



Chapter 4

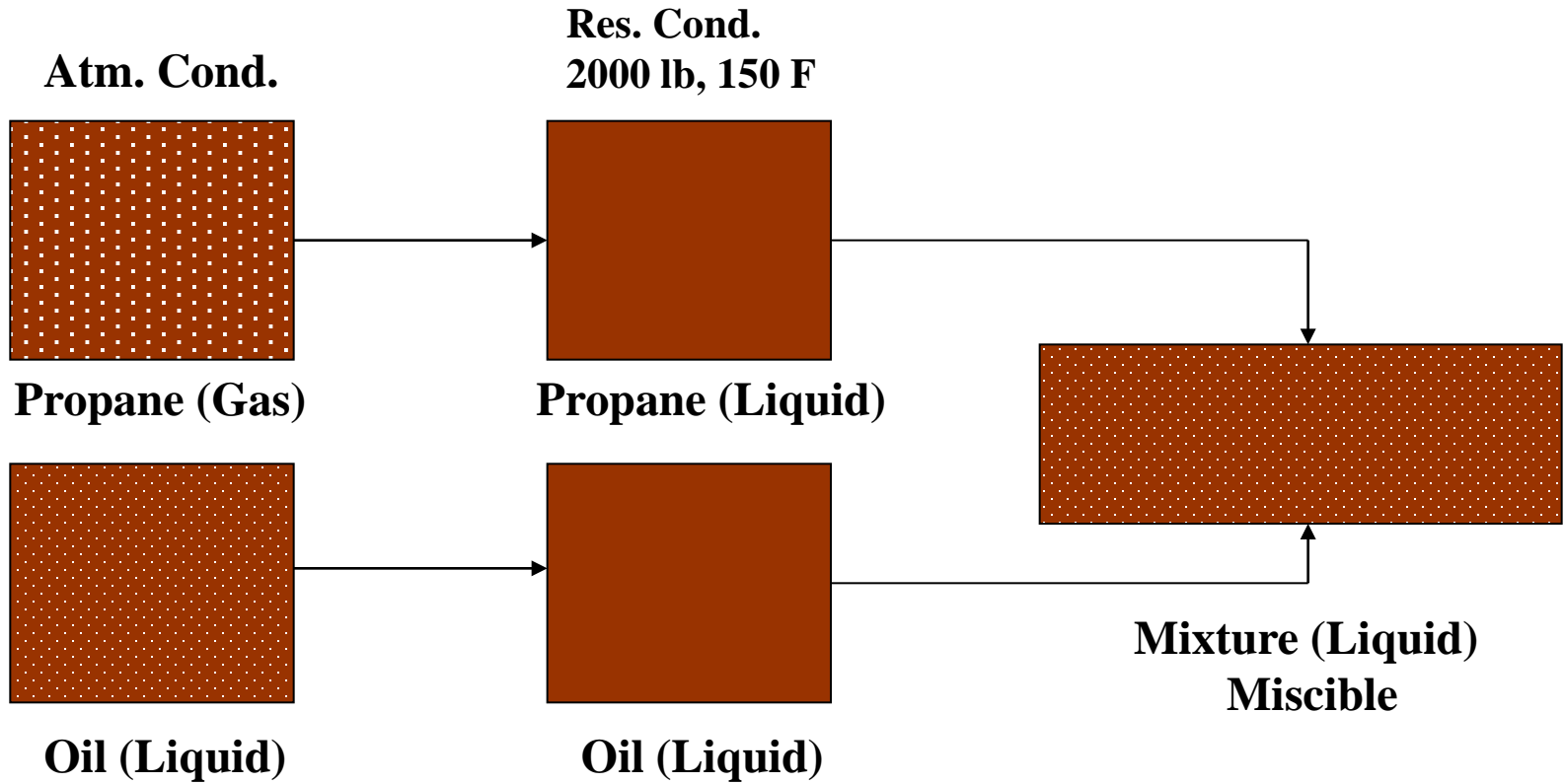
Gas Injection Process



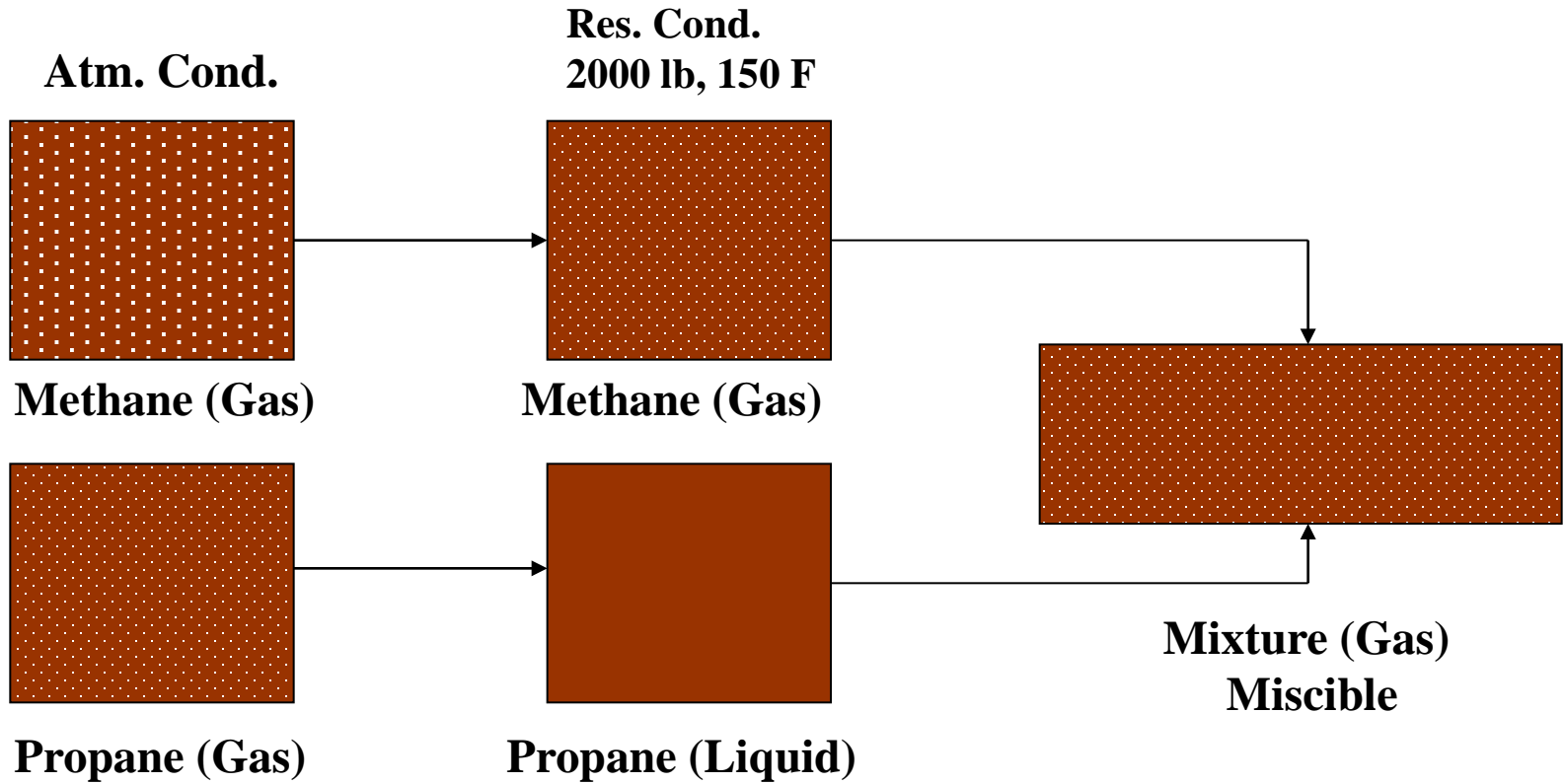
Contents

- Introduction
- General description of phase behavior
- Principle of phase behavior
- FCM process
- MCM process
- Immiscible process
- Measurement & prediction of MMP

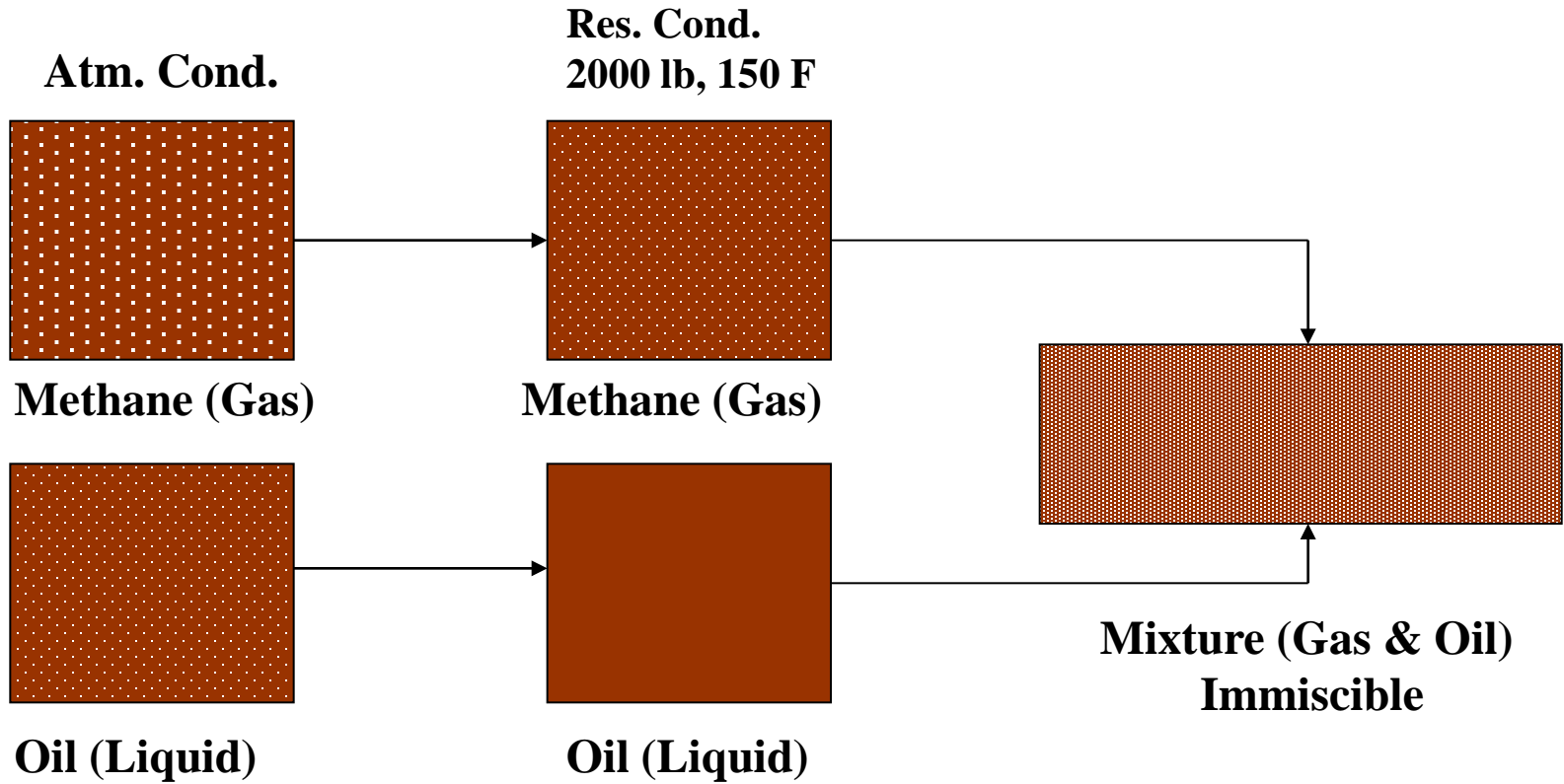
First-Contact Miscible



First-Contact Miscible

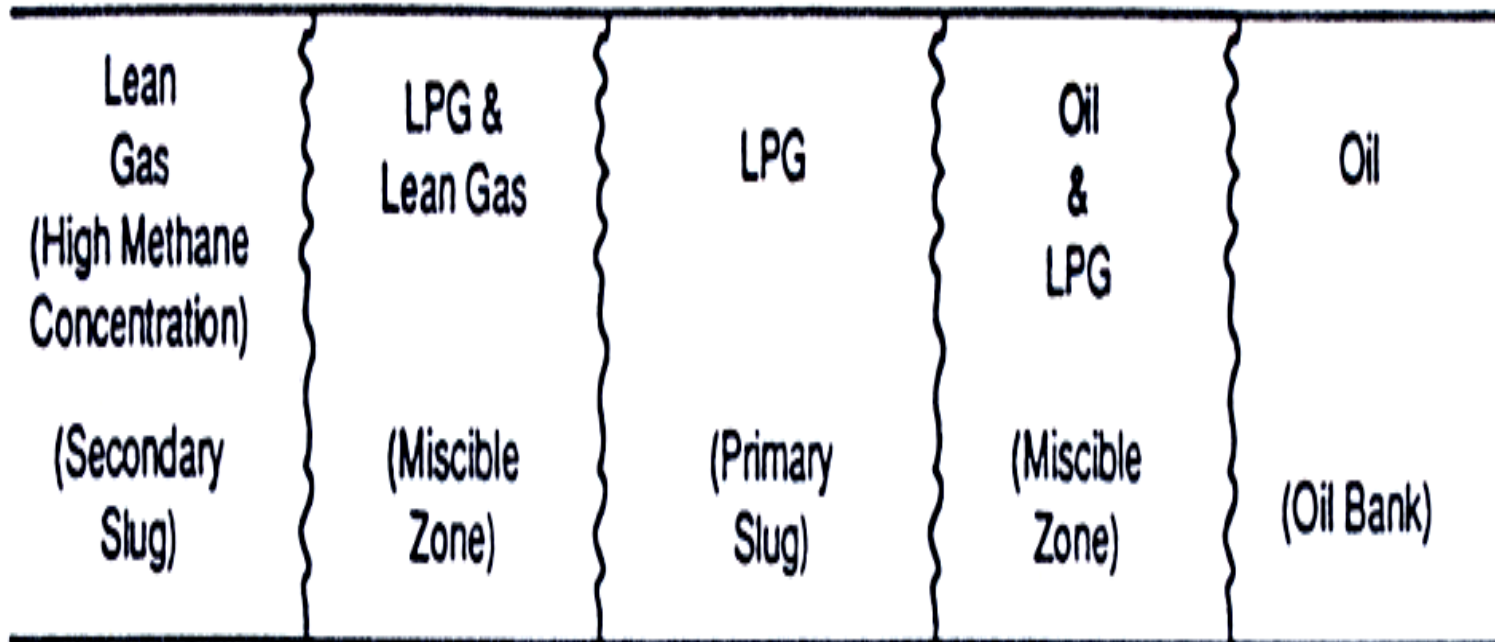


Immiscible Process

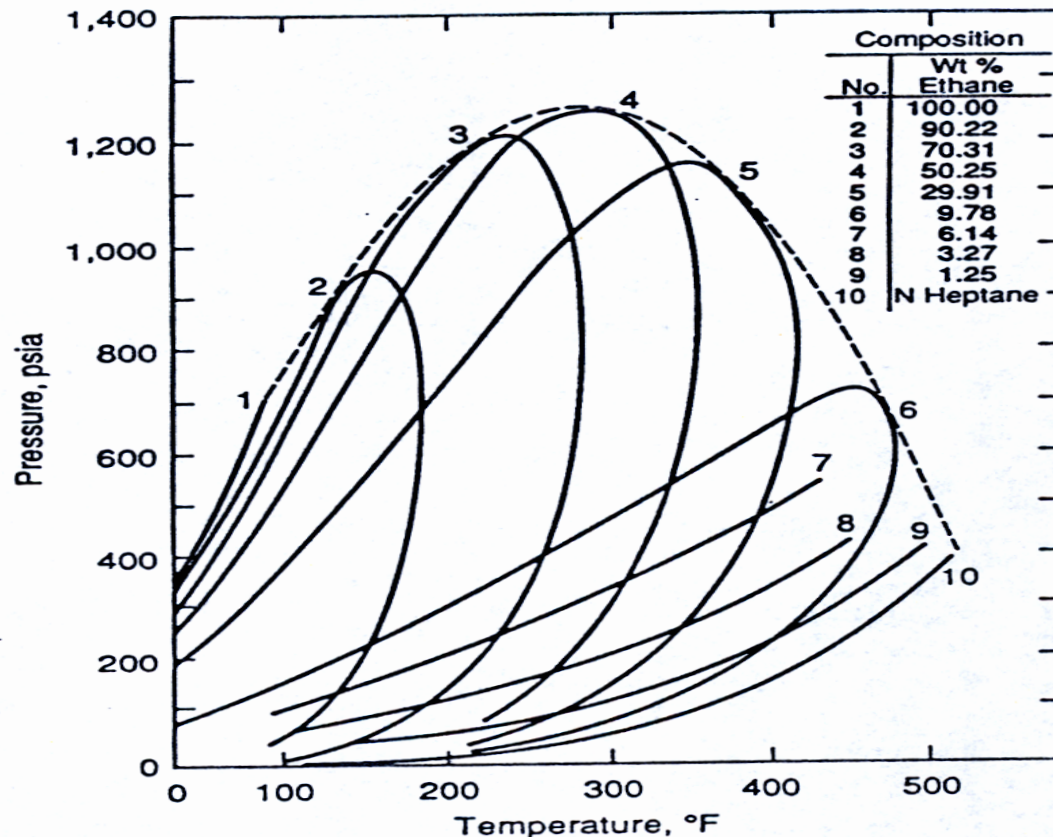




Idealized Miscible Displacement



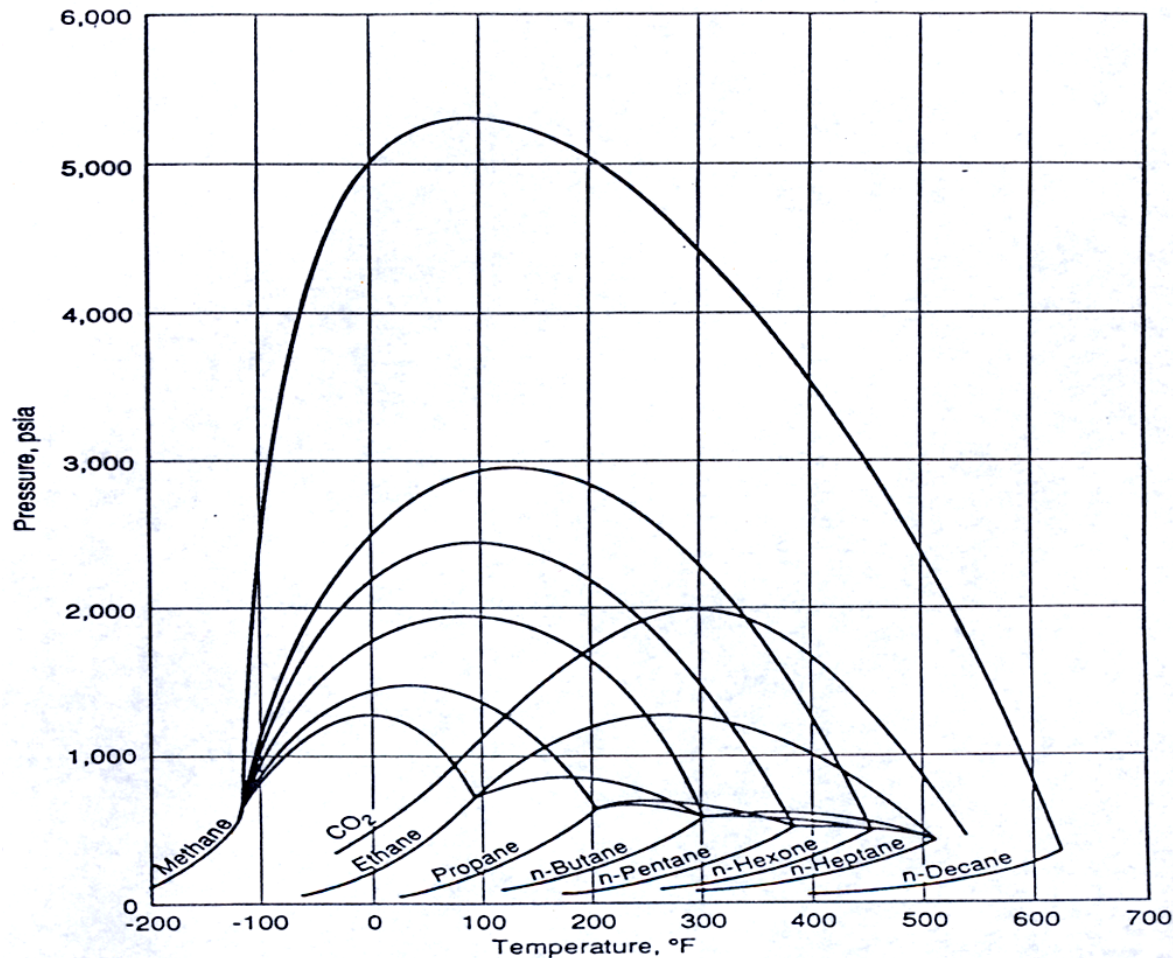
Pressure/temperature phase diagrams or mixtures of ethane & n-heptane



Shows how P-T diagram changes with changing composition of a binary.

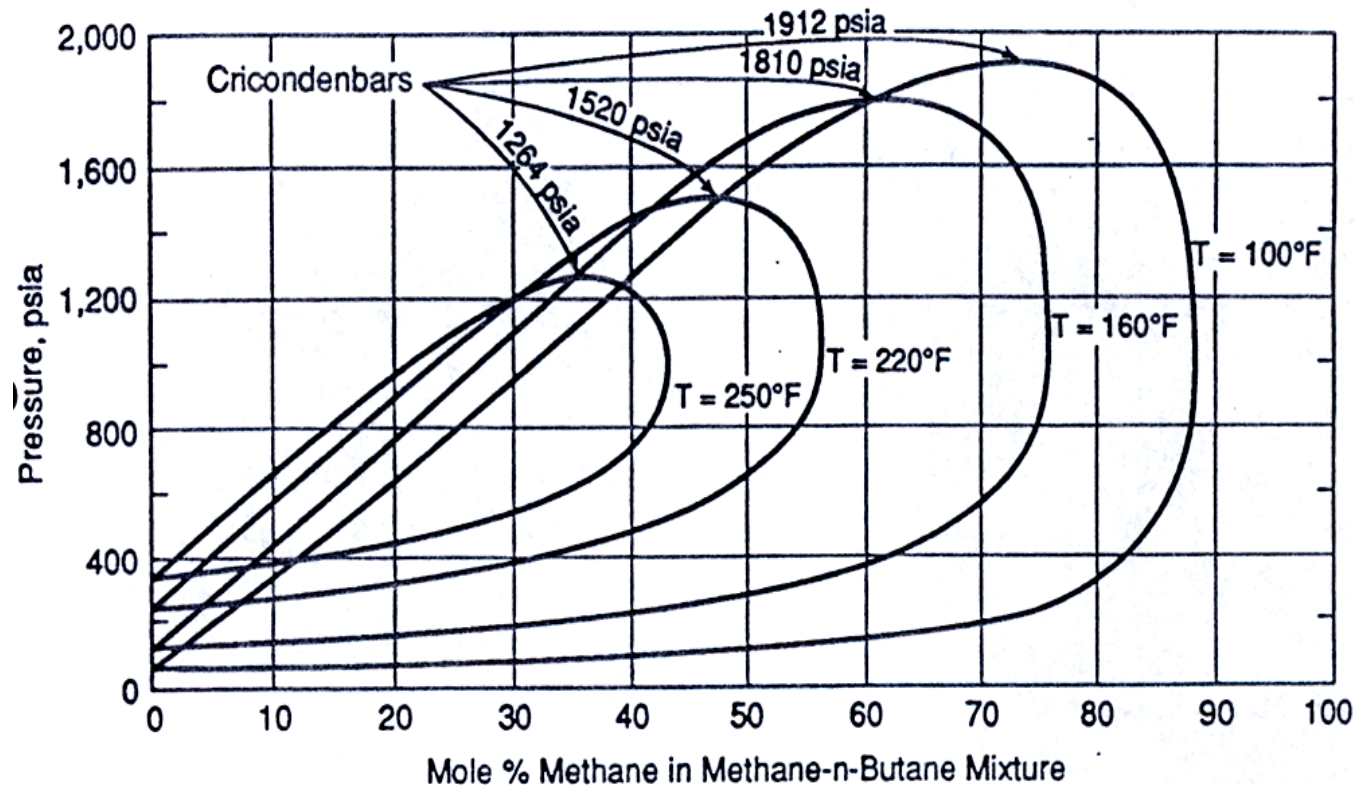
- For a pure component the two-phase envelope shrinks to a single curve that ends at the critical point.
- The dashed line is the locus of critical points of various compositions

Critical loci of binary n-paraffin systems



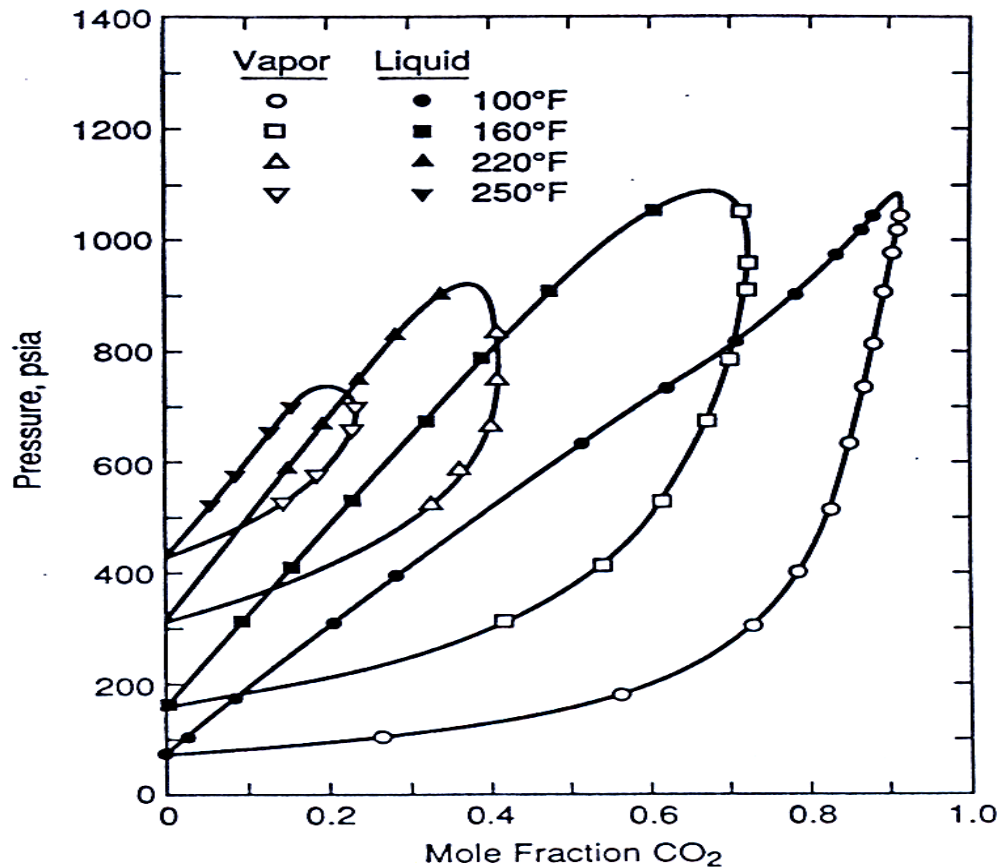
- This figure shows the loci of critical points of several pairs of hydrocarbons.
- The loci start at the critical point of a pure component and end at the critical point of the other pure component in the binary mixtures.
 - These loci are similar to the dotted line in the previous figure.

Pressure/composition isotherms for the methane/n-butane system



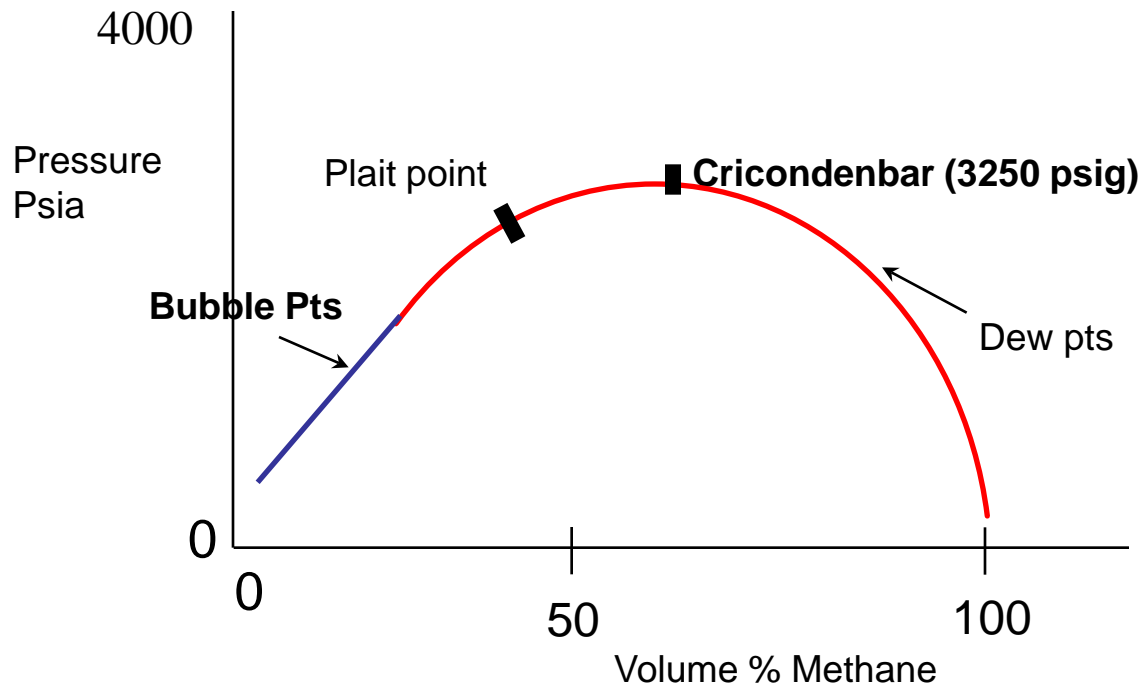
When the temperature is above the critical temperature of the more volatile component, some compositions can be single phase at all pressures.

Pressure-equilibrium phase composition diagram for i-butane/CO₂ system

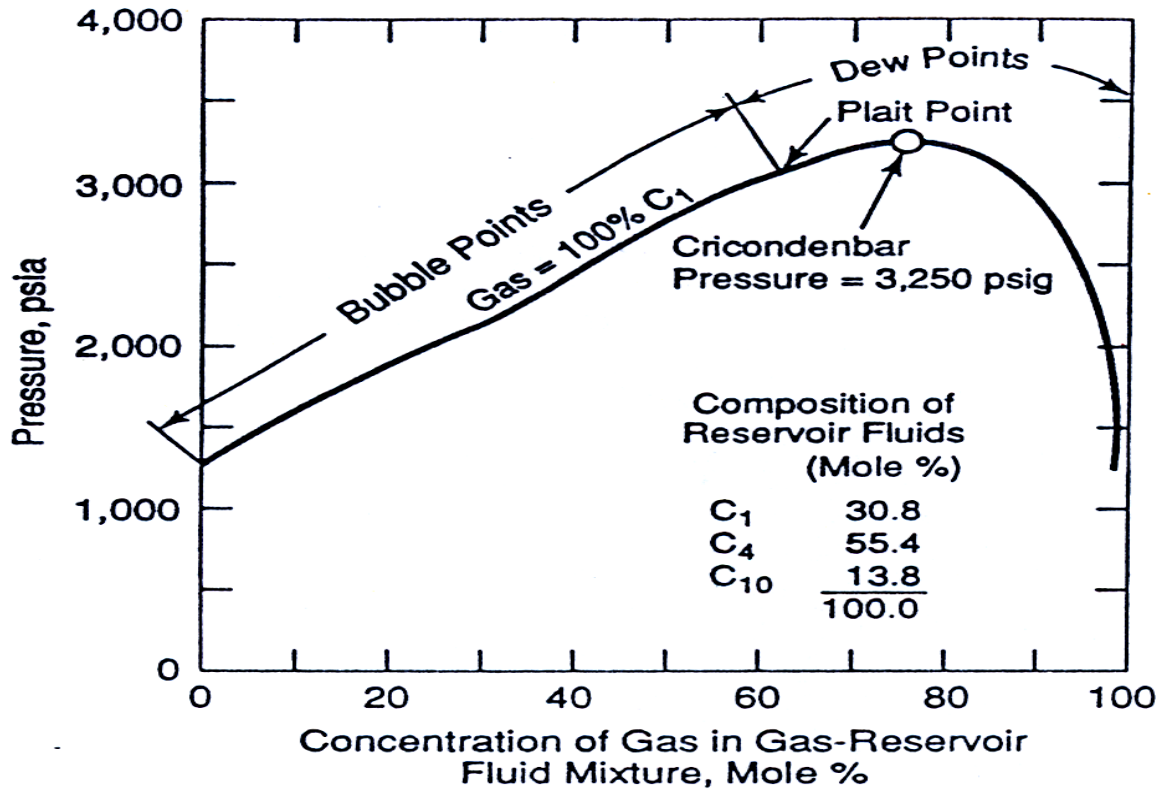


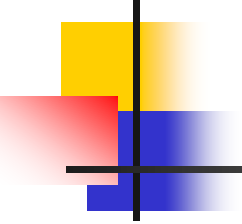
Compositional Processes

Rule: For 1st Contact Miscible - Pressure of Displacement must be above Cricondenbar

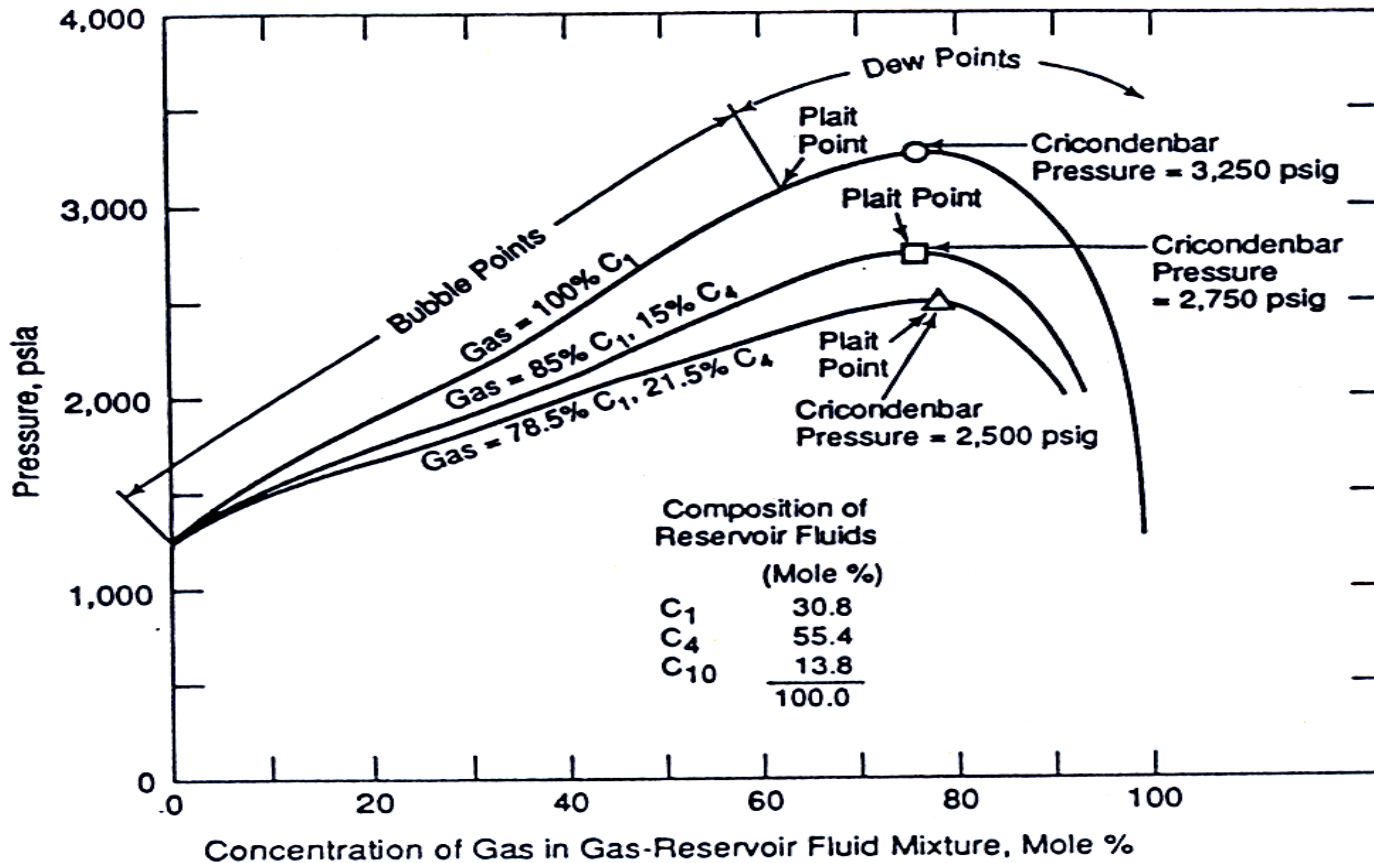


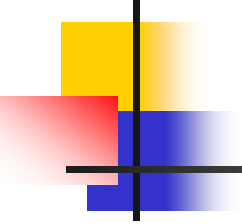
Pressure/composition diagram for mixture of C_1 with a $C_1/n-C_4/C_{10}$ liquid



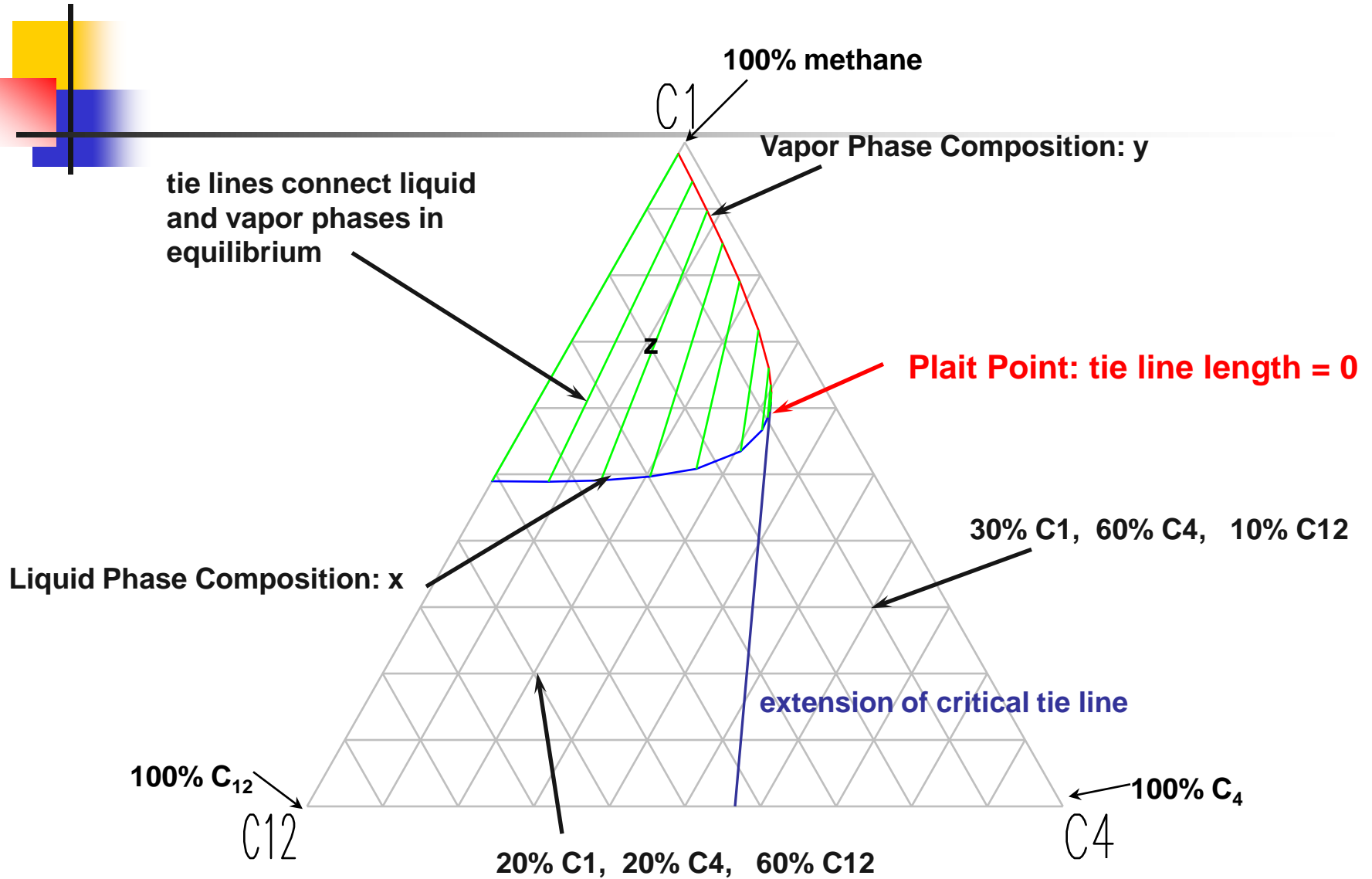
- 
-
- The reservoir fluid, comprising 30.8% C1, 55.4% C4 and 13.8% C10 is used as a pseudo component.
 - The diagram presents the results of adding C1 to this fluid, exactly the same way as would be done if it were a pure component.
 - The bubble point and dew point curves are shown as well as the plait point and the cricondenbar pressure.
 - It is an approximate way of describing the behavior.
 - By defining this pseudo component, we are saying that in any phase, C4 and C10 ratio will remain fixed at 55.4 to 13.8.
 - This is not strictly true, since C4 is more volatile and its ratio in the vapor phase will be higher.

Effect of gas composition on the cricondenbar of the gas (C₁ to nC₄)/decane system at 160°F

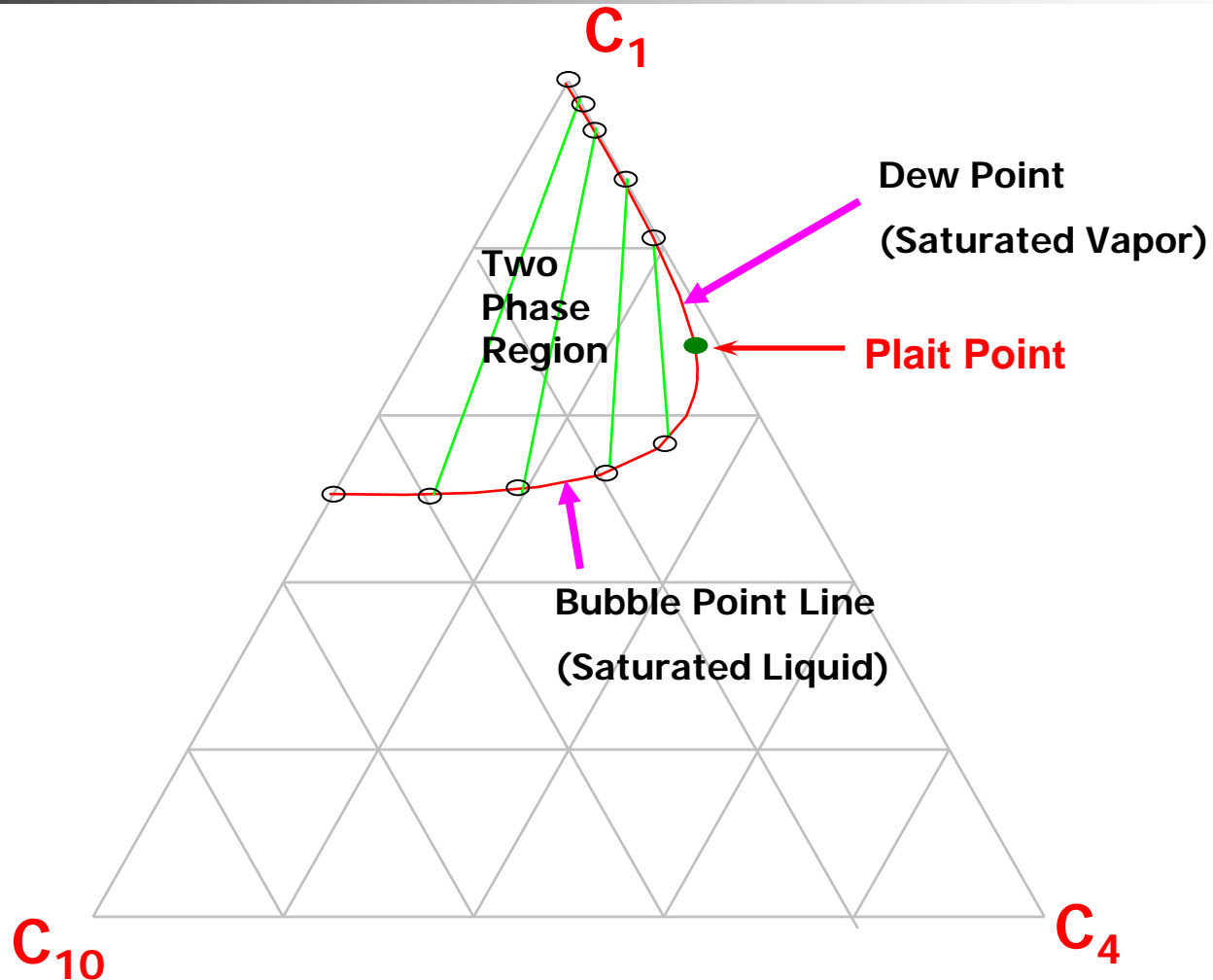


- 
-
- Here three different compositions are used for the gas phase.
 - Gas compositions containing more than one component are pseudo components.
 - As the gas becomes richer in C4, the cricondenbar pressure decreases.
 - The gas can achieve first contact miscibility with the reservoir fluid at a lower pressure when it becomes richer in intermediate components

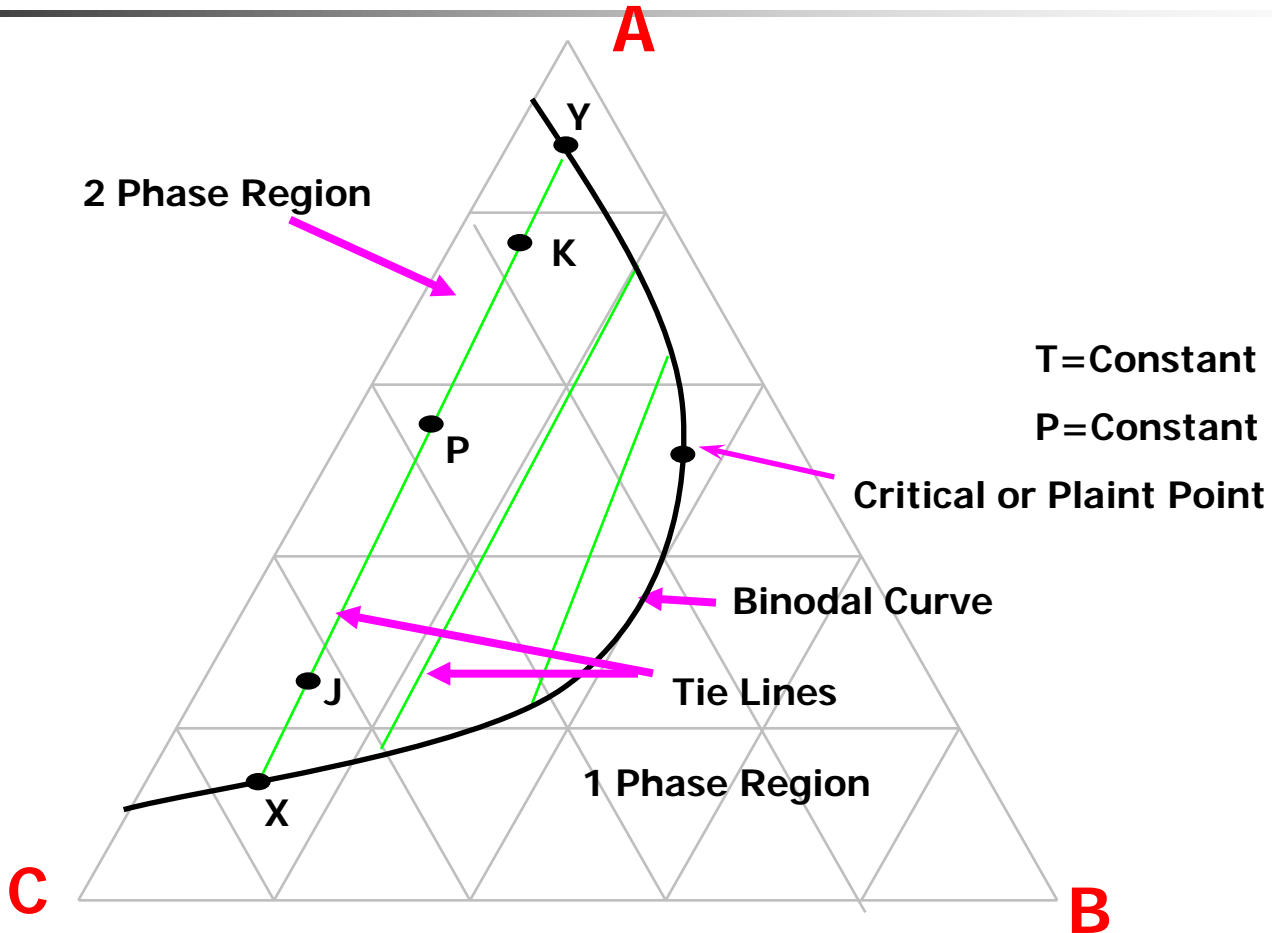
Ternary Diagram



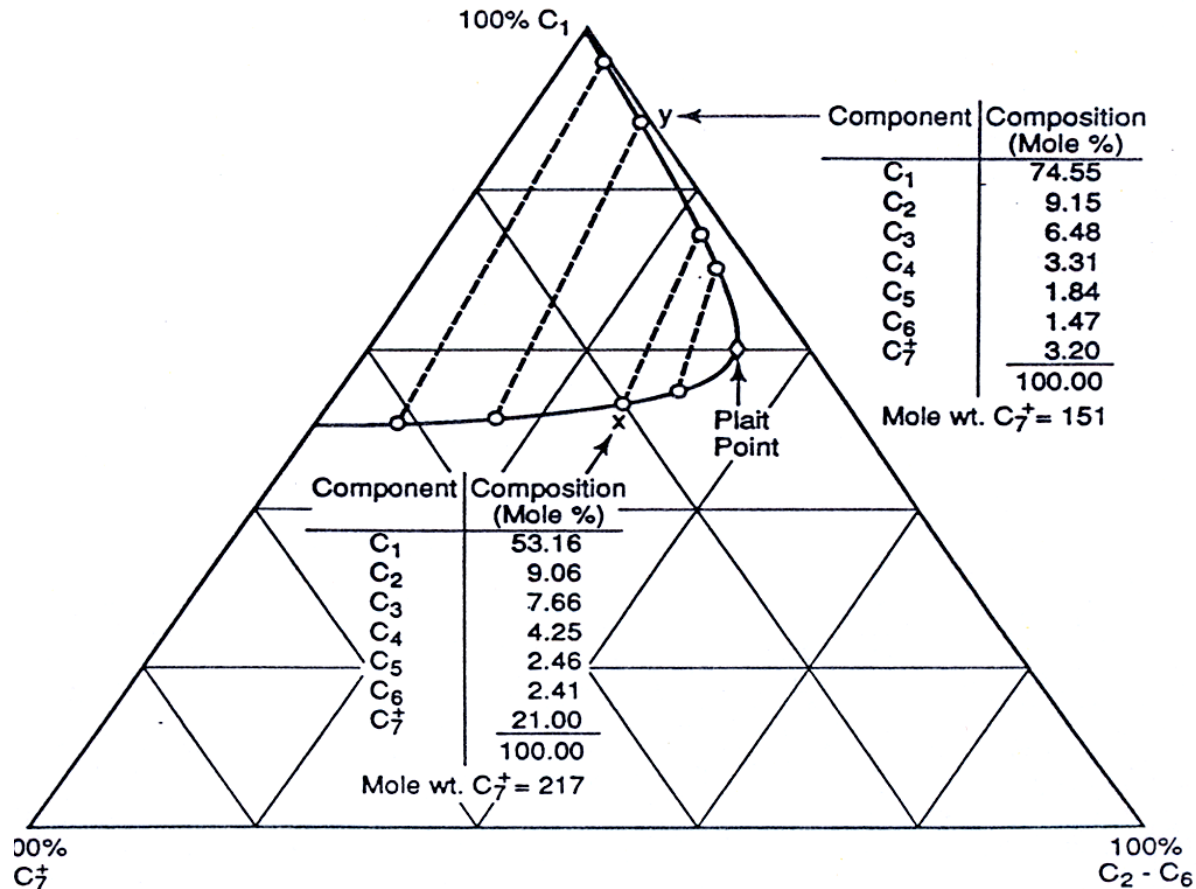
Phase relation for methane/n-butane /decane system at 160°F and 2500 psia



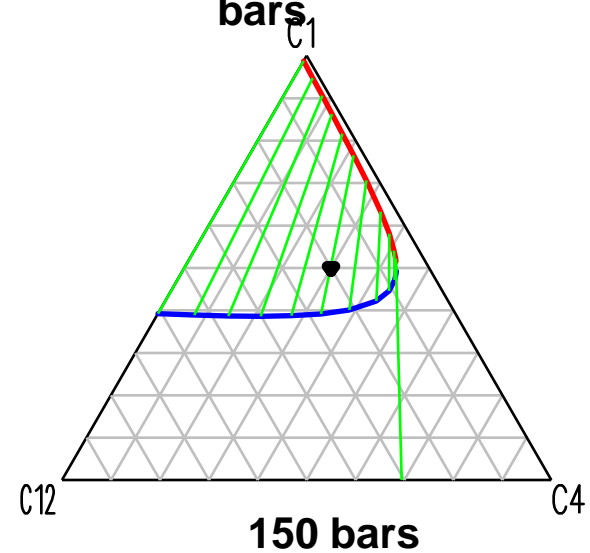
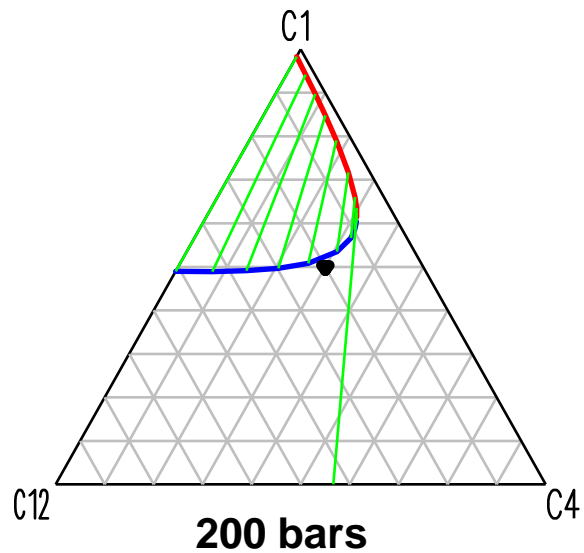
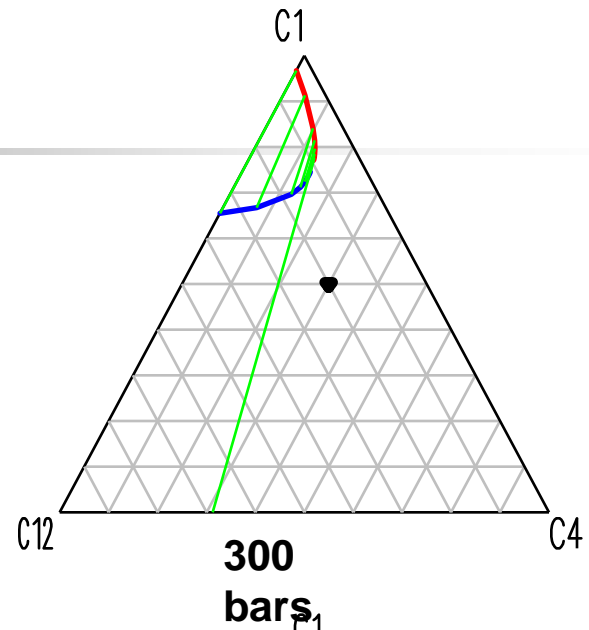
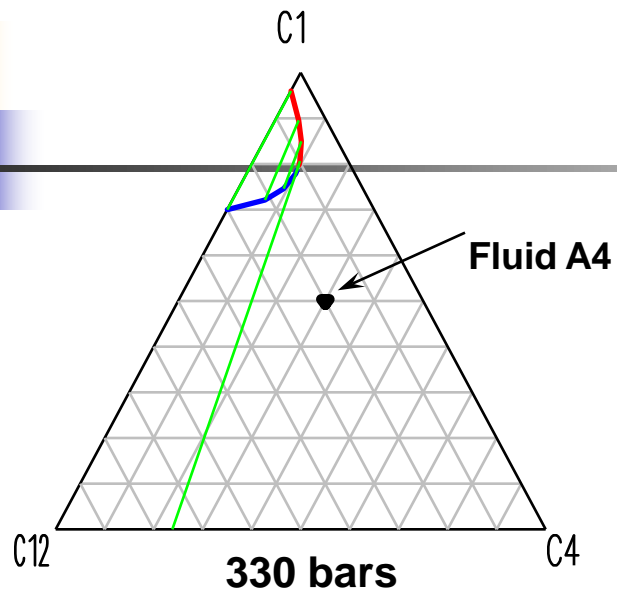
Ternary Diagram



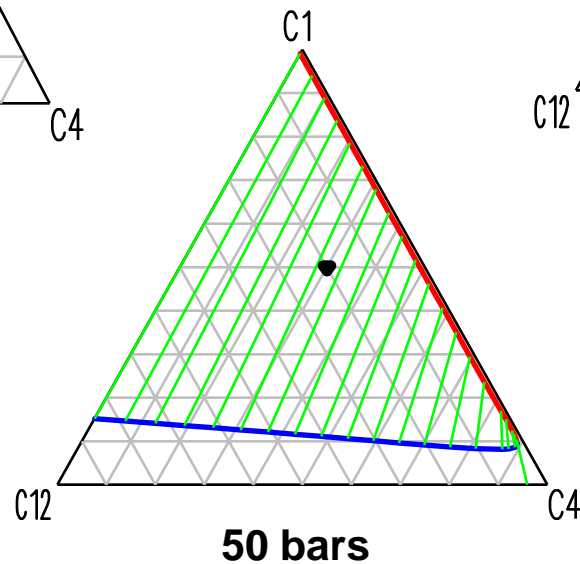
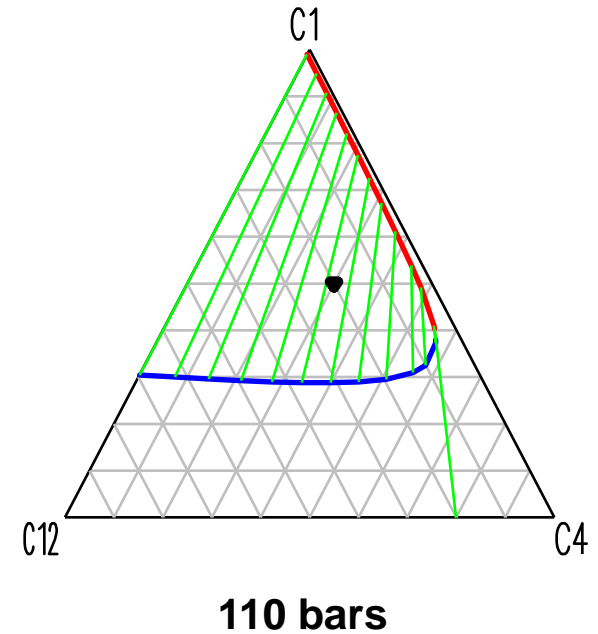
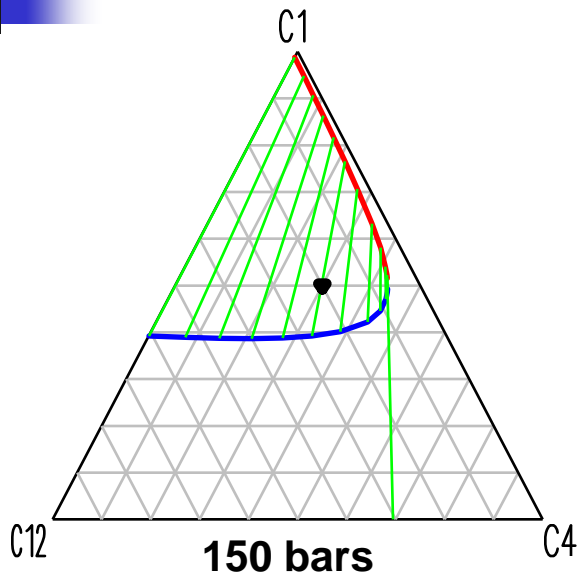
Phase relations of reservoir fluid at 140°F and 4000 psia



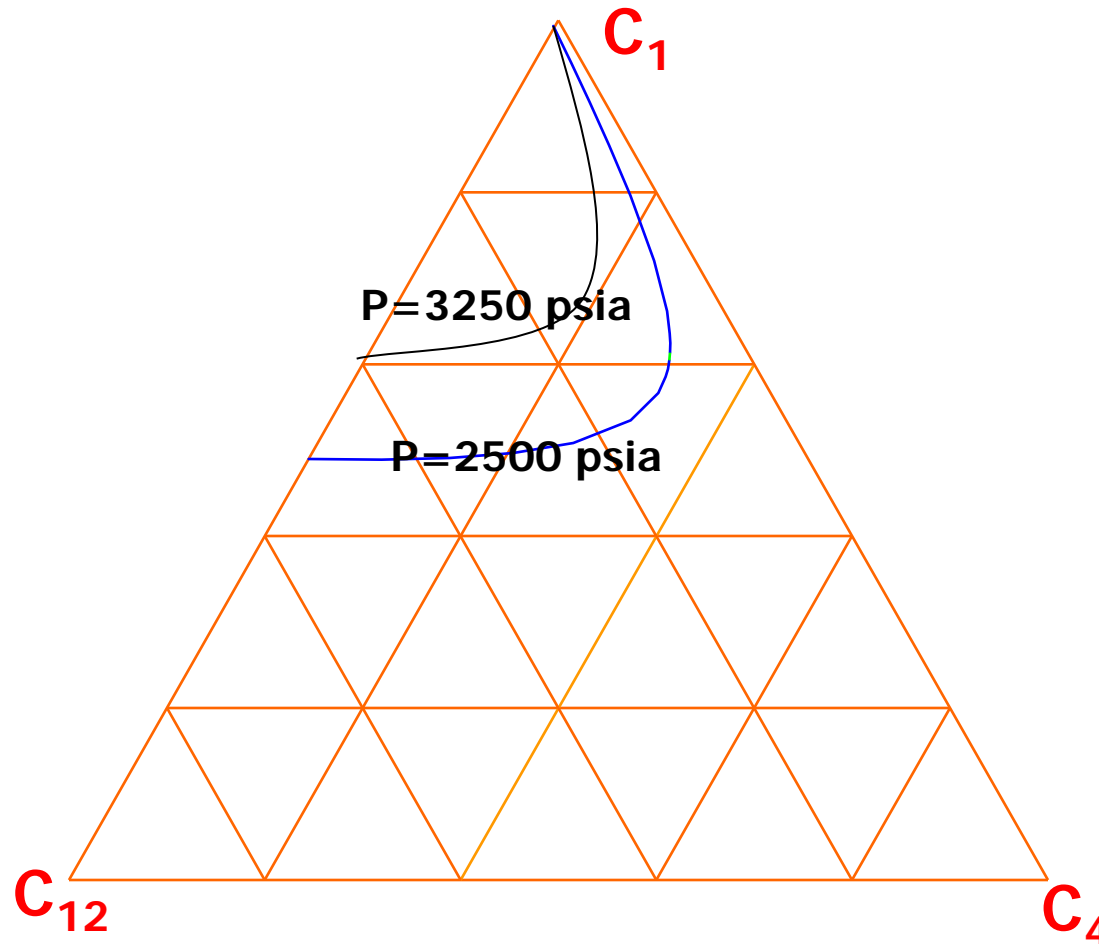
Two Phase Envelope at Various Pressure



Two Phase Envelope at Various Pressures



Effect of pressure on phase behavior for methane/n-butane/decane system





Miscible Processes

- Three basic types of miscible process
 - First-contact miscibility
 - Condensing-gas drive
 - Vaporizing-gas drive



What is Miscibility?

- Under normal conditions, oil & gas reservoir fluids form distinct, immiscible phases
- Immiscible phases are separated by an interface
 - associated with inter-facial tension (IFT)
 - when $IFT=0$, fluids mix => MISCIBILITY
- residual oil saturation to gas (and water) directly proportional to IFT
- miscible displacement characterized by low/zero residual oil saturations



Miscible Conditions

- Establishment of miscibility depends on
 - pressure (MMP)
 - fluid system compositions
- Miscibility normally determined by laboratory measurement



Compositional Processes

- First Contact Miscible
- LPG slugs - designed to achieve first - contact miscibility with oil at leading edge of slug and with driving gas at trailing edge



First Contact Miscibility

- Pressure $>$ MMP
- All points between solvent and reservoir oil lie in single phase region
- Need high concentrations of solvent
- expensive



FCM Processes

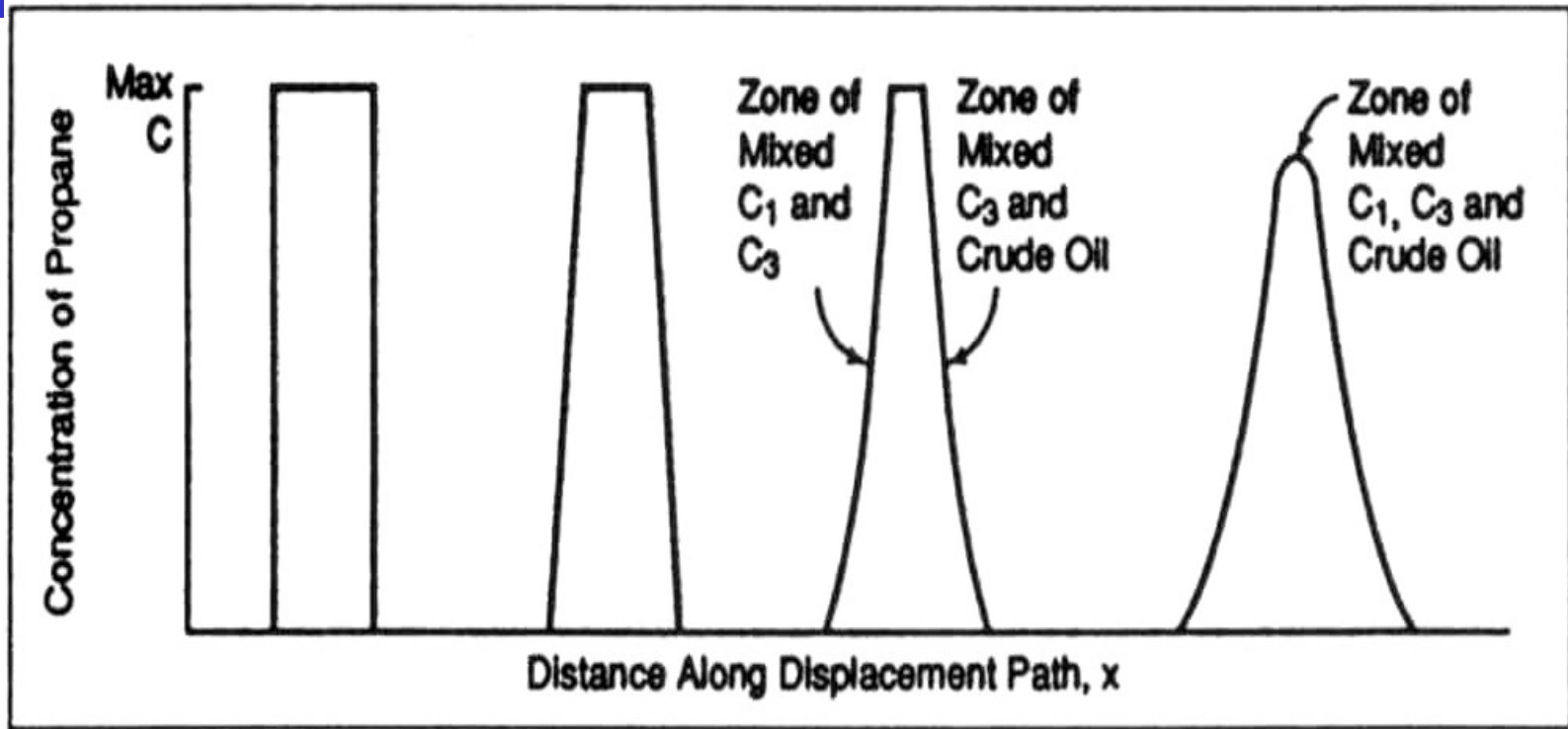
- The simplest FCM process would be the one in which a FCM fluid is injected continuously to displace the oil.
- Such a process would technically work but would be a money losing venture.
- The cost of FCM fluids is so high that one can only afford to inject a small slug.
- The slug is then displaced miscibly with a less expensive drive fluid.
- Note that this drive fluid is miscible with the FCM slug but not miscible with the oil at the reservoir conditions.
- On a ternary diagram, the first contact miscibility can be inferred if the line joining two points that represent the composition of two fluids stays in the single-phase region.



Design of FCM processes

- The first step is to select a primary slug that would be first contact miscible with the crude oil and the drive gas at the reservoir temperature and the operating pressure.
- If the reservoir temperature is lower than the critical temperature of the primary slug fluid, a hydrocarbon slug is likely to be miscible with the oil if it is a liquid at the reservoir temperature.
- When the reservoir temperature is above the critical temperature of the slug, estimating miscibility condition requires experimental information.
- To ensure miscibility between the slug and the drive gas, it is necessary to operate at a pressure that is higher than the cricondenbar pressure for the binary system formed by the slug and the drive gas.
- The size of slug is designed to prevent mixing of all three fluids by dispersion
- Mixing zones develop on both sides of the slug and the slug size must be large enough to prevent these mixing zones from overlapping.

Idealized concentration profiles for a miscible displacement process as the miscible slug advances through the reservoir



- * When the mixing zones overlap, miscibility may be lost.
- * Knowledge of the dispersion behavior is essential for designing the correct slug size.



Multiple Contact Miscibility

The minimum pressure at which after many contacts the gas and liquid (oil) become one phase.

Called MCMP - Multiple Contact Miscibility Pressure



MCM Processes

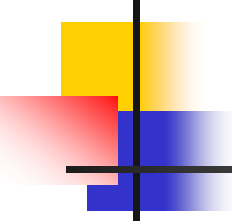
- MCM processes rely on development of miscibility in the reservoir by repeated contacts between the injected fluid and the crude oil.

- These processes can be characterized into two categories.
 1. Vaporizing-gas drive
 2. Condensing-gas drive

A third category involves both and can be called condensing/vaporizing drive.

- **In vaporizing-gas drive**, the injected fluid vaporizes the intermediate components from the oil and eventually becomes rich enough in such components to be miscible with the fresh oil that lies ahead.

- **In condensing-gas drive**, the oil near the injection end absorbs intermediate components from the gas and eventually becomes rich in such components to be miscible with incoming gas.

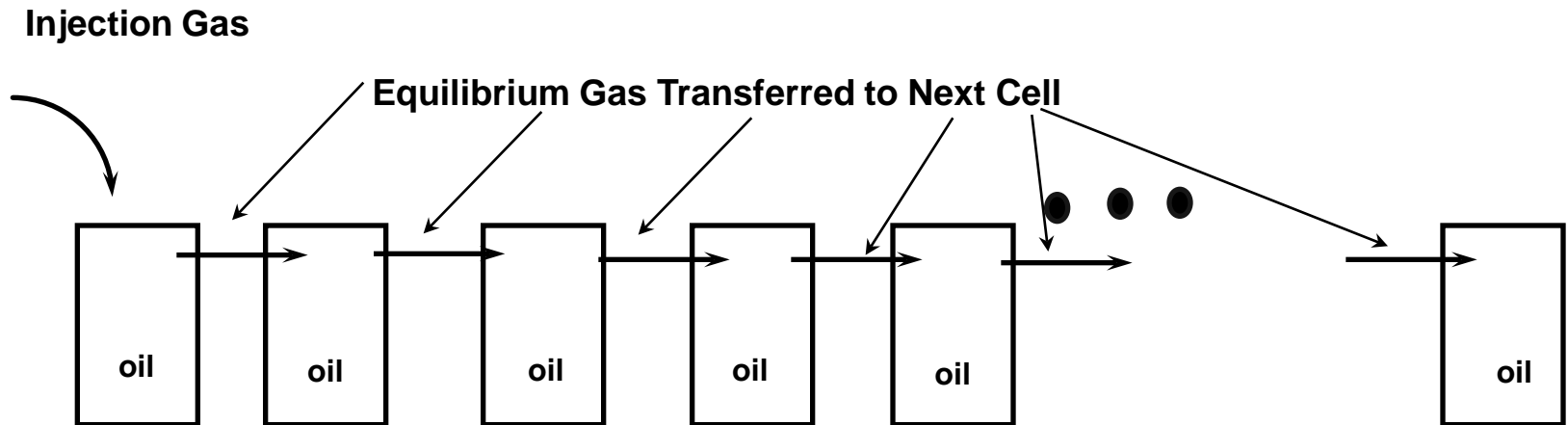
- 
-
- Enriched hydrocarbon gas flooding has been viewed traditionally as a condensing-gas drive.
 - However, the recent thinking on enriched gas processes views it as a combination of condensing and vaporizing mechanisms.
 - Lighter components (C2 - C4) are absorbed from the gas by the oil and the middle components (C5 - C7) are vaporized from the oil into the gas phase.
 - The miscibility develops as a result of both processes.
 - CO₂ flooding is viewed as a vaporizing-gas drive.
 - A ternary diagram can be used to explain how miscibility develops in MCM processes.
 - We will first examine the development of miscibility in a vaporizing-gas drive.



Vaporizing Gas Drive Process

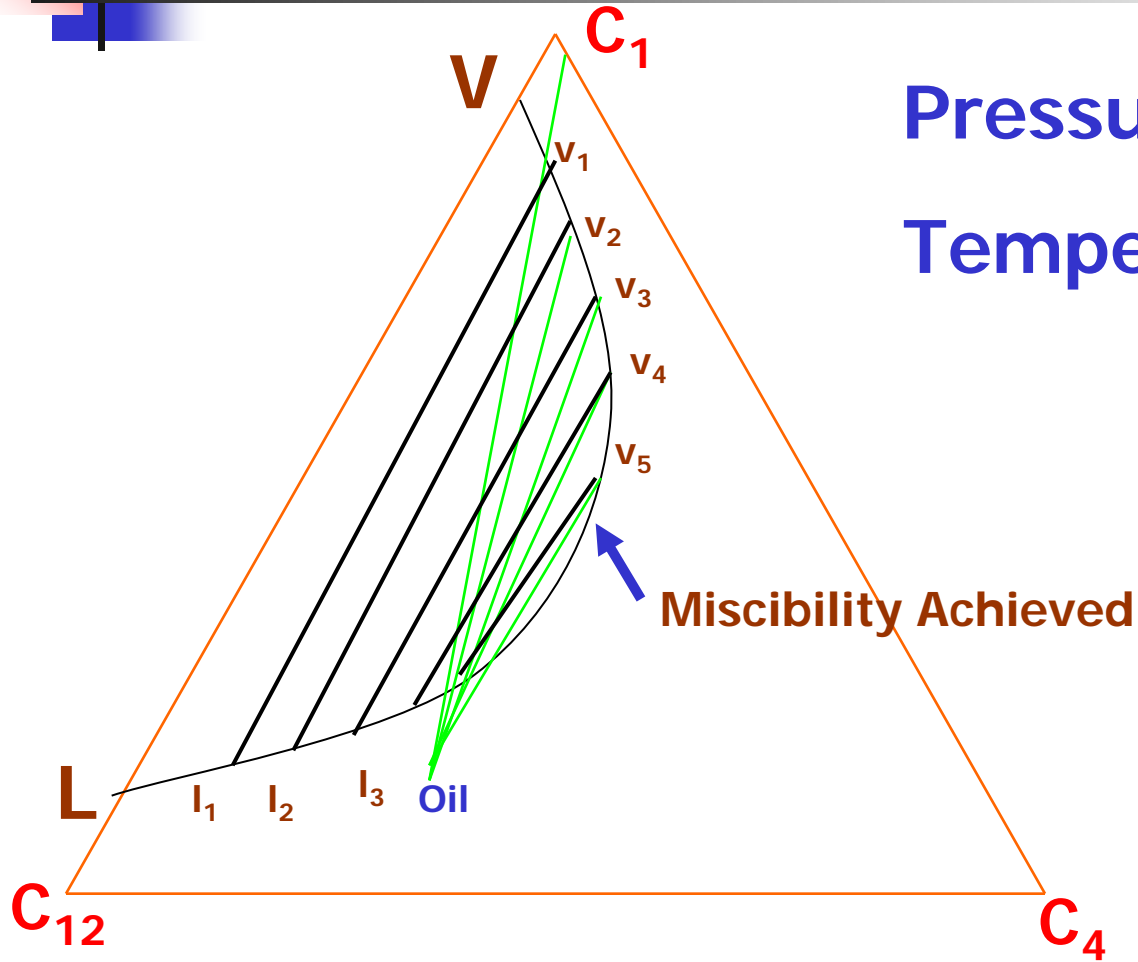
- Injection Gas - Lean Gas, C_1 , CO_2 , N_2
- For vaporizing gas drive - multiple contact miscibility
- Mechanism: Intermediate hydrocarbon components in the oil vaporize to enrich the gas.
- As the leading edge of the gas slug becomes sufficiently enriched, it becomes miscible with the reservoir oil.

Multiple Contact Experiment



Vaporizing Gas Drive

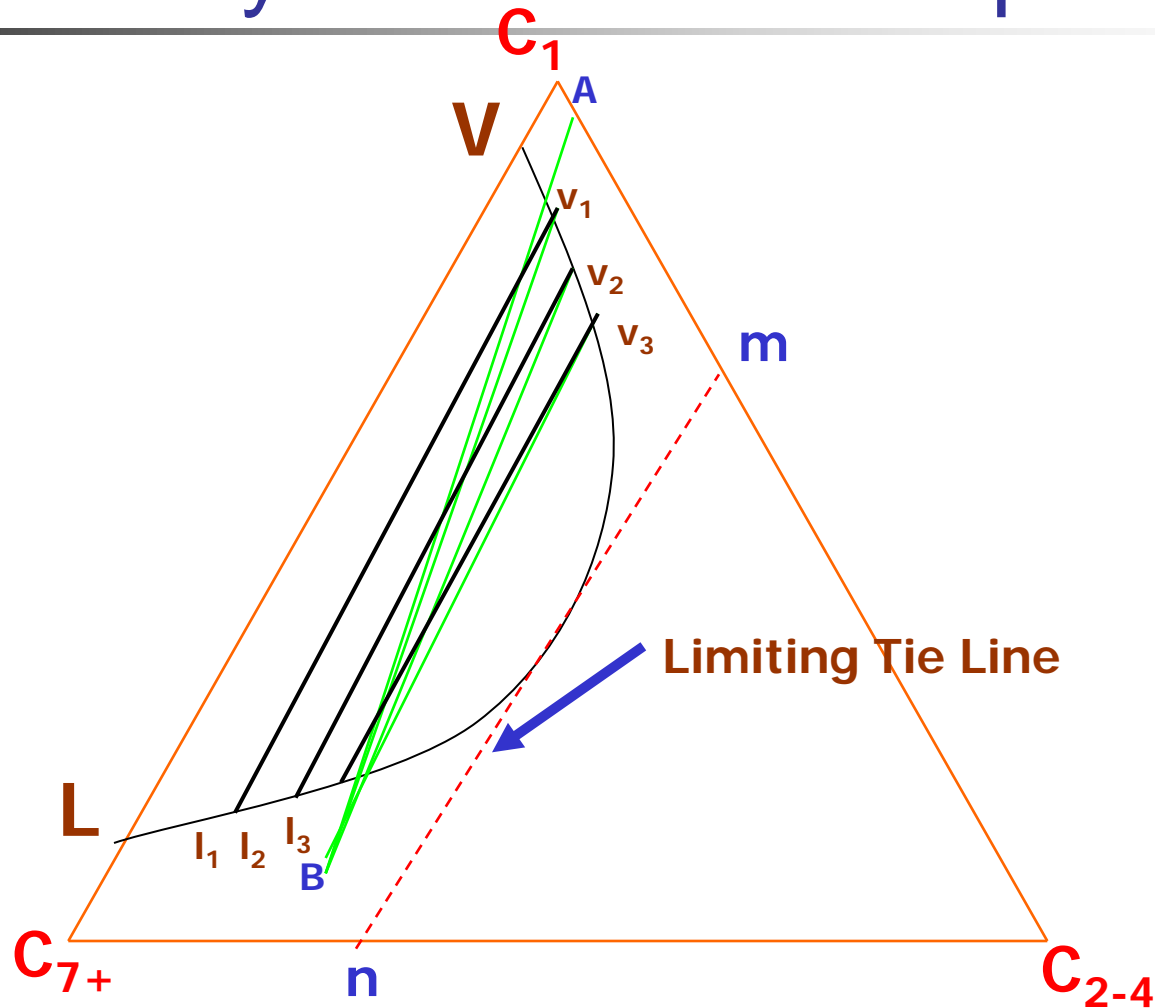
Vaporizing Gas Drive Miscibility (VGD)



Pressure constant

Temperature constant

Representation of a process in which miscibility does not develop

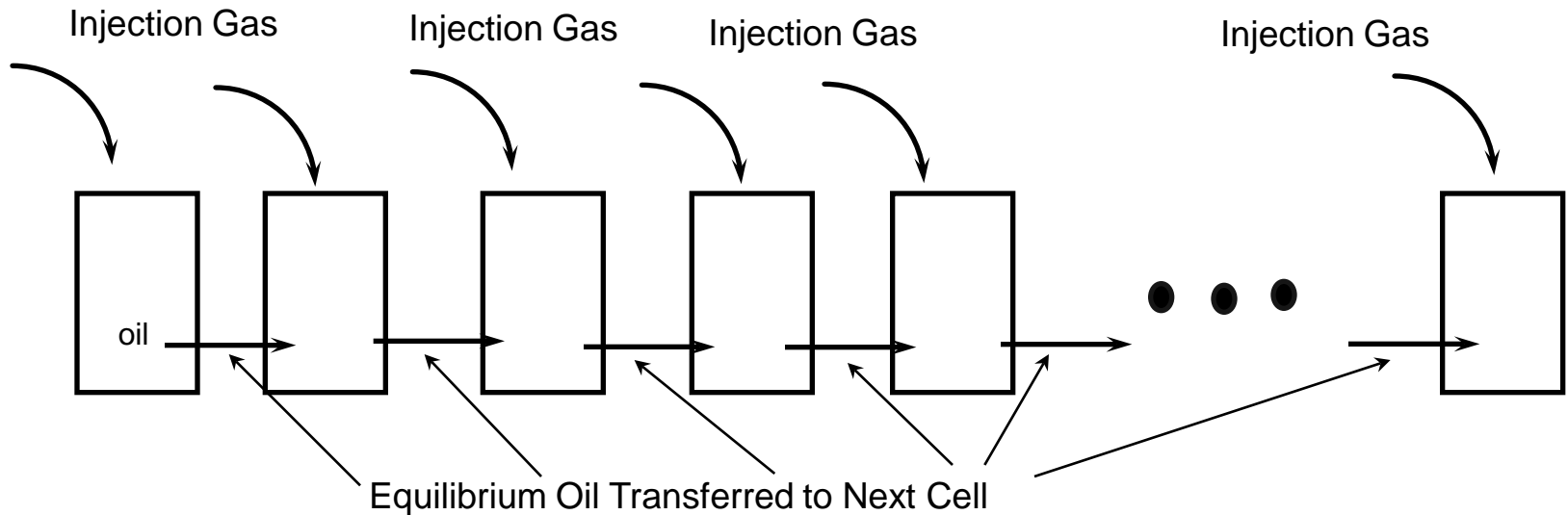




Condensing - Gas Drive Process

- Injection gas is enriched with intermediate components such as:
 - C_2 , C_3 , C_4 etc
 - Mechanism:
 - Phase transfer of intermediate MW hydrocarbons from the injected gas into the oil. Some of the gas “Condenses” into the oil.
 - The reservoir oil becomes so enriched with these materials that miscibility results between the injection gas and the enriched oil.

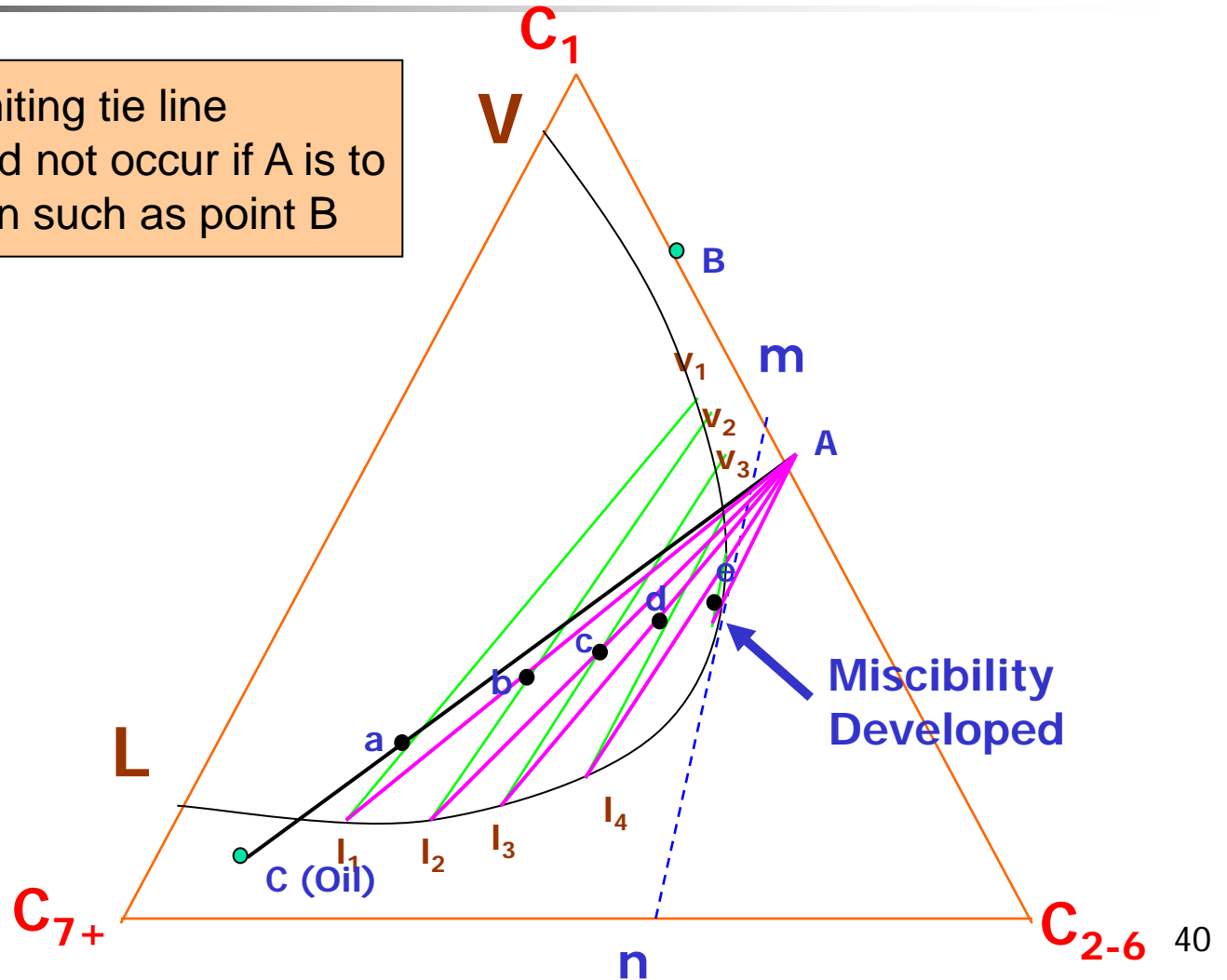
Multiple Contact Experiment



Condensing Gas Drive

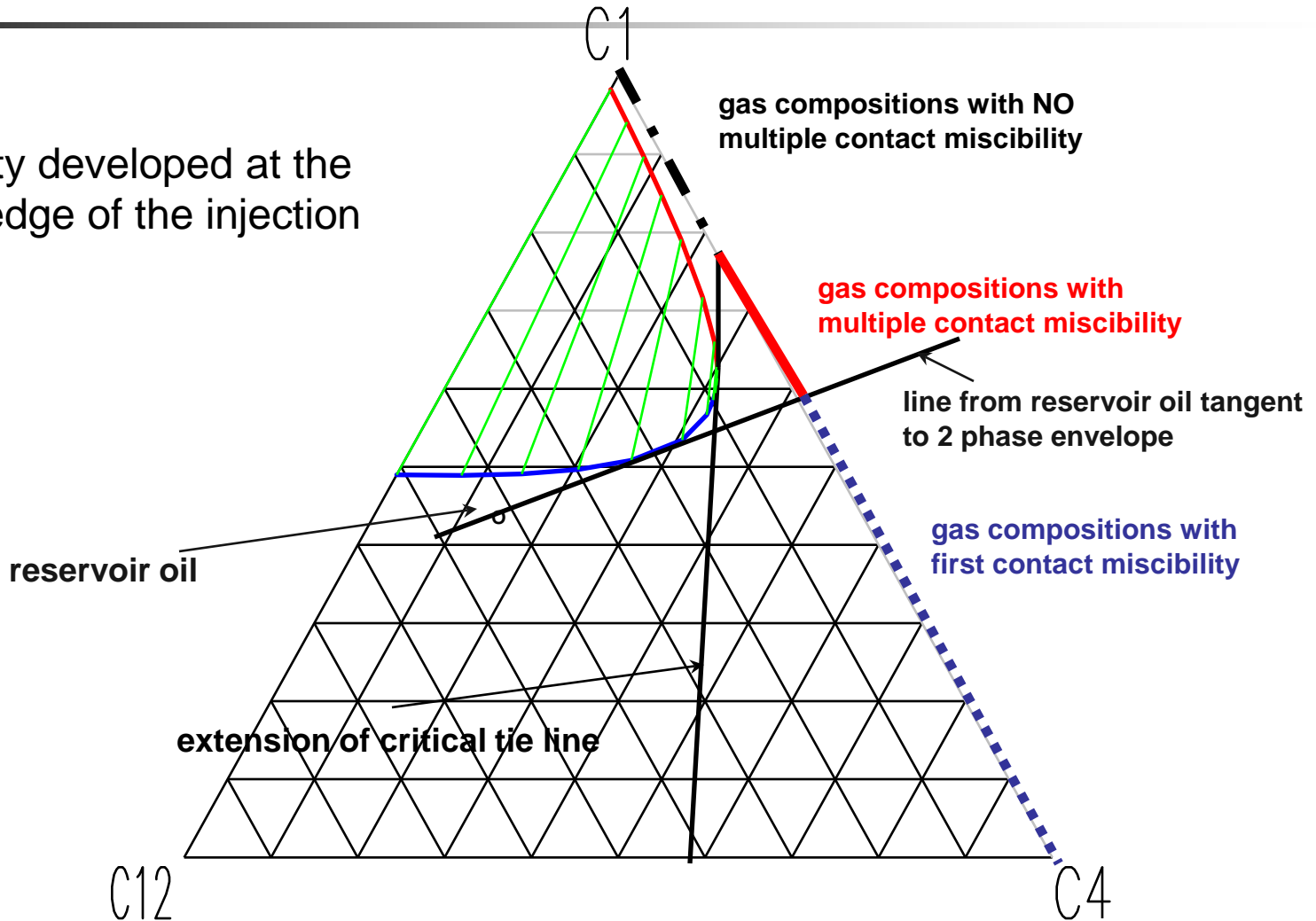
Enriched Gas - Condensing Process

mn limiting tie line
 Miscibility would not occur if A is to the left of mn such as point B



Summary of Gas Drive Miscibility

Miscibility developed at the trailing edge of the injection gas





Condensing - Gas Drive (CGD)

- Pressure < MMP
- Solvent and oil not miscible initially
- Solvent components transfer to liquid oil phase
- Repeated contact between oil and solvent moves system towards plait (critical) point (dynamic miscibility)



Condensing - Gas Drive

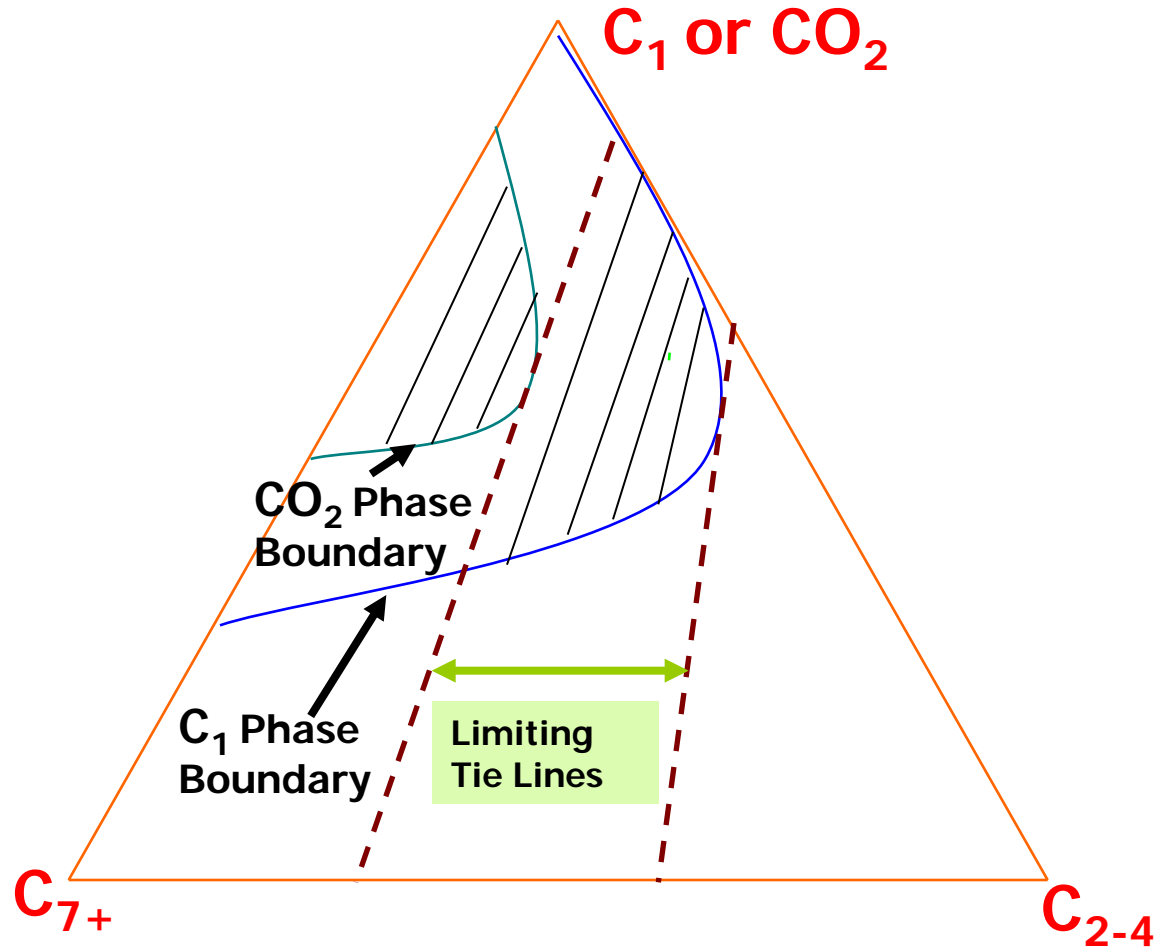
- For systems with oil composition to left of tie line, solvent composition must lie to right
- Field behavior is more complicated
 - continuous, not batch, contact
 - both phases flow
 - actual phase behavior more complicated, especially near plait point



CO₂ Miscible Process

- Same as high pressure vaporizing process
- Limiting tie line for the CO₂ system is more parallel to the CO₂-C₇₊ side than the CH₄ system.

CO₂ Miscible Process



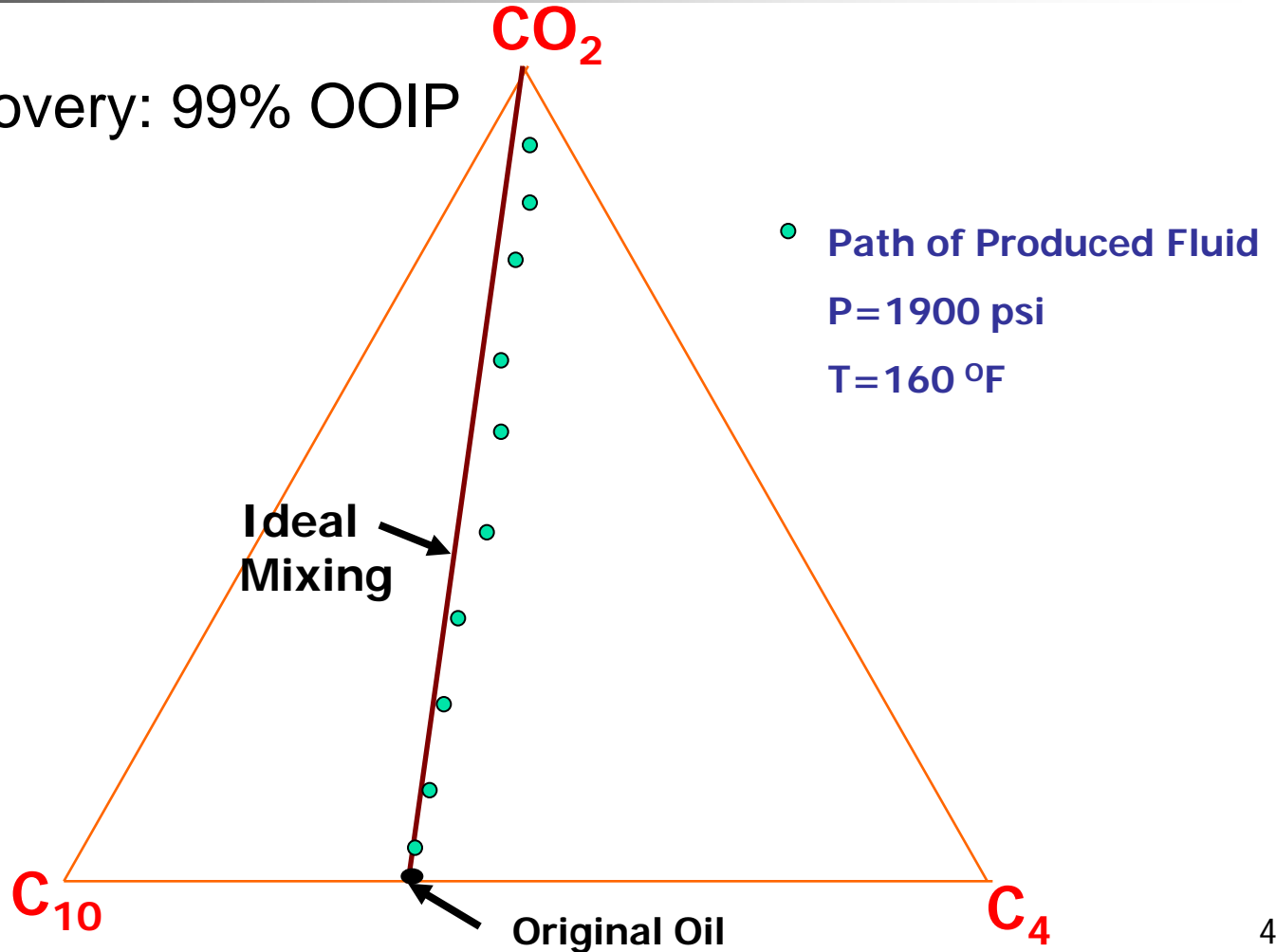


Experimental verification of the role of phase behavior in Miscible displacement

- The porous medium consisted of an 8 ft long, 2 in. diameter Bera sand stone core
- Displacing fluid pure CO₂
- Hydrocarbon to be displaced is a mixture of 40 mol% butane and 60 mole decane
- Temperature 160°F, the pressure was varied from 1900 to 1500 psia
- A miscibility of 1800 psia is predicted

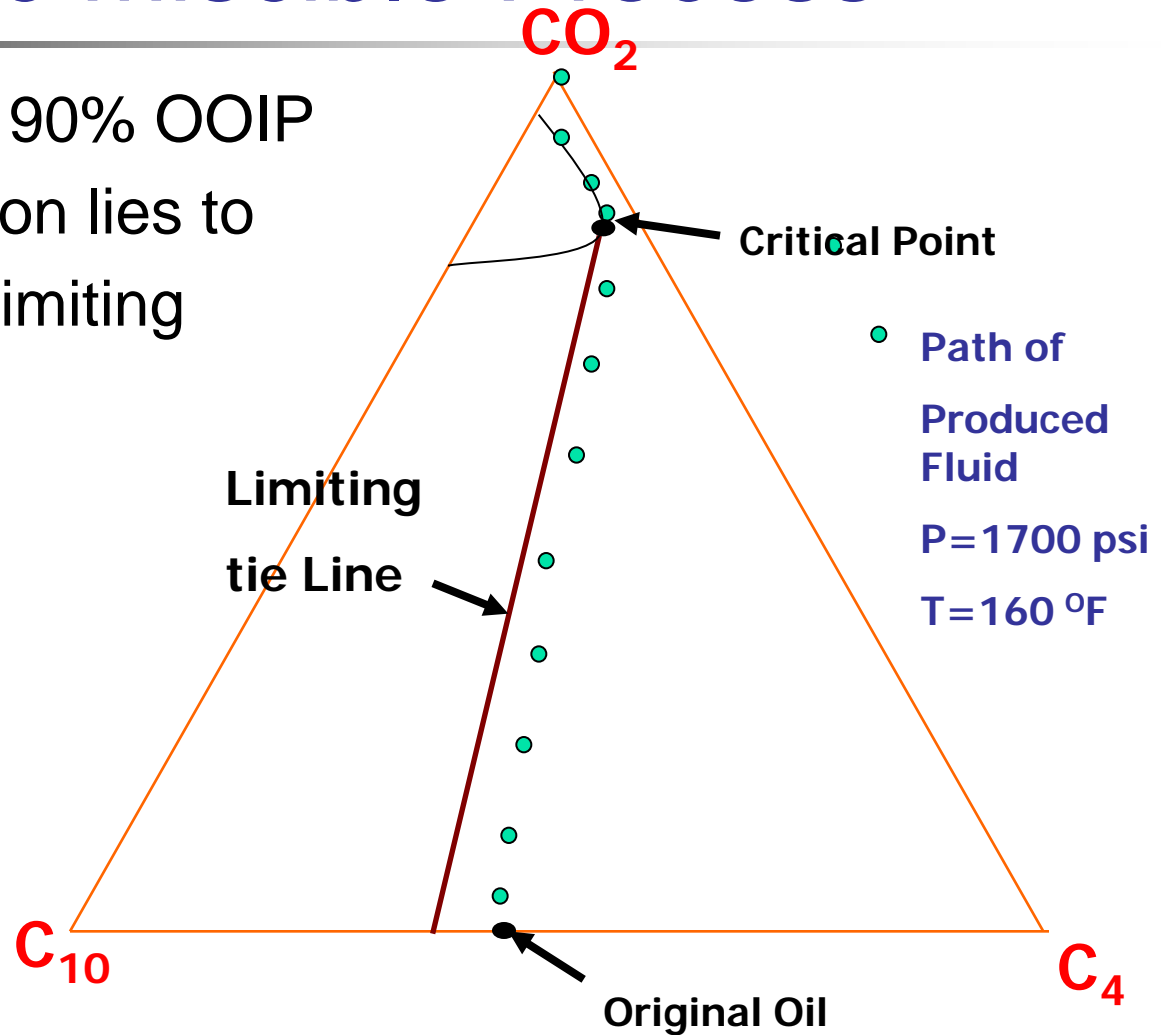
Experimental Verification of Ternary Diagram

- Oil recovery: 99% OOIP



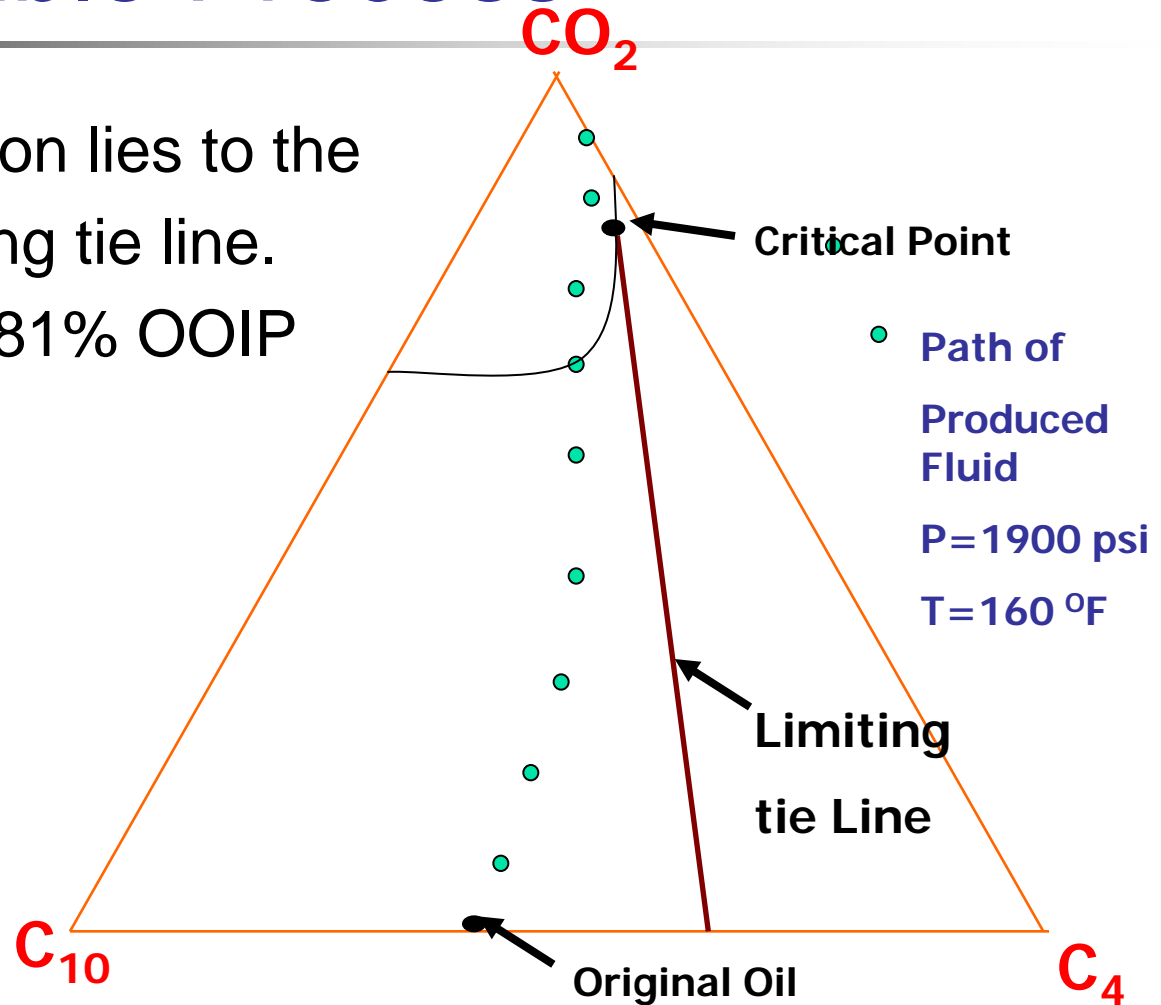
Dynamic Miscible Process

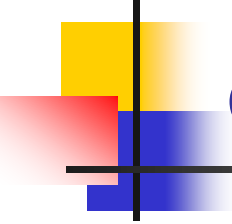
- Oil recovery: 90% OOIP
- Oil composition lies to the right of the limiting tie line



Immiscible Process

- Oil composition lies to the left of the limiting tie line.
- Oil recovery: 81% OOIP





Measurement & Predication of the MMP or MME in a Multiple Contact Process

- Temperature of process is set by reservoir condition
- Pressure may be controlled by certain limit
- Injected gas composition can be set
- MMP Minimum Miscibility Pressure
- MME Minimum Miscibility Gas Enrichment at which miscibility will be achieved in a multiple contact process for a specified reservoir fluid composition and reservoir temperature



Experimental Measurement of MMP or MME

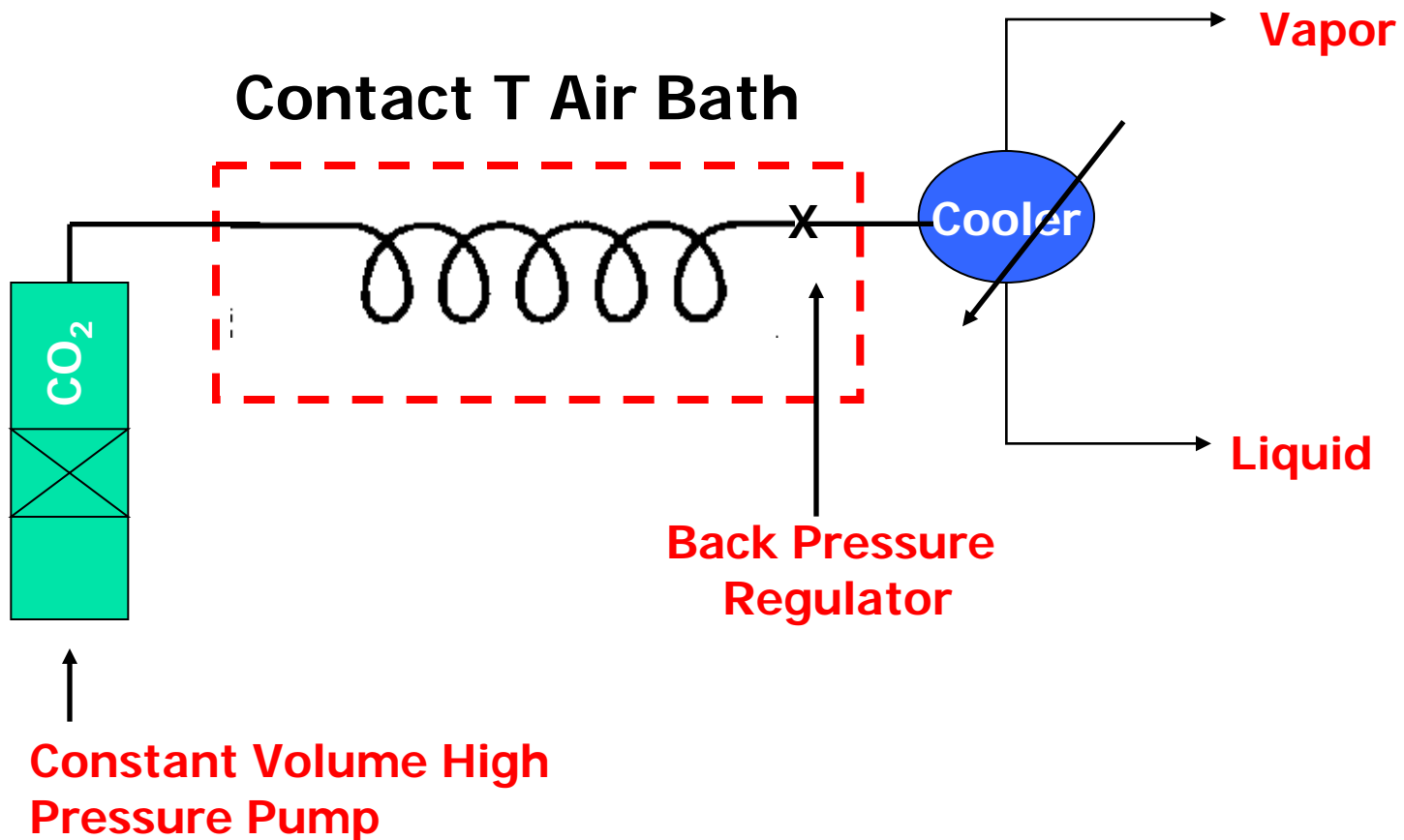
- The most commonly used technique is based on a series of slim tube displacement tests.
- Such tests use a long tube of about 5/16 to 7/16 inch i.d. packed with sand or glass beads.
- Oil displacement tests are run at different pressures and the results are analyzed for recovery at a fixed value of pore volumes injected.
- A plot is made of the recovery versus the test pressure.
- The minimum miscibility pressure is the lowest pressure at which the high recovery expected from miscible displacements is observed.
- An alternate method is based on the rising bubble apparatus.



Experimental Measurement of MMP or MME

- A slim tube test equipment
- Stainless steel tube about 5/16 in. ID and about 40 ft long
- The tube is packed uniformly with fine grade sand or glass beads of a size on the order of 100 mesh.
- The tube is coiled in a manner so that flow is basically horizontal and gravity effects are insignificant

Schematic of slim tube apparatus for experimental measurement of miscibility pressure

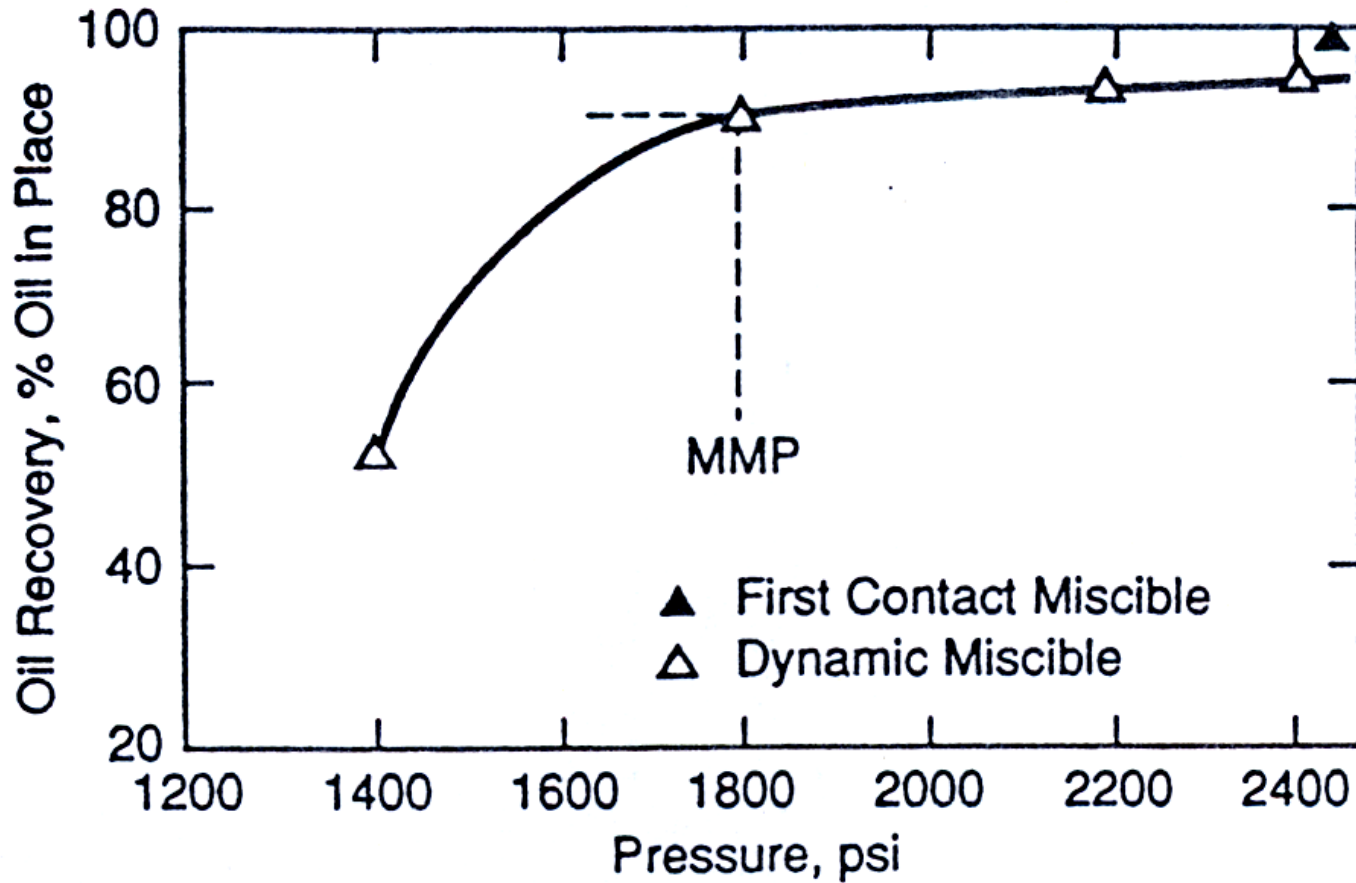




Experimental Measurement of MMP

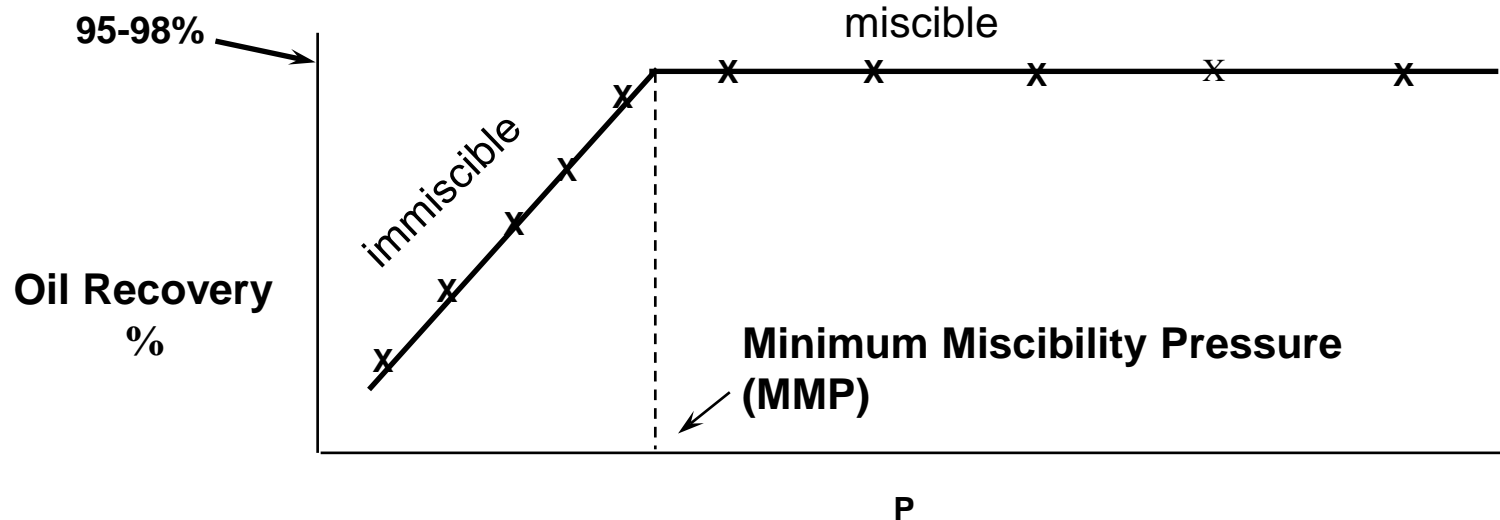
- Three recovery points at different P's can be monitored.
 - ER at breakthrough
 - ER at 1 PV injection
 - ER ultimate

Slim tube data

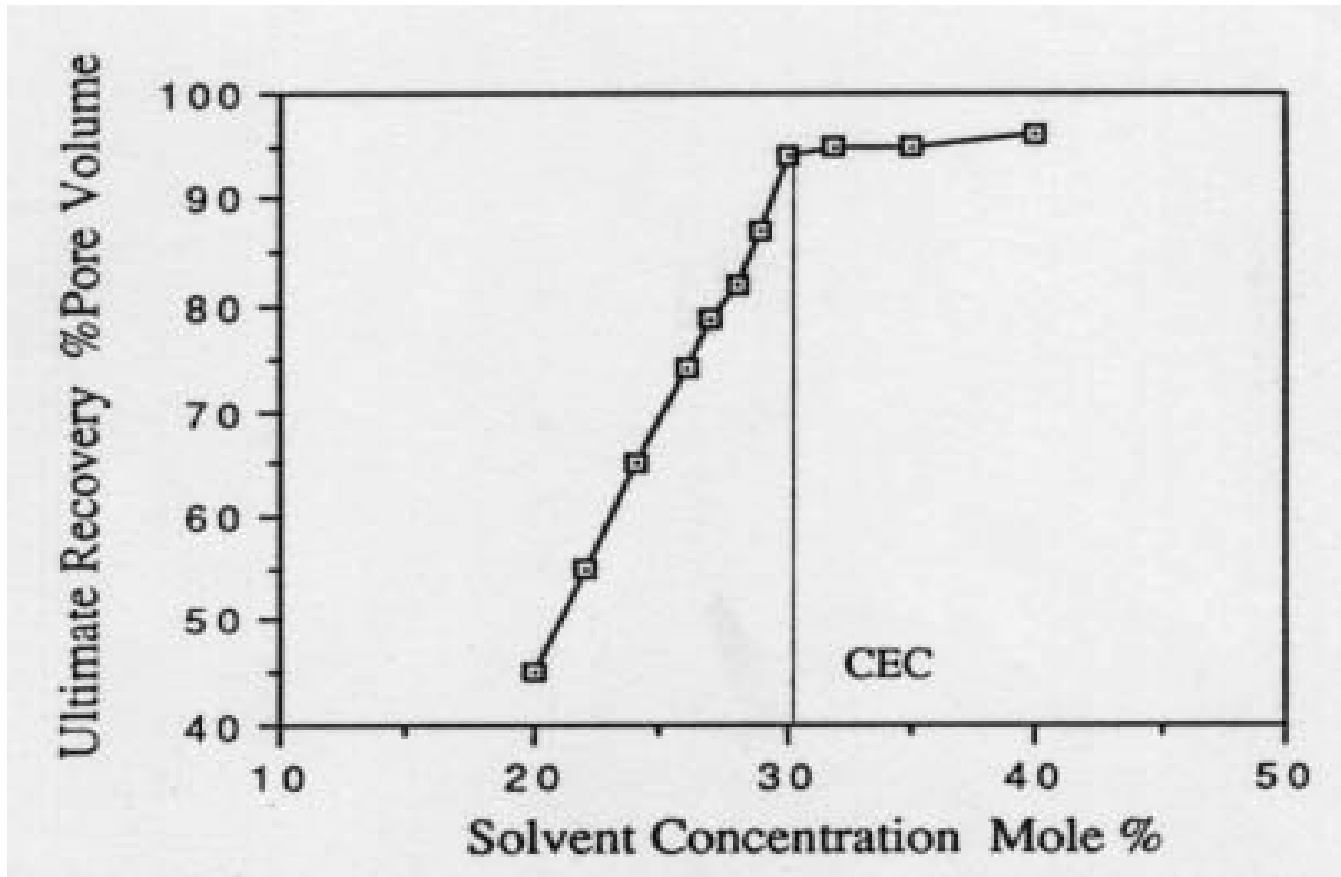


Condensing - Gas Drive Process

Results from slim tube displacements at various pressures



Procedure to Find Minimum Enrichment

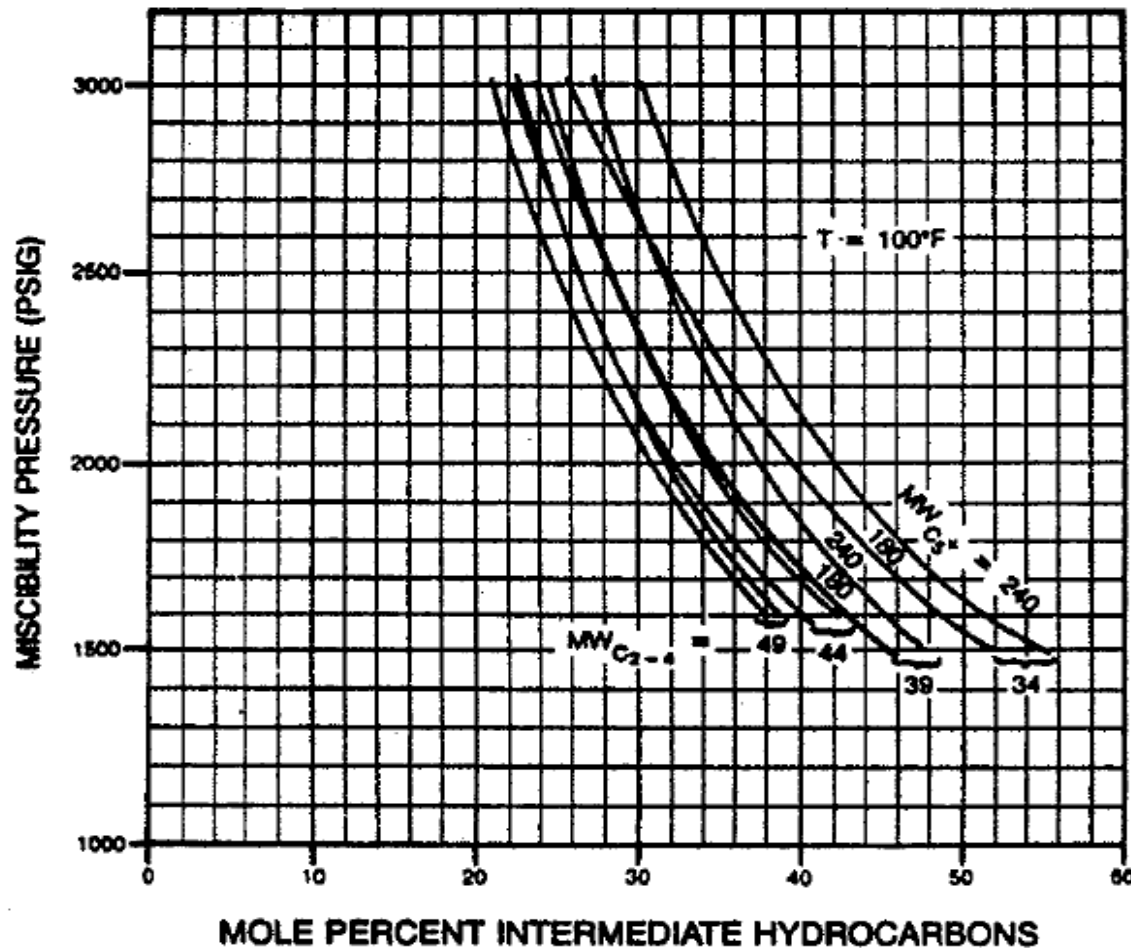




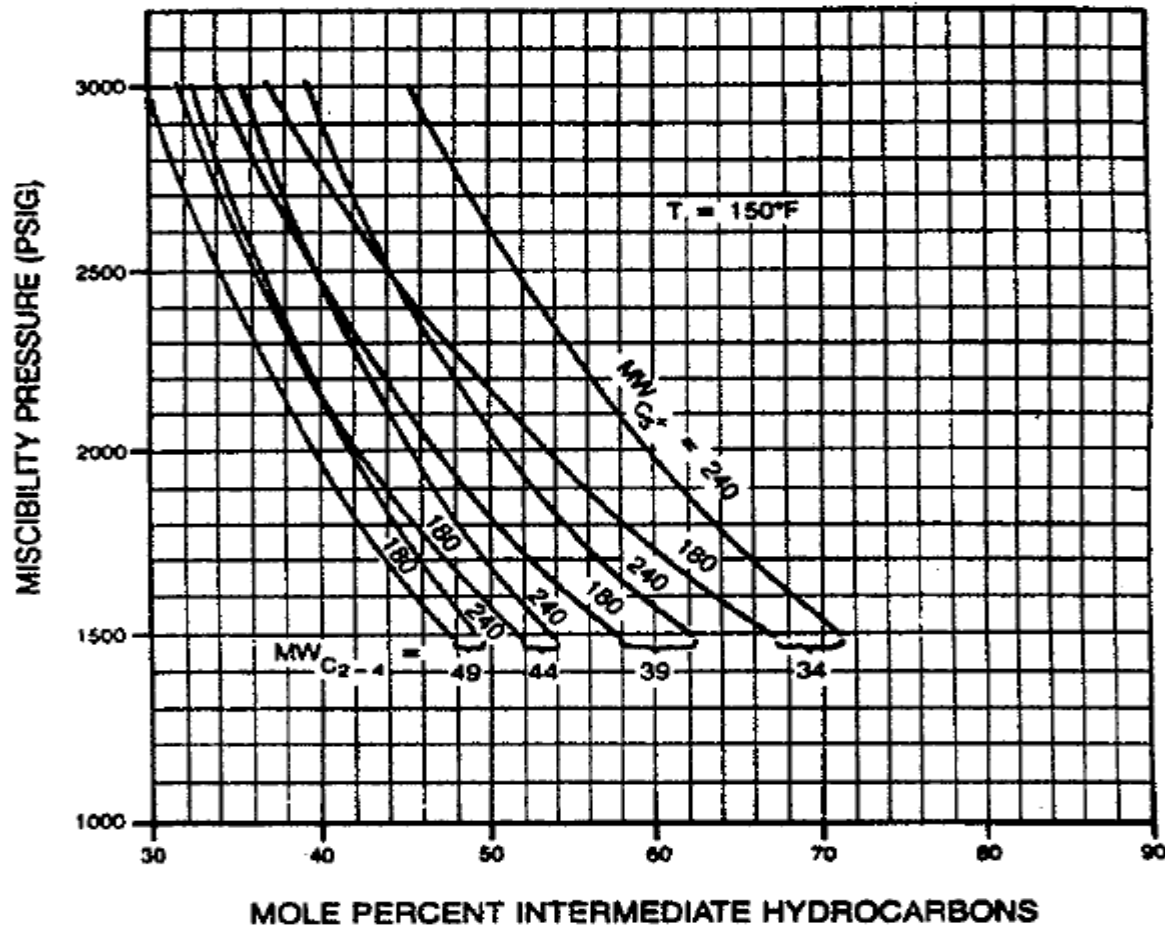
Prediction of Minimum Miscibility pressure

- Two basic techniques can be used for making approximate predictions of the minimum miscibility pressure
 1. Empirical correlations
 2. Equation of state based on calculations
- MMP can be correlated with Temperature, molecular weight of C_5 plus fraction of the reservoir oil, mole fraction of C_2 to C_4 components in the injected gas and the molecular weight of the C_2 to C_4 fraction in the injected gas.

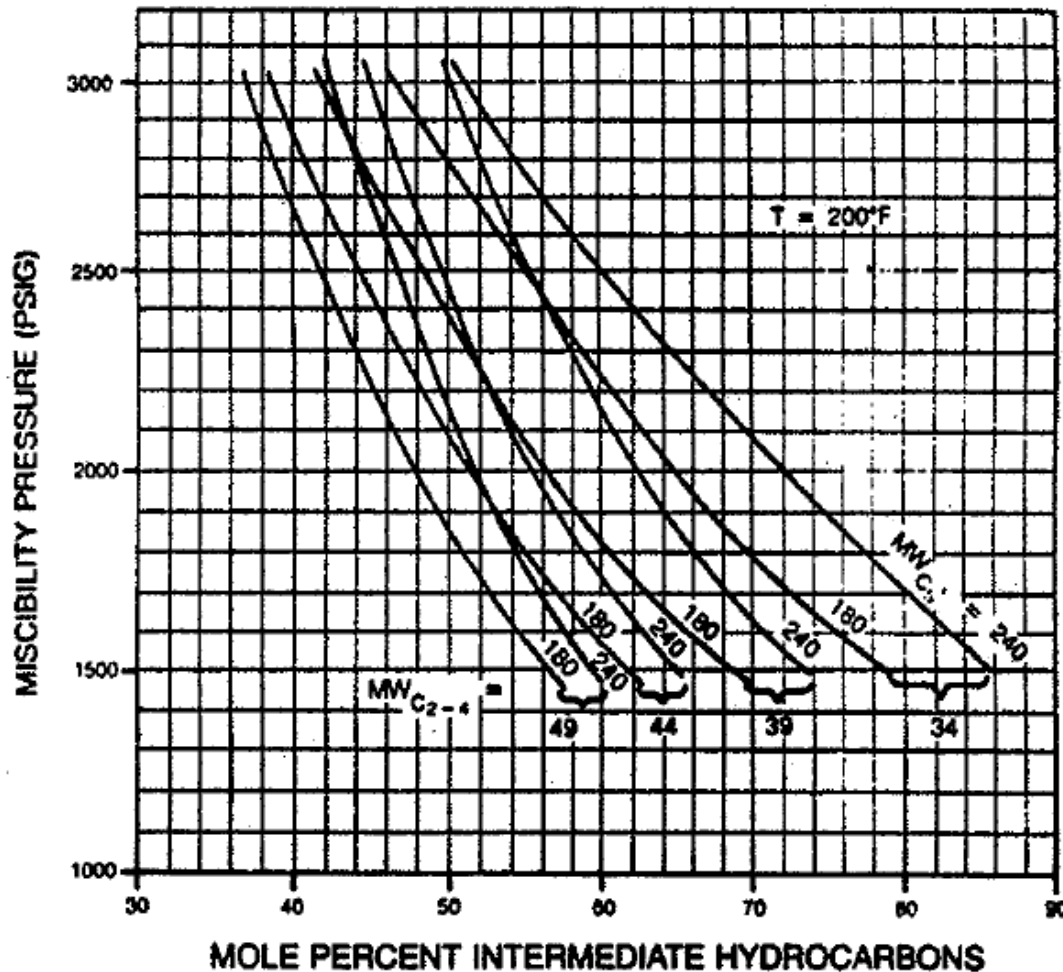
Condensing gas drive miscibility pressure correlation, $T=100^{\circ}\text{F}$

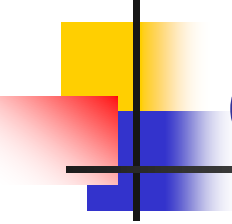


Condensing gas drive miscibility pressure correlation, $T=150^{\circ}\text{F}$



Condensing gas drive miscibility pressure correlation, $T=200^{\circ}\text{F}$





Example of MMP calculation for a Condensing Gas Displacement Process

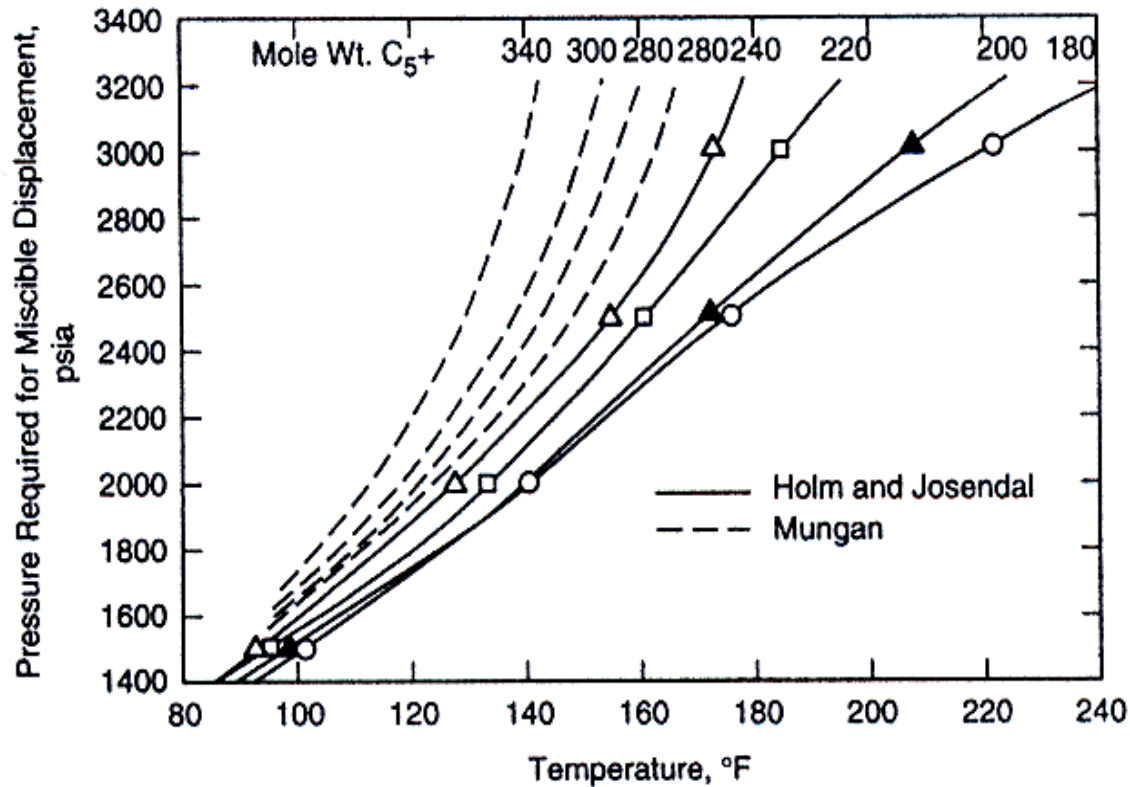
- Assume that a reservoir that is to be flooded with a condensing gas process is at 150°F
- The average molecular weight of the C₅₊ fraction of the reservoir oil is 200
- A displacement gas is available with the composition 60 mol% CH₄, 30 mol% C₃H₈, and 10 mol% C₄H₁₀.
- Determine the MMP
- What should be done to lower the MMP?



Solution

- The MW of C₃ and C₄ must be calculated first.
- The molar composition of the intermediates is 75% C₃ and 25% C₄.
- The average molecular weight of the intermediates is: $Mw\ average = 0.75 \times 44 + 0.25 \times 58$
- $= 47.5$
- The intermediates make up 40 mol% of the composition
- From the figure we can see the Mw of C₂ through C₄ is 49.
- The MMP IS 2070 psia
- To lower the MMP the composition of the intermediates components in the displacing gas should be increased.

Pressure required for miscible displacement in CO₂ flooding



MMP in vaporizing gas drive for lean hydrocarbon gas systems.

The data used for developing this correlation covers the following range of parameters:

Temperature 140 – 265 °F

Saturation pressure of res. Oil 596 to 4035 psia

Avg. Mol Wt. Of C7+ fraction in oil 149 to 216

MMP from 3250 to 4750

•The correlation is expressed algebraically as:

following range of parameters:

Temperature

140 – 265 °F

Saturation pressure of res. Oil

596 to 4035 psia

Avg. Mol Wt. Of C7+ fraction in oil

149 to 216

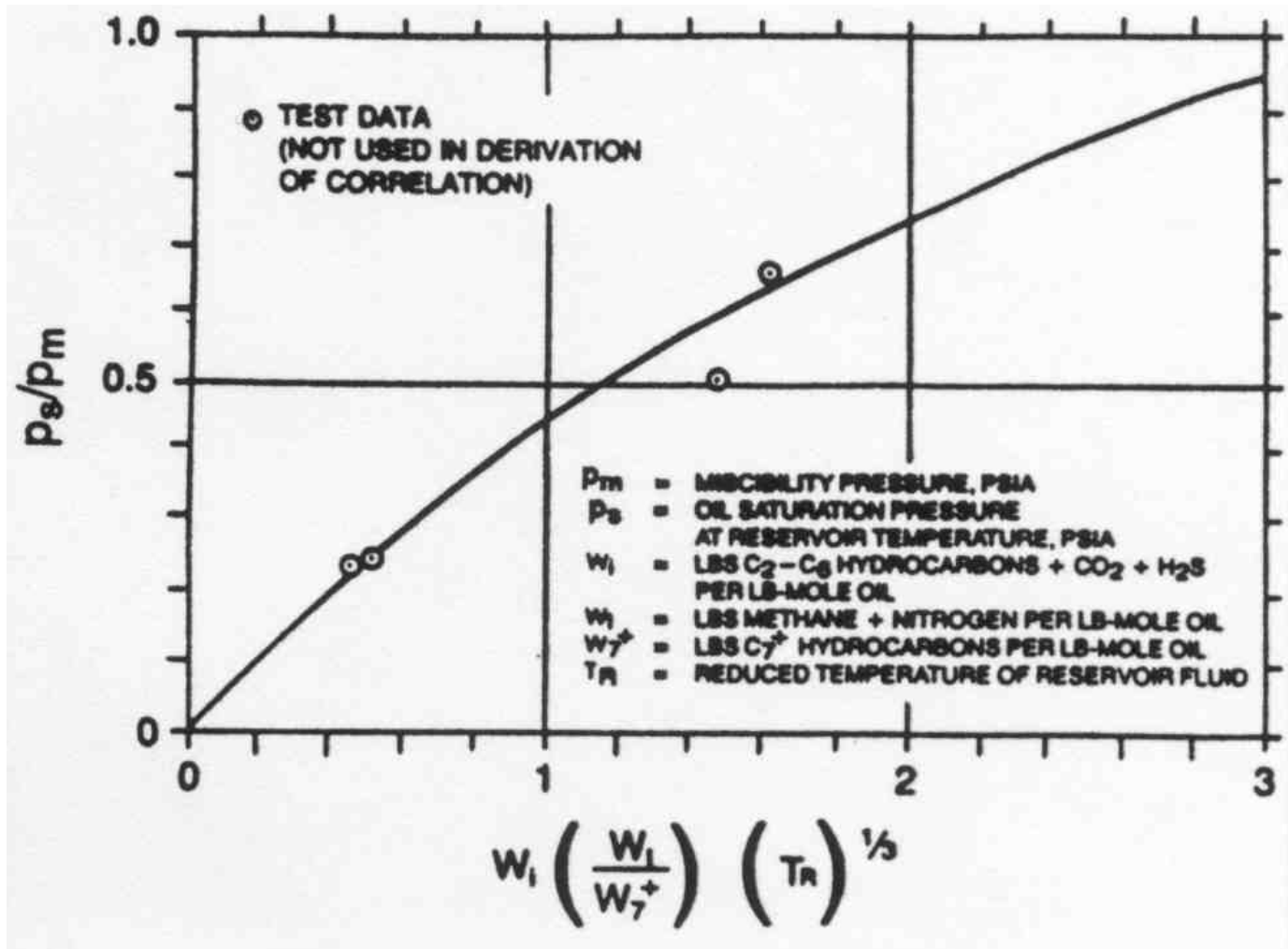
MMP

from 3250 to 4750

The correlation is expressed algebraically as:

$$\frac{p_{so}}{p_m} = \frac{2.252 x^*}{x^* + 4.901} \quad \text{and} \quad x^* = \frac{W_i W_1 T_R^{1/3}}{W_{C7+}}$$

Vaporizing gas derive miscibility pressure correlation



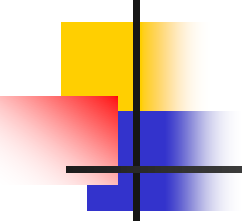


Johnson ad Pollin correlation

- For pure CO₂

$$P_{CO_2} = 8.78 \times 10^{-4} (T)^{1.06} (MW_{C5+})^{1.78} \left(\frac{X_{vol}}{X_{int}} \right)^{0.136}$$

- X_{vol} = mole fraction of the volatile component in the oil, assumed to consist of C₁ + N₂
- X_{int} = mole fraction of the intermediate component in the oil, assumed to consist of C₂ through C₄, CO₂ and H₂S

- 
-
- When the CO₂ stream is contaminated with other components, the MMP is affected
 - The addition of C₁ or N₂ to the CO₂ increases MMP
 - The addition of C₂, C₃, C₄ or H₂S reduces the MMP



Alston et al. correlation

- This correlation is based on pseudocritical temperature of the impure CO₂ stream defined with a weight fraction mixing rule.

$$T'_{cm} = \sum_{i=1}^n X_i T_{ci} - 459.7$$

- Where T'_{cm} = weight average critical temperature
 T_{ci} = critical temperature of component i .
 X_i = mass fraction of component i

$$F_{imp} = \left(87.8 / T'_{cm} \right)^{1.935 \times 87.8 / T'_{cm}}$$

the MMP is given by;

$$p_{CO_2-imp} = P_{CO_2} F_{imp}$$



Sebastian et al.

- The correlation relates MMP to the MMP for pure CO₂ and the pseudocritical temperature of the drive gas.

$$\frac{P_{CO_2-imp}}{P_{CO_2}} = 1.0 - 2.13 \times 10^{-2} (T_{cp} - 304.2) + 2.51 \times 10^{-4}$$

$$x (T_{cp} - 304.2)^2 - 2.35 \times 10^{-7} (T_{cp} - 304.2)^3$$

$$T_{cp} = \sum_i X_i T_{ci}$$



Example

- Estimate the MMP for a specified crude oil. The reservoir temperature is 130°F, The C5+ molecular weight for oil components is 185.8, the volatiles make up 5.0 mol% of the oil and the intermediates 7.5 mole %, and the ratio of mole fractions of volatiles to intermediates in the oil is 0.667.
- Two different displacing fluids are to be considered
 - 100%CO₂
 - A mixture of 92.5 mole% CO₂ and 7.5 mole% C₁



Solution

Pure CO₂

MMP=1880 psia (Yellig & Metcalfe)

MMP=1581 psia (Alston et al.)

Impure CO₂

MMP=1818 psia (Alston et al.)

MMP=1954 psia (Sebastian et al.)



Prediction of MMP with an EOS

- Equations of state, such as S.R.K or Peng-Robinson, can be used for predicting MMP.
- This requires modeling the crude oil with several pseudocomponents and fine-tuning these pseudo-components by matching experimental phase behavior results.
- The utility of this approach is limited due to the necessity of obtaining experimental information



Factor affecting Miscible displacement efficiency: Microscopic Displacement Efficiency

- Miscible processes involve no capillary trapping
- Theoretically the microscopic displacement efficiency should be 100%.
- In FCM processes, typical recoveries are 97% to 100% when a continuous injection of FCM fluid is used.
- Laboratory tests of MCM processes typically give only 90% to 97% recoveries even under ideal conditions of a slim tube experiment.
- Reasons for less than 100% recovery are:
 - 1.Distance required for developing miscibility
 - 2.Imperfect mixing due to fingering
 - 3.Dispersion can cause the system



Factor affecting Miscible displacement efficiency: Macroscopic Displacement Efficiency

- Factors that affect the macroscopic displacement efficiency include the following
 1. Mobility ratio – viscous fingering effects
 2. Density difference – gravity segregation
 3. Reservoir heterogeneity – uneven propagation
- We will first examine the effects of these factors under the simpler situation in which no mobile water is present.
- Later we will examine the effect of mobile water



Design Procedure and Criteria

This discussion focuses on the preliminary design of a miscible flood, which precedes the more detailed design.

1. Test
2. Mobility control
3. Gravity segregation
4. Core flood
5. Modeling



1. Laboratory tests

1. The first step is developing an understanding of the phase behavior and selecting a solvent. Considerable laboratory work is needed at this stage:
 - a. Slim tube tests to determine MMP and/or MME
 - b. Classical PVT studies
 - c. E.O.S. fine tuning to define pseudo-components that adequately describe the phase behavior.



2. Mobility Control Considerations

- The main concern is to determine whether or not acceptable sweep can be achieved with the operating mobility ratio and the level of heterogeneity present.
- If sweep is a problem, mobility control, such as WAG, must be considered.
- This requires estimation of sweep improvement with WAG as well as estimation of the effect of WAG on miscible flood residual oil saturation
- Experimental tests are generally needed to determine the effect of water blocking



3. Gravity segregation considerations

- An estimate of the extent of gravity segregation can be obtained using correlations or simulation studies.
- The Rv/g based correlations provide a reasonable estimate.
- An important consideration is the feasibility of gravity stable miscible displacement.
- If such a displacement is feasible, a downdip displacement is likely to be the best option.



4. Core Floods

- Corefloods provide additional information about the process, including:
 - a. The value of S_{orm} that will be left behind by the miscible slug
 - b. Relative permeability curves and hysteresis
 - c. Effect of water blocking on S_{orm}
- Corefloods need to be designed and executed carefully.
- Long cores are generally preferable to short plugs.
- If short plugs are stacked to make a long core, careful attention must be paid to capillary continuity at the joints between the plugs.



5. Modeling Studies

- Numerical modeling is used to make detailed predictions of the flood behavior.
- Both the simple black oil models and the more sophisticated compositional models can be used.
- Compositional simulation can provide more accurate answers by using E.O.S. based phase behavior calculations.
- The compositional simulation is also more expensive to run and requires more input data on component properties.
- Numerical dispersion is always a concern in modeling miscible displacements.
- Often, the numerical dispersion overshadows the physical dispersion – makes it difficult to model the true dispersion behavior.