3,300 - 50,000	50-60	Light Clear	20 - 300
Wet 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 P_{pc} 4 = 2 x 3	COMP T_c 5	Stream T_{pc} 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

<u>COMP</u>	<u>P_c</u>	<u>x%</u>	<u>T_c</u>	<u>x%</u>
70% C ₁	666		343	
20% C ₂	706		550	
10% C ₃	616		666	

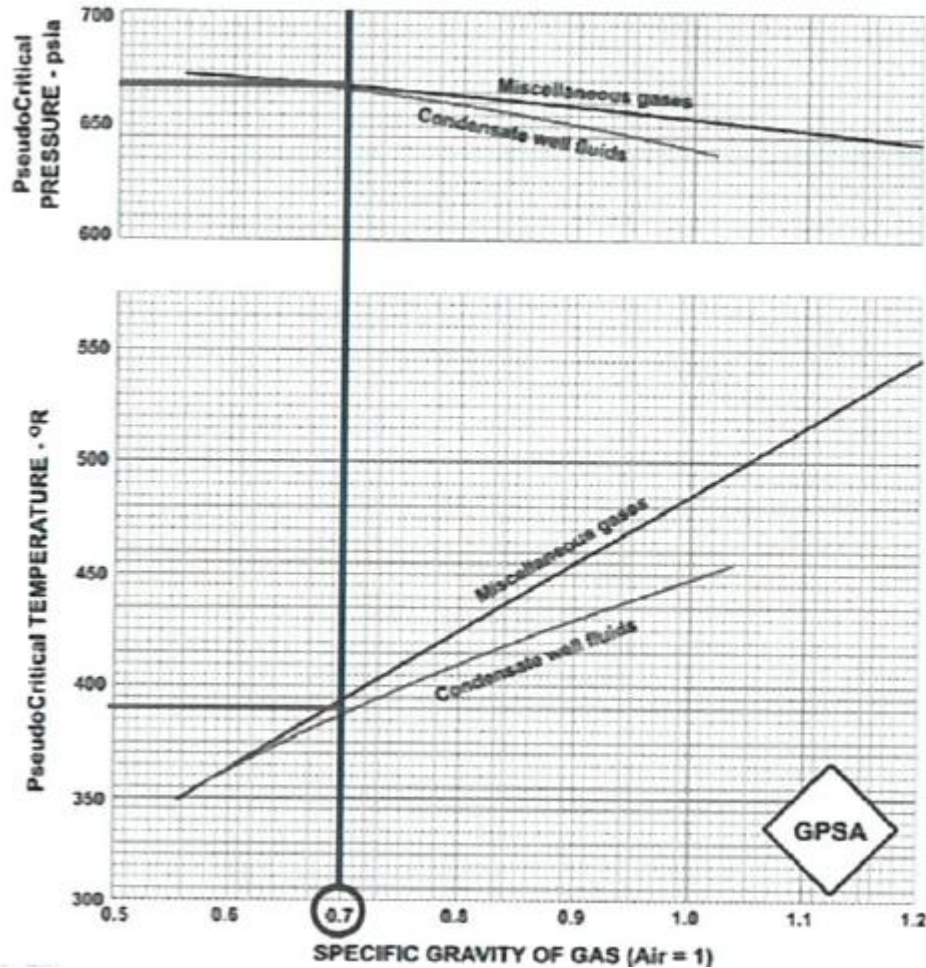
Ppc

Tpc

Critical P_c & T_c of a Mixture is referred to as

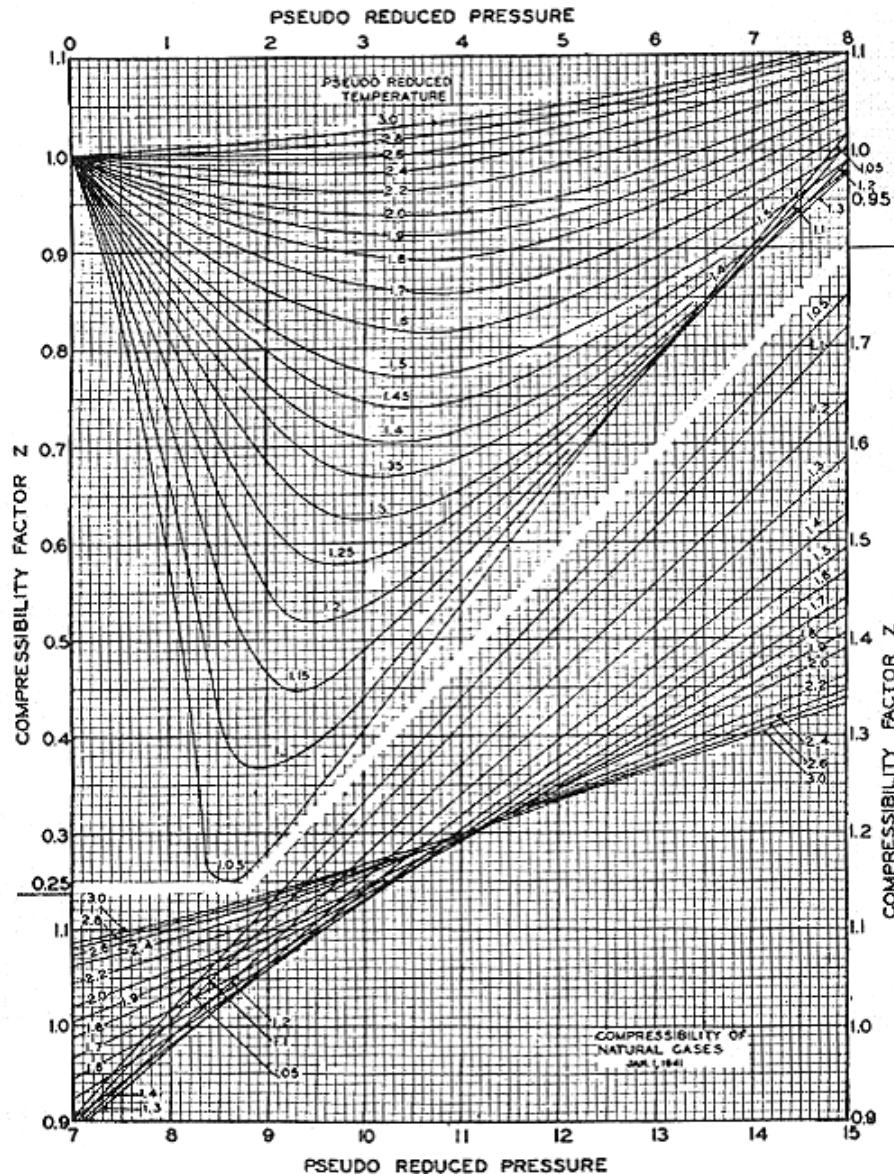
Pseudo - Critical Pressure & Pseudo - Critical Temperature
 P_{pc} & T_{pc}

T_c, P_c from SG



FIND P_{pc} and T_{pc}
of a GAS with
 $SG_g = 0.7$

Compressibility Factor: Z



Find Z

Exercise

P = 3000 psia

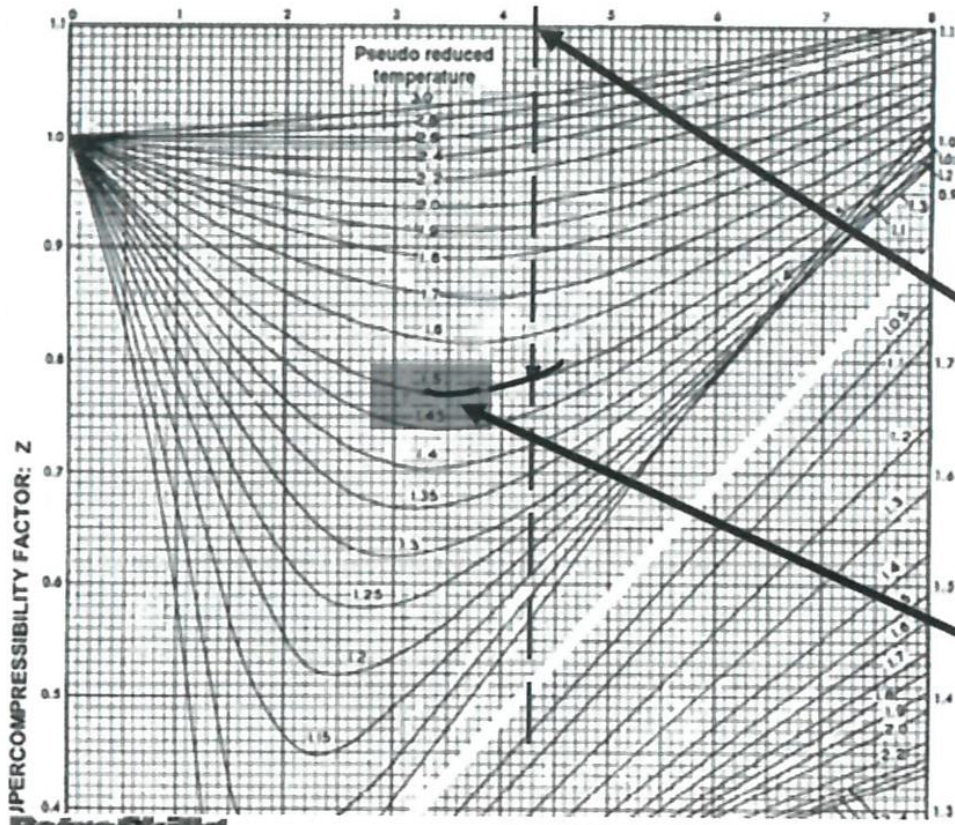
T = 120°F = 580°R

SG = .7 ∴

P_{pc} = 666 psia

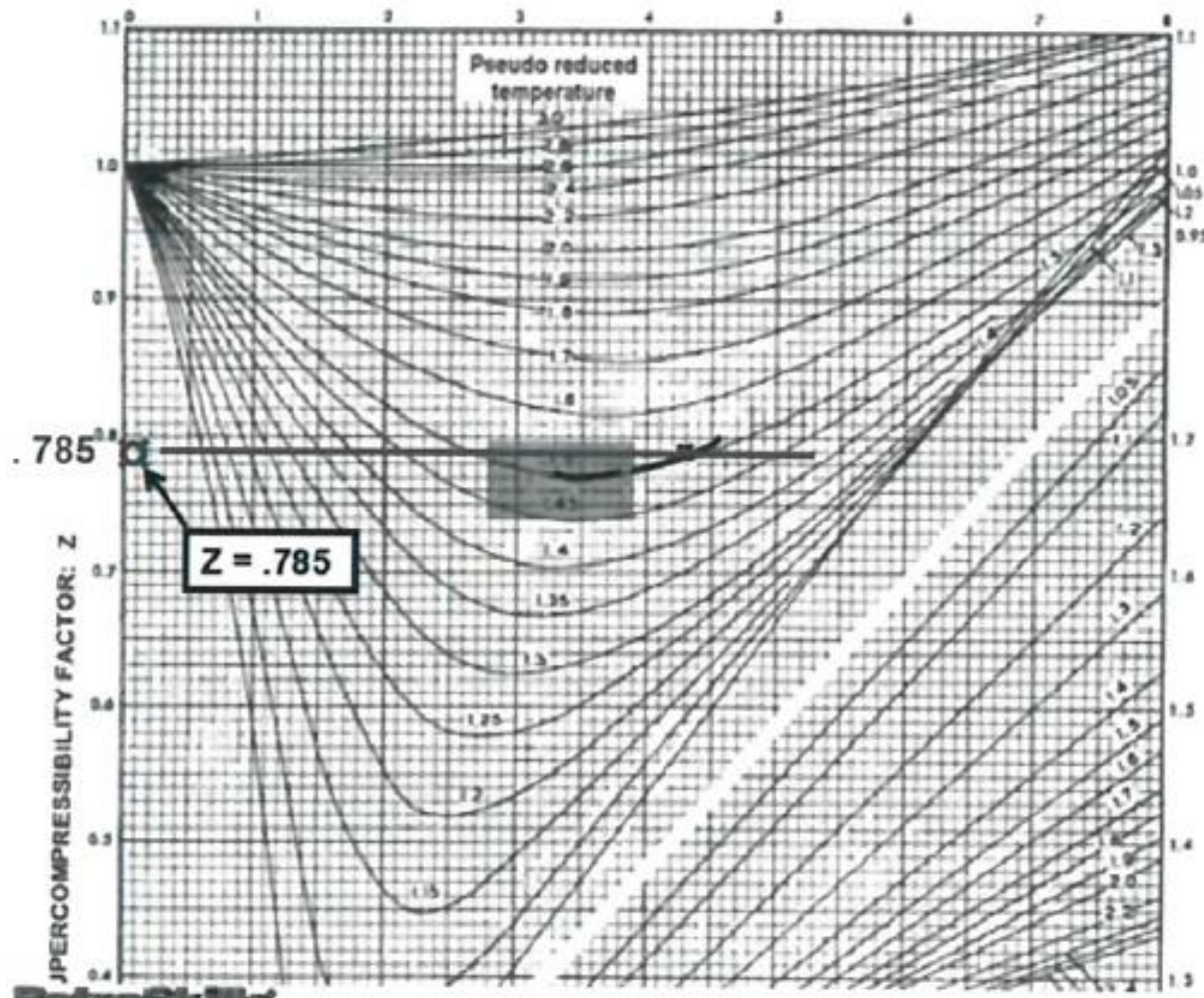
T_{pc} = 390 °R

Compressibility Factor: Z



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

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



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

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

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

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

Standard Conditions

Pipeline Conditions



Thank you