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UNIVERSITY OF ALBERTA

INVESTIGATION OF MINIMUM MISCIBILITY PRESSURE PREDICTION

BY

FREDERICK J. YURKIW ©

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR

THE DEGREE OF

Master of Science

IN

Petroleum Engineering

DEPARTMENT OF

MINING, METALLURGICAL AND PETROLEUM ENGINEERING

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The undersigned certify they have read, and recommended to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled INVESTIGATION OF MINIMUM MISCIBILITY PRESSURE PREDICTION submitted by Frederick J. Yurkiw in partial fulfillment of the requirements for the degree of Master of Science in Petroleum Engineering.

....
Dr. D.L. Flock (Supervisor)

....
Dr. J.M. Whiting

....
Dr. R.G. Bentsen

....
Dr. L. Hepler

Date: JULY 23, 1990

ABSTRACT

A large number of correlations have been presented for predicting the minimum miscibility pressure (MMP) for a multiple-contact miscible gas flood. The MMP represents the displacement pressure at which a practical maximum oil recovery can be expected from the swept reservoir rock. Unfortunately, virtually no work has been presented regarding the feasibility of using any of the lean-gas, rich-gas, or nitrogen MMP correlations for accurate MMP predictions. The main purpose of this study is to determine the reliability of these correlations, using a data set composed almost exclusively of literature MMP measurements.

No consistent experimental procedure exists for measuring the MMP, resulting in some question as to the range of uncertainty in MMP values listed in the literature. A series of displacement experiments was performed to provide some indication of the influence varying experimental procedures have on MMP measurements. This range of MMP uncertainty should be considered when evaluating a correlation using an MMP data base in which inconsistent measurement procedures have been used.

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NOMENCLATURE

C_1 = methane
C_2 = ethane
C_3 = propane
C_4 = butane
C_5 = pentane
C_6 = hexane
C_7 = heptane
C_8 = octane
C_9 = nonane
C_{10} = decane
C_2-C_4 = ethane through butane
C_2-C_5 = ethane through pentane
C_2-C_6 = ethane through hexane
C_{5+} = pentanes plus
C_{7+} = heptanes plus
CO_2 = carbon dioxide
CGD = condensing-gas-drive
FCMP = first-contact miscibility pressure
FVF = formation volume factor
H_2S = hydrogen sulphide
LG = lean-gas
MMP = minimum miscibility pressure (KPa or MPa)
N_2 = nitrogen
P = pressure (Kpa or MPa)
RBA = rising bubble apparatus
RG = rich-gas
T = temperature (°C or K)
VGD = vaporizing-gas-drive

1. Introduction

Injecting fluids into a reservoir to displace oil towards producing wells is a practice used to increase the ultimate recoveries of many large oil fields. During an immiscible reservoir fluid displacement process such as a waterflood, the injected water and displaced reservoir oil remain as distinct phases with an interface between them and do not mix. A significant amount of residual hydrocarbons remain in the swept reservoir pore space after such immiscible displacements, largely due to the immiscibility existing between the injected and displaced fluids.

Miscible floods involve injection of fluids into a reservoir that are in some form mutually soluble with the hydrocarbons being displaced. This results in the formation of a transition zone containing a single-phase mixture of displacing and displaced fluids. The interfacial tension, and thus the capillary forces, are reduced to zero in this single-phase (or miscible) zone. Under suitable circumstances, the amount of residual hydrocarbons remaining in the reservoir pore space after the miscible zone has passed can be reduced to a minimum.

Economic restraints have generally prevented the feasibility of the use of a slug, or continuously injecting a solvent into the reservoir which is miscible upon first contact with the reservoir fluid. Miscible processes involving injection of relatively inexpensive hydrocarbon, nitrogen, or carbon dioxide gases, have been studied and applied to actual reservoirs. A miscible zone is gradually developed during these floods by a mass transfer of components between the injected gas and reservoir oil. This process has been referred to as multiple-contact miscibility.

It should be recognized that due to adverse mobility ratios, a miscible displacement is unstable in most cases. This instability can result in a substantially lower recovery than that for a waterflood. However, the effects of adverse mobility ratios can be reduced by using a vertical flow system where gravity is beneficial to the system stability, and/or a combination of water and gas injection in a horizontal miscible displacement.

An optimum displacement pressure exists for a multiple-contact miscible flood, and this pressure is commonly referred to as the minimum miscibility pressure (MMP). In order to evaluate the feasibility of performing a multiple-contact miscible displacement in a reservoir, it is necessary to determine the MMP. Experimental procedures and numerous numerical and graphical correlations have been developed to estimate this pressure requirement. The use of an MMP correlation, proven reliable over a large range of conditions, is considered acceptable for preliminary studies. The object of this study was to evaluate available MMP correlations, the majority of which have been proposed during the last few years.

2. Miscible Displacements

2.1 Introduction

The initial stage of production for most oil reservoirs is referred to as "primary recovery". This is a time period during which a reservoir's natural energy sources are used to recover a portion of the oil contained within the rock pore space. Buckley and Craze (1943) described the recovery characteristics of primary recovery programs, subsequent to which typically 60 to 90% of the original oil-in-place remains trapped in the reservoir.

Enhanced development programs involving the injection of a driving fluid into a reservoir were also described by Buckley and Craze (1943). Gas injection into an existing gas cap, water injection into an aquifer, or either gas or water pattern injection into the oil zone are the usual fluid injection techniques. Injection of fluids into a reservoir has two major advantages with regard to oil production: moderating a decline in reservoir pressure, which allows producing rates to be maintained at higher levels for a longer duration than would have been possible from primary producing mechanisms alone; and displacing oil from the rock pore space towards producing wells.

Waterflooding is referred to as an immiscible displacement because water and oil, when mixed, do not form a single-phase mixture. Early gas injection schemes into a reservoir or into an existing gas cap typically occurred at injection and reservoir pressures such that the injected gas and reservoir oil were also immiscible. Residual oil saturations as high as 40 to 60% of the original oil-in-place remain after waterflood or immiscible gas injection schemes.

In addition to being affected by rock pore structure, residual oil saturation is affected by the interfacial tension at the oil/injection fluid interfaces. Schilthuis (1938) discussed how these forces present at the interfaces of immiscible fluids reduce oil recovery. Since a single-phase results from mixtures of miscible fluids, there are no interfaces, and consequently no interfacial tension between the fluids. Under proper displacement conditions, displacing a miscible zone through a reservoir can minimize the residual hydrocarbons remaining in the swept rock pore space.

The obvious approach for a miscible displacement would be to inject a displacing fluid which behaves as a solvent and is completely miscible (first-contact miscible) with the reservoir oil. However, continuous injection of first-contact miscible solvents for oil recovery has been considered impractical because of the high cost of these solvents.

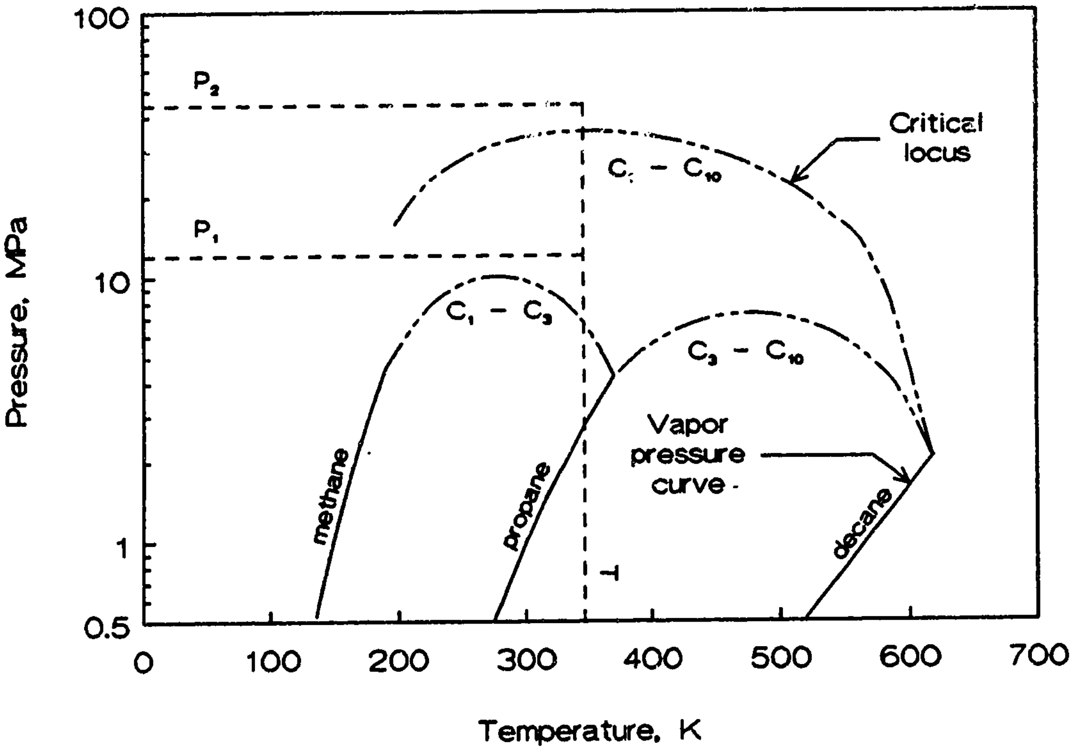
Operations have been developed which do not require that the reservoir oil be displaced by continuous injection of a first-contact miscible fluid. Whorton and Kieschnick (1950) first proposed the injection of gas into oil reservoirs at pressures much higher than those used in conventional gas displacement or pressure maintenance schemes. The increased injection pressure was found to improve the efficiency of gas displacements, and these processes were initially described as "high pressure gas injection." During these floods, the injected gases are not initially miscible with the reservoir fluid, but miscibility is gradually developed by a mass transfer of components between the displacing and displaced fluids. This miscibility mechanism was described by Slobod and Koch (1953), and miscibility generated in such a manner is commonly referred to as multiple-contact miscibility.

2.2 P-T Phase Behavior of Binary Mixtures

The concept of miscibility between the various components of a gas/oil mixture can be introduced using a pressure-temperature (P-T) diagram. Two-phase liquid/vapor equilibrium is encountered with most field hydrocarbon systems at common reservoir pressure and temperature conditions. This type of hydrocarbon P-T phase behavior was described by Nouar (1987).

Figure 2-1 contains the P-T phase relationships for the C_1-C_3, C_3-C_{10}, and C_1-C_{10} binary systems. The critical locus and vapor pressure curves of each binary were plotted using Soave (1972) equation of state calculations made by Nouar (1987). The P-T diagram of each binary system is bounded by the vapor pressure curves of the two components and the critical locus joining their critical points. The enclosed inner region represents pressure and temperature conditions at which two-phase equilibrium may result for certain compositions of the

Fig. 2-1: Sample P-T Diagram
(plotted using data from Nouar, 1987)



binary system. The outer region corresponds to P-T conditions at which the binary systems remain in the single-phase region.

The phase behavior of the C_1-C_3-C_{10} ternary system can be described with the aid of Figure 2-1. At a constant reservoir temperature T and pressure P_1, the binary systems C_1-C_3 and C_3-C_{10} are both in the single-phase region. Certain compositions of the C_1-C_{10} binary are in the two-phase region, and consequently, so are certain compositions of the ternary system C_1-C_3-C_{10}. If the pressure is increased to P_2, the system C_1-C_{10} is in the single-phase region, and so is the ternary system C_1-C_3-C_{10}. This illustrates that an increase in pressure will result in a shrinkage of the two-phase region of the ternary system C_1-C_3-C_{10} at a fixed temperature.

At a fixed temperature, the critical pressure of a binary mixture increases as the critical temperature of the light component decreases, or the critical temperature of the heavy component increases. The critical temperatures of the paraffin series (C_n) increase with increasing carbon number(n). The critical pressure of the C_3-C_{10} binary would then be less than that of the C_1-C_{10} binary because the critical temperature of C_1 is less than that of C_3. Light-ends such as C_1 and N_2 contained within an oil will, therefore, increase the critical pressure of the mixture. Increasing these light-end concentrations within an oil has the effect of enlarging the range of pressures over which two-phase equilibrium would be expected for a gas/oil mixture.

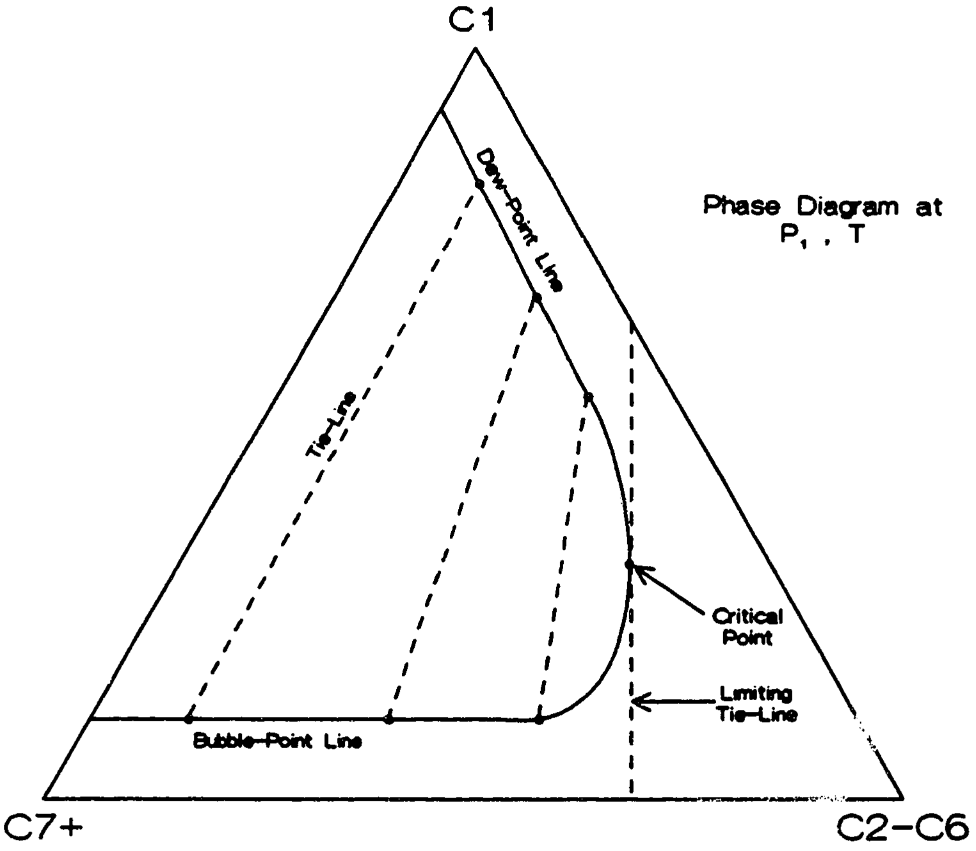
2.3 Phase Behavior of Multicomponent Mixtures

Actual reservoir hydrocarbon systems consist of hundreds of components, and a graphical representation of the system phase behavior at a specific pressure and temperature would require a diagram of n-1 dimensional space, where n represents the number of components. For convenience and presentation clarity, the phase behavior of a multicomponent hydrocarbon system at a constant pressure and temperature was presented on a pseudocomponent ternary diagram by Slobod and Koch (1953).

The complex multicomponent hydrocarbon system was divided into three component groups; the light-ends were represented by C_1, the intermediates by C_2-C_6, and the heavy-ends by the C_{7+} fraction. Such component groupings are today referred to as pseudocomponents, and the triangular diagram as a pseudocomponent diagram. Generally, lighter volatile ends (C_1 and N_2) are grouped into a "light" pseudocomponent, hydrocarbons of intermediate volatility (C_2 through C_6, CO_2, and H_2S) are grouped into an "intermediate" pseudocomponent, and the heavier non-volatile hydrocarbons (C_{7+} fraction) into a "heavy" pseudocomponent.

The phase behavior of a hypothetical pseudoternary mixture at a constant pressure (P_1) and temperature (T) is illustrated in Figure 2-2. The pseudoternary diagram is a compositional diagram, with each apex of the triangle corresponding to 100% of one of the constituting pseudocomponents. Any point within the triangle represents a

Figure 2-2: Phase Behavior of a Pseudoternary System



system with a specific composition made up of definite amounts of each pseudocomponent. Although such a representation is not thermodynamically rigorous, it allows for a visualization of expected phase behavior.

The two-phase region in Figure 2-2 is bounded by the phase envelope which comprises the dew-point curve (locus of points where the vapor phase is in equilibrium with an infinitesimal amount of liquid) and the bubble-point curve (locus of points where the liquid phase is in equilibrium with an infinitesimal amount of vapor). The bubble-point and dew-point curves meet at the critical point, where all the properties of the coexisting liquid and vapor phases become identical. This phase boundary curve separates the single-phase and two-phase regions of the diagram.

If a hydrocarbon system has a composition that places it inside the phase envelope, two-phases will result at equilibrium. The point representing the composition of the vapor phase will be located on the dew-point curve, and the point representing the liquid phase composition on the bubble-point curve. The line connecting these points is referred to as a tie-line. Each point on this tie-line represents the overall composition of a system which, at equilibrium, will have coexisting vapor and liquid phases having compositions corresponding to the intersection points of the tie-line with the dew-point and bubble-point curves, respectively. Several tie-lines are illustrated in Figure 2-2. As the critical point is approached, the tie-line coincides with the tangent to the phase envelope at the critical point. This line is referred to as the limiting tie-line.

When pressure is reduced the size of the two-phase region increases. An increase in temperature has this same effect. Figure 2-3 illustrates the effect of pressure on the hypothetical system illustrated in Figure 2-2 at a constant temperature. An increase in pressure to P_2 is accompanied by a shrinkage of the phase envelope. Also, the critical point composition moves from the critical point of the light/intermediate pseudobinary to the critical point of the light/heavy pseudobinary, at which point the two-phase region vanishes.

2.4 Pseudoternary Representation of Miscible Displacements

A pseudoternary representation of a displacement is shown in Figure 2-4. The reservoir fluid and injection gas compositions are given by points O and G respectively. If the reservoir oil (O) and injection gas (G) are mixed, the composition of the resulting infinite possible number of mixtures is located on the line connecting the two compositions. If this line does not intersect the two-phase region, the two fluids are first-contact miscible since any mixture of two fluids forms a single-phase.

The size of the two-phase region increases with decreasing pressure (for a constant temperature), and a

Figure 2-3: Phase Envelopes with Changing Pressure

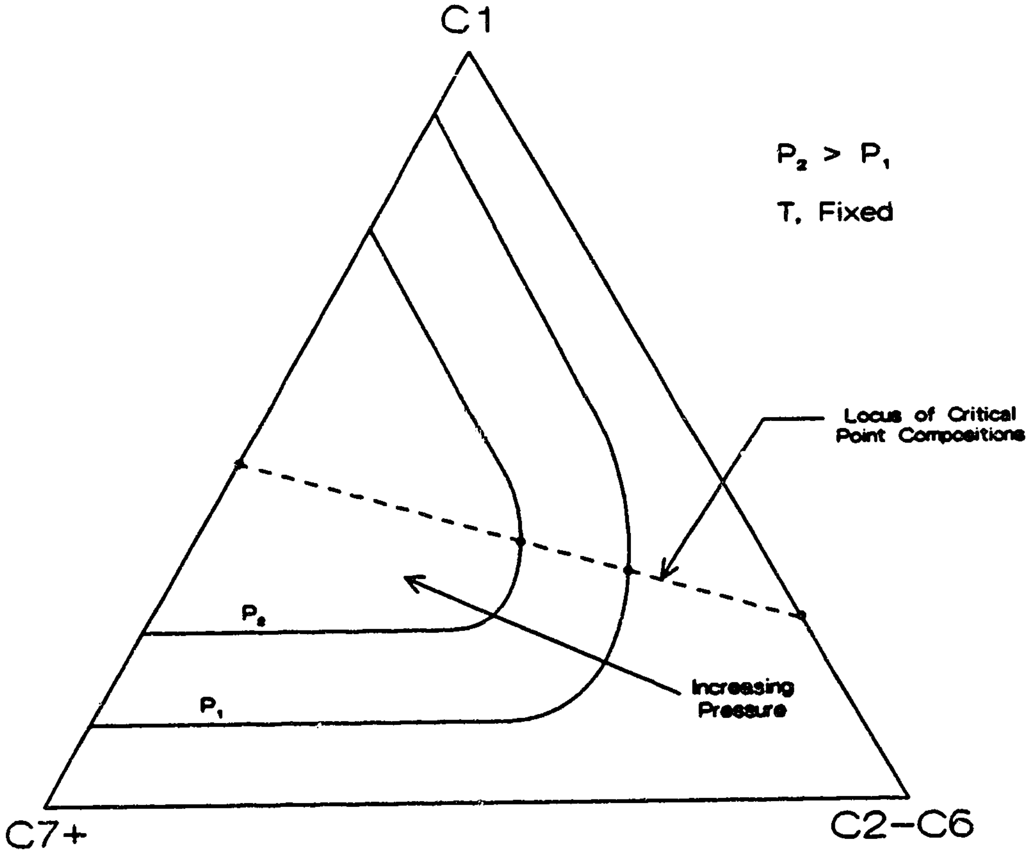
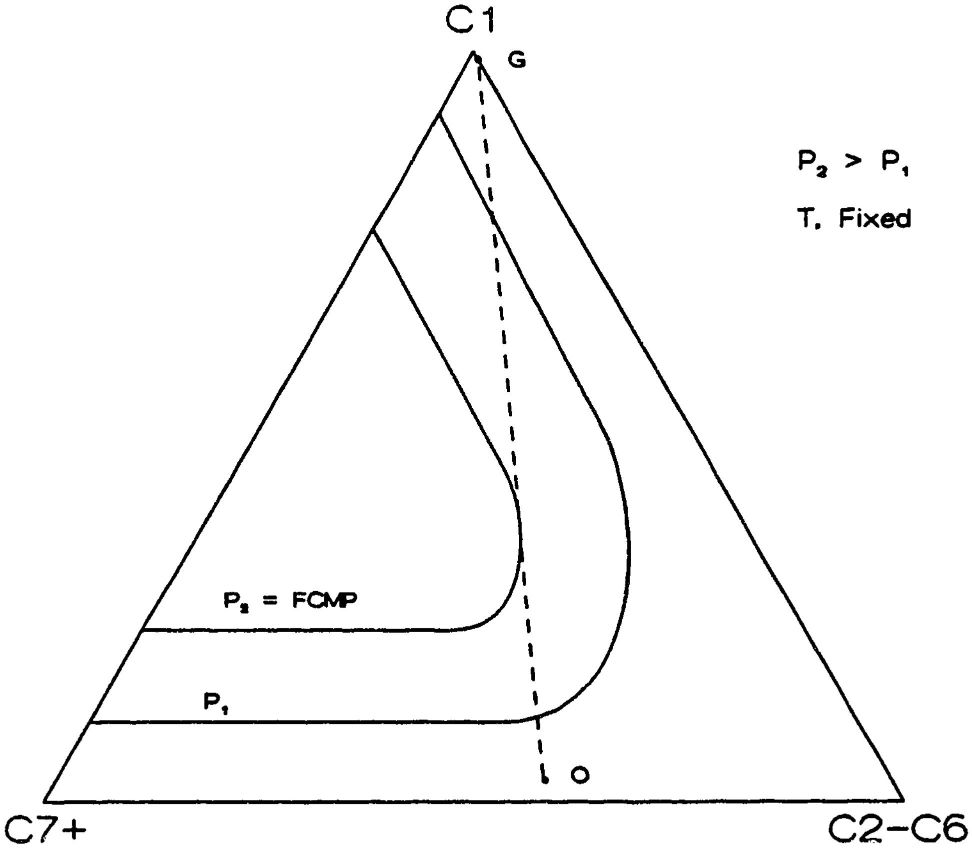


Figure 2-4: First-Contact Miscibility Pressure



pressure limit exists for obtaining miscibility by first contact. The pressure at which the line connecting points G and O is tangent to the two-phase boundary is the lowest pressure where first-contact miscibility can be obtained. This pressure is commonly referred to as the first-contact miscibility pressure (FCMP).

In Figure 2-4, pressure P_2 represents the FCMP for the hypothetical mixture. The FCMP is generally excessively large for gas/oil mixtures, and injecting a displacing fluid at this pressure is usually either uneconomical or impossible (FCMP exceeds formation fracturing pressure). However, miscibility can be obtained at pressures lower than the first-contact miscibility pressure. This phenomenon is referred to as multiple-contact miscibility, and is caused by a mass transfer between the co-currently flowing gaseous and liquid phases. The mass transfer occurs because the injected gas is generally much more mobile than the reservoir fluid. The gas is in continuous contact with reservoir oil at the displacement front, allowing this mass transfer mechanism to occur.

Two different classical mechanisms for obtaining multiple-contact miscibility have been presented. These are called the vaporizing-gas-drive (VGD) and the condensing-gas-drive (CGD). The condensing-gas-drive process was described by Stone and Crump (1956) and the vaporizing-gas-drive process by Clark, Schultz, and Shearin (1956).

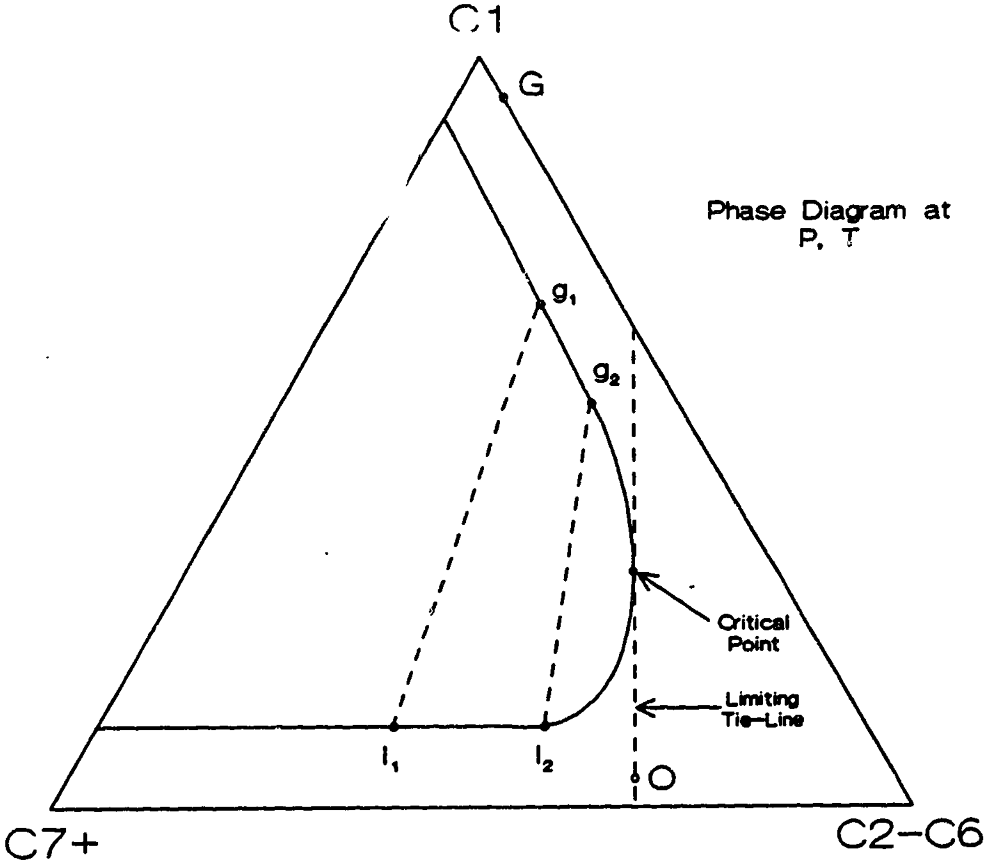
2.4.1 Vaporizing-Gas-Drive

In the case of a vaporizing-gas-drive (VGD), mass transfer occurs between the injected gas (lean in C_2-C_6 intermediates) and reservoir oil (rich in intermediates) until miscibility is established. Figure 2-5 illustrates the VGD mechanism between an injection gas (G) and reservoir oil (O) at a constant pressure (P) and temperature (T).

At the beginning of the displacement, the injected gas (G) comes into contact with the reservoir fluid (O), and the two fluids are not initially miscible. As the injected gas travels through the porous medium the overall composition of the injection front changes. The gas at the flood front will continually contact virgin reservoir oil (O), and "vaporize" intermediate components within the oil. In the ternary diagram, the gas phase composition path will follow the dew-point curve in the direction of increased intermediates (i.e. compositions g_1, g_2). Eventually the gas will reach the composition indicated by the critical point in Figure 2-5. The line joining the enriched-gas composition (represented by the critical point) to point O does not cross the phase envelope. At this point, miscibility has been achieved. For a vaporizing-gas-drive, miscibility develops at the displacement front.

The pressure at which the limiting tie-line passes through the point describing the composition of the reservoir oil represents the lowest pressure (i.e. the MMP) at which a

Figure 2-5: MMP of a Vaporizing-Gas-Drive



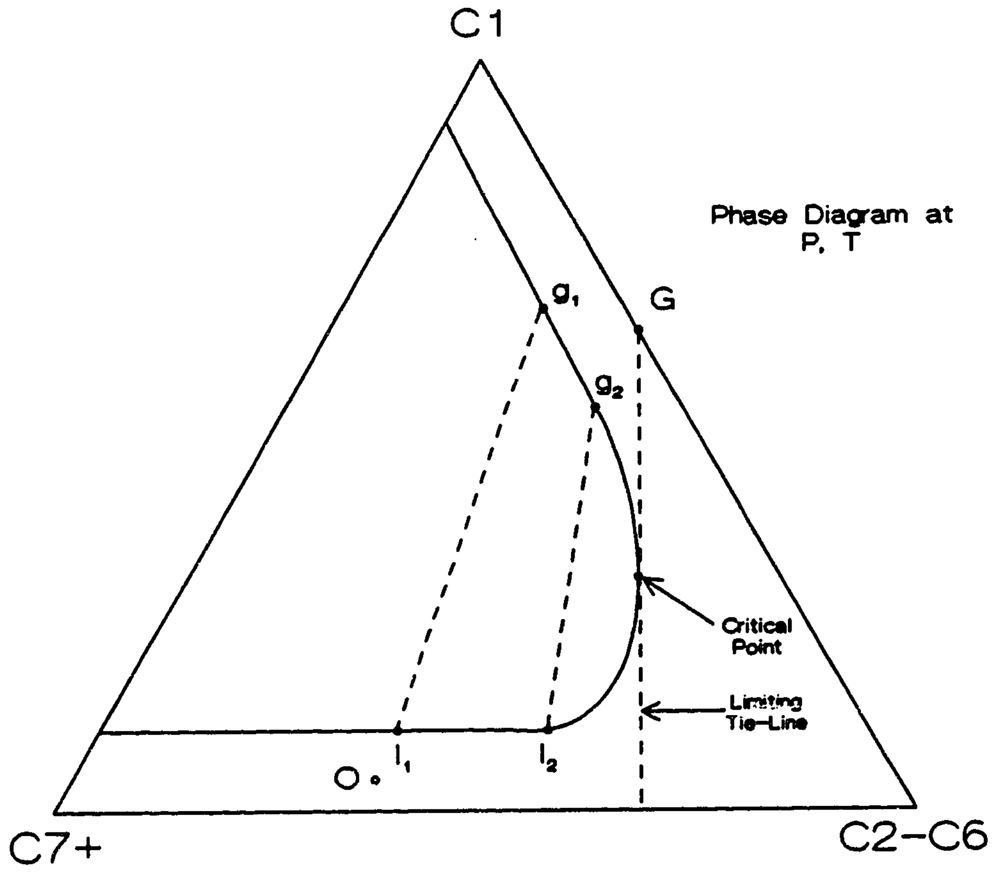
VGD is possible. Any oil having a composition which falls to the right of the limiting tie-line in Figure 2-5 can be displaced miscibly by the injected gas (G).

2.4.2 Condensing-Gas-Drive

For the condensing-gas-drive (CGD), the injected gas would be rich in the intermediate components, while the oil would be lean in these components. The mass transfer during a CGD involves a "condensation" of the intermediates present in the rich injection gas into the reservoir oil.

Figure 2-6 illustrates the composition paths followed by the gaseous and liquid phases in the transition zone for the case of a condensing-gas-drive. The point representing the composition of the displacing fluid (G) is located on the limiting tie-line at the specified pressure (P) and temperature (T). As the displacement proceeds, the oil left behind will be contacted by fresh rich displacing gas, and will be continually enriched in intermediate components. Its composition path will follow the bubble-point curve in the direction of increasing intermediate components (i.e compositions l_1, l_2). Eventually the enriched oil will reach the composition indicated by the critical point in Figure 2-6. The injection gas (G) is now completely miscible with the oil, as the line joining point G to the enriched oil composition (critical point) does not cross the two-phase envelope. In the CGD, miscibility is developed at the rear of the

Figure 2-6: MMP of a Condensing-Gas-Drive



displacement, or at the injection point.

For the CGD, the MMP may be defined as the pressure necessary for the limiting tie-line to pass through the point representing the composition of the displacing gas. CGD miscibility can be achieved also by injecting a gas sufficiently rich in intermediate components. This minimum enrichment must be such that, at the reservoir pressure, the limiting tie-line passes through the point representing the composition of the injected gas.

2.4.3 New CGD Interpretation

The classical description of a condensing-gas-drive (CGD) involves the transfer of intermediates from a rich injection gas to a reservoir oil. Stalkup (1965) indicated that the mechanism of miscibility development in rich-gas drives may be more complex than traditionally explained. In a much later study, Zick (1986) concluded that many rich-gas drive processes might be more accurately described as "combined condensing/vaporizing" drives.

Novosad and Costain (1987a) speculated that rather than involving a mass transfer of intermediates in generating miscibility, the dominant feature of many rich-gas drives involved enrichment of the injected gas in C_{6+} components. In a following study, Novosad and Costain (1987b) provided experimental evidence of what was called the "liquid extraction mechanism." Intermediates (C_3-C_5) were found to not participate in the mass transfer process of many rich-gas drives. Similar to VGD's, miscibility in liquid extraction drives develops at the front of the displacement, but by an extraction of C_{6+} components in the reservoir oil.

Novosad and Costain (1987b) suggested that condensing-gas-drives occur mostly in low temperature reservoirs, below about 50°C. In warmer reservoirs and for ethane-rich injection gases, the liquid-extraction mechanism was thought to prevail. Unfortunately, very little discussion is presently available on the liquid extraction mechanism in rich-gas drives.

2.5 Displacement Mechanism for Common Injection Gases

Hydrocarbon gases (C_n components), nitrogen, and carbon dioxide are the most common injection fluids used for multiple-contact miscible displacements. Whether a particular displacement will be of a condensing or vaporizing nature depends on several factors. These include the reservoir pressure and temperature, and the compositions of the injected gas and reservoir fluid.

When the compositions and phase behavior of a gas/oil mixture are illustrated on a pseudoternary diagram, the mechanism of miscibility development can be identified in many situations. If the reservoir oil composition lies on or to the right of the limiting tie-line, dynamic miscibility can be attained by the vaporizing-gas-drive mechanism with gas that has a composition lying to the left of the limiting tie-line. Generally, a high pressure reservoir containing an oil with a large fraction of intermediates is required for a VGD to be possible. For reservoir oils whose compositions lie to the left of the limiting tie-line, dynamic miscibility can also be achieved, but via the condensing-gas-drive mechanism. In this case, the injection gas composition must lie on or to the right of the limiting tie-line.

Early studies on multiple-contact miscibility evaluated reservoirs for displacements involving hydrocarbon gases. The low-in-intermediates hydrocarbon gases (mainly C_1) used for VGD's were described as "lean" gases (LG), and the enriched-gases (high C_2-C_4 fraction) used for CGD's were referred to as "rich" gases (RG). The miscibility pressure of a lean VGD is inversely related to the amount of intermediates (C_2-C_6) in the reservoir oil. Similarly, the MMP of a rich CGD is inversely related to the amount of intermediates (C_2-C_4) in the injection gas.

Dynamic miscibility in nitrogen (N_2) floods is achieved by a VGD mechanism, but Koch and Hutchinson (1958) felt that a slightly different type of mass transfer occurs than that described for lean-gases. The concentration of C_1, as well as the intermediate (C_2-C_6) fraction in the reservoir fluid, was found to be important in fixing the miscibility pressure of N_2 floods. Koch and Hutchinson speculated that the presence of C_1 in the reservoir fluid was helpful in volatizing the C_2-C_6

fraction into the N_2 gas. Alcocer and Menzie (1984), Hudgins et al. (1988), and Glasø (1988) experimentally confirmed Koch and Hutchinson's original observation. In general, N_2 MMP's are higher than lean-gas MMP's for displacements of identical oils, as suggested by Firoozabadi and Aziz (1986).

Floods using carbon dioxide (CO_2) gases are similar to lean-gas and N_2 VGD's. The mechanism of displacement differs primarily in the extent of vaporization or extraction of hydrocarbons from a reservoir oil. Holm and Josendal (1974) noted that the development of dynamic miscibility with CO_2 does not require the presence of intermediate (C_2-C_4) molecular weight hydrocarbons in the oil. The C_5-C_{30} fraction within the oil was found to be a major factor influencing the development of dynamic miscibility with CO_2. This extraction of a large range of hydrocarbons from the reservoir fluid allows CO_2 dynamic miscibility to be achieved generally at lower pressures than are possible with a lean-gas or N_2.

Miscibility develops at the flood front of a CO_2 displacement, and CO_2 floods have been referred to as VGD processes. The hydrocarbons extracted (C_5-C_{30}) from a reservoir oil by CO_2 indicate that the displacement mechanism is actually more similar to the rich-gas liquid extraction process described by Novosad and Costain (1987a,b).

3. Evaluation of the MMP

3.1 Constructing Pseudocomponent Diagrams

As noted earlier, it is usual to use pseudocomponent ternary diagrams to ease the visualization of complex multicomponent hydrocarbon systems. Inspection of such diagrams allows for both the minimum miscibility pressure and the type of displacement mechanism (CGD or VGD) to be estimated. Experimental and numerical methods have each been used to construct pseudoternary diagrams for these purposes.

Vapor/liquid equilibrium experiments performed in a PVT cell have been used to provide equilibrium gas and liquid compositions for various mixtures for a simulated multiple-contact displacement. A pseudoternary diagram can then be constructed by plotting the experimentally determined vapor and liquid compositions, along with the corresponding tie-lines. Equations of state or K-value correlations can also be used to calculate vapor/liquid equilibria for a mathematically simulated multiple-contact displacement.

3.1.1 PVT Cell Method

The PVT Cell method of identifying the MMP of a gas/oil system involves a series of batch-contact experiments repeated at different pressures and a constant (reservoir) temperature. The experimental procedure involves simulating the enrichment of the injected lean-gas as it continuously contacts virgin reservoir oil during a vaporizing-gas-drive, or the enrichment of the reservoir oil as it contacts fresh rich injection gas in a condensing-gas-drive. Benham, Dowden, and Kunzman (1960) and Peterson (1978) provided good descriptions of PVT experiments for MMP determination.

The PVT cell experiment involves mixing a reservoir oil and injection gas. The PVT cell is originally filled with oil (O), and then some of the oil is replaced with the injection gas (G) under constant pressure and temperature conditions. Upon reaching equilibrium, the resulting mixture will separate into a gaseous (g_1) and a liquid (l_1) phase.

During a vaporizing-gas-drive, the injected gas at the flood front is in continuous contact with virgin reservoir oil. The VGD mechanism is simulated in the PVT cell by removing the equilibrium liquid phase (l_1) and replacing it with original oil (O). At equilibrium the resulting mixture will separate into gaseous (g_2) and liquid (l_2) phases. The equilibrium liquid phase (l_2) is removed and fresh oil (O) is again placed in contact with the existing equilibrium gas (g_2).

This process is repeated a number of times until the windowed PVT cell observations allow for a classification of the simulated displacement as being either miscible or immiscible. Miscibility can be inferred from the liquid saturation level within the cell. For the VGD process, a vanishing liquid saturation (representing an extraction of intermediates from the oil into the gas) indicates that the experimental pressure is greater than or equal to the MMP. This situation corresponds to a multiple-contact miscible displacement. The VGD MMP corresponds to the minimum pressure for which a vanishing liquid saturation is observed. Vapor/liquid equilibria compositions obtained for the various steps of the lowest pressure miscible PVT experiment can then be used to plot a pseudoternary diagram.

The major drawback of the PVT cell method is that it can be time consuming to identify precisely the MMP. Stalkup (1983) indicated that the experimental gas and liquid equilibrium data can be difficult to determine, and such data are generally not taken near the critical point. As the critical point is approached, it becomes increasingly difficult to distinguish equilibrium gas and liquid compositions. The critical point and limiting tie-line slope are usually obtained by extrapolation of data measured near the critical point.

3.1.2 Vapor/Liquid Equilibria Calculations

Numerous researchers have used equations of state or k-value correlations to generate phase envelopes for gas/oil mixtures while concurrently simulating the multiple-contact mechanism: Benham et al. (1960) and Rowe and Silberg (1965) each used NGSMA (1957) equilibrium constants; Williams and Zana (1980), Lee and Reitzel (1982), Kuo (1985), Firoozabadi and Aziz (1986), Benmekki and Mansoori (1986), and Novosad and Costain (1987a,b) all used the Peng-Robinson (1976) equation of state; and Choen and Shirer (1983) used the Exxon Benedict-Webb-Rubin-Starling (BWRS) equation of state as proposed by Lin and Horpke (1974).

A gas/oil mixture is presented in terms of pseudocomponents when calculating vapor/liquid equilibria. At fixed conditions of pressure and temperature, flash calculations can be performed for various mixtures of the pseudocomponents. When liquid and vapor phases are found to coexist at equilibrium, the composition of the coexisting phases can be represented in terms of the selected pseudocomponents. The phase envelope, which separates the single-phase from the two-phase region, is obtained by repeating the above procedure to other mixtures.

In generating a phase envelope for pseudocomponent mixtures, the multiple-contact mechanism must be simulated mathematically. In a condensing-gas-drive, for example, reservoir oil is in continuous contact with a fresh (rich) injection gas. Calculated CGD equilibrium liquid compositions for one stage of the "displacement", must then be mathematically combined with fresh injection gas for the next stage of the "displacement".

Benmekki and Mansouri (1986) described some limitations in using any equation of state (EOS) to predict miscibility conditions for multicomponent mixtures. An equation of state usually is joined with a set of mixing and combining rules when its application is extended to mixtures. For pure fluid and binary mixtures, an EOS can represent mixture properties correctly through the use of experimentally calculated binary interaction parameters which are used in the combining rules. However, when the EOS is used for multicomponent mixtures (ternary and higher systems), there necessarily will be some deficiency in the mixture property representation.

Katz and Firoozabadi (1978) and Williams and Zana (1980) noted that the method of calculating gas and liquid equilibria to predict accurate miscibility relies largely on experimentally measured PVT phase behavior data near the critical point. Experimental PVT phase behavior data is necessary to calibrate k-value correlations or equations of state. Essentially, parameters in the correlation or equation of state are adjusted to achieve a prediction of the known PVT data. Stalkup (1983) indicated that it generally is accepted that near-critical PVT data may not be sufficiently accurate for these purposes.

The utility of the Peng-Robinson equation of state (PR-EOS) has been tested with limited success in predicting the phase behavior and minimum miscibility pressures of gas/oil mixtures. Lee and Reitzel (1982) found that for multicomponent mixtures, the PR-EOS generally predicted higher MMP than obtained from displacement experiments. Firoozabadi and Aziz (1986) and Benmekki and Mansoori (1986) both found that, even for pure ternary systems, sharp changes in the critical region are not well represented by the PR-EOS. In both cases, the PR-EOS over-estimated the MMP of ternary systems.

3.2 Direct Calculation of Critical Conditions

A direct estimation of the MMP for a pseudoternary system requires determining the critical point and limiting tie-line for the mixture. The PVT cell and vapor/liquid equilibria calculation methods indirectly accomplish this by constructing the two-phase envelope for gas/oil mixtures. Generally, the critical point and limiting tie-line are obtained by extrapolation of measured/calculated data near the critical point.

In proposing a direct critical point calculation method, Peng and Robinson (1977) described the governing equations of the critical state of a three-component system. Two equations involve evaluation of the partial derivatives of the mixture's molar Gibbs free energy, and are solved for the critical composition. A third equation describes the limiting tie-line slope in terms of partial derivatives of the molar Gibbs free energy. The molar Gibbs free energy can be calculated using any pressure-explicit EOS.

Peng and Robinson (1977) used their equation of state to calculate mixture critical points. Heidemann and Khalil (1980) and Michelson (1984) used the Soave (1972) equation of state. Nouar and Flock (1988) later used the Soave EOS to generate a correlation for predicting the MMP of lean hydrocarbon VGD's. Nouar, Flock, and Dranchuk (1990a,b) extended the method to quaternary systems for predicting the MMP of nitrogen VGD's.

An advantage of this approach is that the critical point and limiting tie-line are calculated directly, not estimated by extrapolation. It generally is accepted that such calculations are more accurate than the numerical pseudoternary approach, as reported by Reid, Prausnitz, and Poling (1986) in a comprehensive study on the properties of gases and liquids. The method of directly calculating the critical composition and limiting tie-line does, however, rely on the use of an equation of state. The same basic limitations discussed before, namely that the EOS is somewhat limited in representing the properties of multicomponent mixtures, apply.

3.3 Slim-Tube Displacement Apparatus

During displacement experiments, one has no direct way of adequately visualizing the displacement to determine miscibility. The amount of oil recovered from the porous medium traditionally has been used to infer whether or not the displacement was miscible. The MMP has been accepted to represent the pressure where a "practical" maximum of the original oil-in-place has been recovered from the porous medium.

For the case of VGD miscibility, some period of immiscible displacement must occur before mass transfer between the reservoir oil and the advancing gas front establishes dynamic miscibility at the front. For the recovery efficiency of a displacement to be used to infer miscibility, the porous medium must be of sufficient length that the length of the column of immiscible displacement relative to that of the miscible displacement is small. This length requirement gives rise to experimental difficulties when using consolidated porous media for displacement experiments.

Deffrenne, Marle, and Pacsirszki (1961) studied the effect of the porous medium on miscibility pressure measurements. Displacements where performed using unconsolidated and consolidated porous media, and it was concluded that the experimentally estimated MMP is independent of the nature of the porous medium. Deffrenne et al. (1961) also noted that the method of using displacement efficiencies can give good results only if the overall displacement efficiency in the gas-swept volume is the principal factor influencing the value of the recovery. Accordingly, reducing the factors causing poor sweep efficiency is desirable. These include gravity segregation, which in a horizontal system tends to cause the lighter fluids to channel through the upper part of the porous medium; the formation and development of fingering; and the heterogeneity of the porous medium.

To suppress the influence of heterogeneities, Deffrenne et al. used a porous medium prepared from sorted unconsolidated sands, as suggested by Koch and Hutchinson (1958). To suppress fingering, Deffrenne et al. recommended performing displacements at a velocity below the critical velocity, which represents the displacement velocity which should not be exceeded in order to avoid fingering. Gravity segregation was controlled by performing the displacement in a vertical sandpack and injecting the less dense solvent at the top of the vertical test column. Deffrenne et al. noted that the velocity requirement for a gravity-stable displacement is proportional to the permeability of the porous medium, and is likely to be impractically low for consolidated cores.

Perkins, Johnston, and Hoffman (1965) described how a displacement apparatus, now referred to as a slim-tube, minimizes the main factors causing poor sweep efficiency. Slim-tube experiments are carried out in a long, elongated small-diameter steel tube packed with glass beads or silica sand. The experiments involve constant-temperature displacement of a live oil from the slim-tube by an injection gas. Perkins et al. indicated that the small width of the slim-tube porous medium aids in the suppression of fingering and the effects of adverse mobility ratios. During such experiments, mixing by transverse dispersion either prevents or severely retards fingering before the injection (gas) front has travelled a significant fraction of the test column length.

A visual sight glass is usually located at the downstream end of the slim-tube, and can be useful for judging miscibility in vaporizing-gas-drives.. At or above the MMP, only single-phase effluent should be observed as the VGD transition zone changes from displaced oil to injected gas. However, the mechanism of the condensing-gas-drive process is such that a zone of distinct two-phase flow may be observed in the visual cell for miscible displacements. Because of this, visual observations of the transition zone may not be helpful for judging minimum miscibility conditions for condensing-gas-drives.

As observed by Orr et al. (1980), slim-tube experimental procedures vary from one investigator to another. There are greatly varying displacement lengths, flow geometries ranging from vertical or flat coils to spirals, and flow velocities varying over nearly two orders or magnitude. Orr et al. also noted that no general consensus exists as to the experimental criteria defining the MMP. This was discussed by Holm and Josendal (1982), who indicated that experimenters have defined MMP in different ways. For example, some researchers have arbitrarily chosen specific breakthrough or ultimate recovery values (i.e. 90%) to represent a miscible displacement. Others have selected the point on the recovery versus displacement-pressure plot at which maximum or nearly maximum recovery is obtained to represent the MMP.

Possible explanations as to why no standard slim-tube apparatus design or experimental MMP criteria exist can be taken from the observations of Holm and Josendal (1982), Stalkup (1983), and Nouar and Flock (1983). Holm and Josendal concluded that the different MMP definitions have resulted in small, but not fundamental, differences in MMP determined by different researchers. Stalkup indicated that several different combinations of tube length, diameter, packing material, and flow velocities can give satisfactory results. Nouar and Flock determined that several tube length and injection rate combinations can provide acceptable MMP measurements.

3.4 Rising Bubble Apparatus

The minimum miscibility pressure for many gas/oil combinations can be determined experimentally by using what is referred to as the rising bubble apparatus (RBA). The rising bubble apparatus was first proposed by Christiansen and Haines in 1983, and later described in a paper by Christiansen and Haines (1987).

The RBA essentially consists of a glass tube mounted in a high pressure sight gauge in a temperature controlled bath. A hollow needle for injecting gas bubbles into the glass tube is mounted at the bottom of the sight gauge. In preparation for an experiment, the sight gauge and glass tube are filled with distilled water. Enough oil is then injected into the glass tube to displace all but a short column of water in the tube's lower end. A small bubble of gas of the desired composition is then injected into the water. The buoyant force on the bubble causes it to rise through the column of water, then through the water-oil interface. As the bubble rises through the oil, its shape and motion are observed.

For a gas-oil pair, rising bubble experiments are repeated over a range of pressures. From the pressure dependence of the behavior of the rising bubbles, MMP is inferred. An initial oil sample is used to locate roughly the MMP through injection of several bubbles at different pressures. Final MMP is determined with live oil which is replaced after injecting only one or two solvent bubbles.

Christiansen and Haines (1987) noted that bubble behavior varies significantly over a range of pressures and distinct patterns separate miscible and immiscible gas/oil mixtures. Below the MMP a bubble slowly shrinks as its gas steadily dissolves in newly contacted oil; at or above the MMP the bubble rapidly disperses when the enriched bubble composition becomes miscible with oil.

A limitation of the RBA is that it would appear to be restricted to measuring multiple-contact miscibility pressures in which miscibility develops through forward contacts. Therefore, it is possible that the MMP of vaporizing-gas-drives, liquid extraction drives, or CO_2 drives can be measured using the RBA. The MMP of condensing-gas-drives would not appear to be measurable because of this limitation.

3.5 Basic Differences Between Methods

Stalkup (1983) discussed possible differences between the mechanism of miscibility development occurring in slim-tube tests, and the mechanism of miscibility that is simulated in PVT experiments and EOS vapor/liquid equilibria calculations. During a displacement in a slim-tube (or in a reservoir) the displaced oil phase has some mobility both in front of and behind the injection gas front, and the porous medium promotes mixing between the phases. The experimental and numerical vapor/liquid equilibria methods simulate the displacement process through a series of processes in which the gas and oil are brought into static contact. Therefore, these methods assume that the oil phase is immobile.

For example, consider the case of a vaporizing-gas-drive. The vapor/liquid equilibria methods simulate the VGD process through a series of static combinations of the injection gas and reservoir oil. The enriched-gas phase after one stage of the simulated displacement is brought into contact with virgin oil for the next stage of the simulated displacement. The further enriched-gas phase resulting from this mixture is again brought into contact with virgin oil. This process continues until miscibility is achieved. On the pseudoternary diagram the compositional front will always be described by the dew-point line.

Novosad, Sibbald, and Costain (1989) discussed how the oil phase mobility would cause the compositional front to differ from the dew-point line during an actual displacement. The compositional front would likely fall within the two-phase envelope due to mixing of the two mobile phases. As well, Novosad et al. noted that if the interfacial tension between the injected gas and reservoir oil is reduced to a very low value through the multiple-contact mechanism, a high displacement efficiency would result. Such processes would appear to be miscible, even though true miscibility had never been achieved.

Experiments performed by Hutchinson and Braun (1961) illustrated the possible differences between miscibility developed through dynamic and static gas/oil contacts. They compared vapor/liquid equilibria from a PVT experiment, to vapor/liquid equilibria measured at various stages of a displacement experiment. It was found that the vapor/liquid equilibria and corresponding tie-lines were noticeably different for the static (PVT cell) and dynamic (displacement experiment) cases.

The numerical MMP estimation method involving direct calculation of the critical point and limiting tie-line slope also does not simulate the development of miscibility in an actual displacement. Similarly, the rising bubble apparatus does not simulate displacement experiments as there is no porous media to promote mixing of the phases. During RBA experiments the reservoir oil is essentially static, and gravity will force the gas bubble up through the oil, regardless of how low the interfacial tension between the gas and oil is. Therefore, the compositional front will always be characterized by the dew-point line, as described by Novosad et al. (1989).

On the basis of the preceding discussion, it can be argued that the various MMP measurement techniques are based upon slightly different miscibility development mechanisms. Exact agreement between MMP's predicted for a particular gas/oil mixture by each of the methods would not be expected. In the literature, the MMP has generally been defined as the pressure at which a practical maximum recovery efficiency is observed in slim-tube displacement experiments. The acceptability of other MMP estimation methods has been based on how their predicted MMP values compare with those obtained from the slim-tube method.

4. MMP Correlations

A total of 29 correlations for predicting the minimum miscibility pressure of lean hydrocarbon, rich hydrocarbon, nitrogen, or carbon dioxide floods was found during a review of the literature. Four of these correlations can be used for rich-gas drives, 5 for lean-gas drives, 7 for nitrogen drives, and 18 for carbon dioxide drives. Some of the miscibility prediction correlations are based on MMP's calculated for selected gas/oil mixtures using the theoretical techniques discussed in Section 3. The calculated MMP's were then correlated with temperature and selected gas/oil compositional properties, and an MMP correlation presented using these results. Other MMP correlations are based entirely on statistics, derived from a data base of experimentally measured MMP's.

4.1 Hydrocarbon MMP Correlations

Benham, Dowden, and Kunzman (1960) published a correlation for predicting the miscibility conditions of rich condensing-gas-drives. The correlation is based on calculated critical point compositions of selected multicomponent systems which were simplified into three pseudocomponents (C_1, C_2-C_4, and C_{5+}). The modified Kurata-Katz (Davis et al., 1954) empirical method was used to evaluate the critical pressures of various combinations of these pseudocomponents at selected temperatures. The limiting tie-line associated with each critical point was assumed parallel to the C_1-C_{5+} edge of the pseudoternary diagram. This assumption has been described as involving a "zero-slope" limiting tie-line (assuming the pseudoternary diagram is a "right" triangle). The required gas enrichment (C_2-C_4 components) for a miscible CGD was correlated as a function of pressure, molecular weight of the oil heavy (C_{5+}) fraction, molecular weight of the gas intermediates (C_2-C_4), and the displacement temperature. As indicated by the authors, the zero-slope limiting tie-line assumption will likely produce slightly low predictions as to the maximum amount of C_1 allowable in the injection gas. Stalkup (1983) later produced crossplots of Benham et al.'s data in which the MMP was presented as a function of the same variables used by Benham et al.

Blackwell produced a lean vaporizing-gas-drive correlation which was first published by Stalkup (1983). The correlation was derived empirically from experimental MMP's for nine oils. The MMP was correlated as a function of reservoir oil compositional properties, reservoir temperature, and the bubble-point pressure of the reservoir oil at reservoir temperature.

Kuo (1985) published a correlation for predicting the MMP of rich condensing-gas-drives. The correlation is based on critical point and limiting tie-line calculations for selected multicomponent systems. The multicomponent systems were simplified into three pseudocomponents (C_1, C_2-C_4, and C_{5+}), and phase envelopes for various combinations of these pseudocomponents were calculated using the PR-EOS at selected temperatures. Critical points and limiting tie-lines were then determined using the phase envelopes. The MMP was correlated as a function of temperature, molecular weight of injection gas intermediates (C_2-C_4), molecular weight of reservoir oil heavy-ends (C_{5+}), and the amount of C_1 in the injection gas.

Glasø (1985) published a correlation for predicting MMP's of lean and rich hydrocarbon gas drives. The correlation was based on a curve fit of Benham et al.'s (1960) data, but was presented using different input parameters. The MMP was correlated as a function of the molecular weights of injection gas intermediates (C_2-C_6) and reservoir oil heavy-ends (C_{7+}), the amount of C_1 in the injection gas, reservoir temperature, and the specific gravity of the stock-tank-oil. Glasø extended Benham et al.'s correlation for use in lean VGD's by assuming that the amount of C_1 in the injection gas for VGD's could be represented (for MMP calculation purposes) by drawing a line parallel to the C_1-C_{7+} edge of the pseudoternary diagram, and through the oil composition. The amount of C_1 used in Glasø's correlation for a VGD is represented by the intersection of this line with the C_1-(C_2-C_6) edge of the pseudoternary diagram.

Firoozabadi and Aziz (1986) published a correlation for predicting the MMP of lean hydrocarbon and nitrogen vaporizing-gas-drives. The correlation was derived using 13 measured MMP's and some PR-EOS simulation data. The MMP was correlated as a function of the amount of intermediates (C_2-C_5), the molecular weight of the heavy-ends (C_{7+}) in the reservoir oil, and temperature. The correlation does not differentiate between nitrogen or lean-gas drives, assuming that both will have identical MMP's.

Nouar and Flock (1988) produced a correlation for predicting the MMP of lean-gas drives. The correlation is based on Soave-EOS critical point and limiting tie-line calculations for various pure three-component systems at selected temperatures. Each ternary system consisted of a light (C_1), an intermediate (C_3, C_4, C_5, or C_6), and a heavy (C_8, C_{10}, C_{12}, or C_{15}) fraction. The MMP was correlated as a function of temperature, molecular weights of intermediate (C_2-C_6) and heavy-ends (C_{7+}) in the oil, and the amount of intermediates (C_2-C_6) and heavy-ends (C_{7+}) in the oil.

Eakin and Mitch (1988) produced a correlation for predicting the MMP of lean, rich, nitrogen, or carbon dioxide drives. RBA MMP data was taken using two reservoir oils, at two temperatures, with a large combination of injection gas mixtures. The MMP was correlated as a function of gas compositional properties, temperature, and the molecular weight of heavy-ends (C_{7+}) in the reservoir oil. Because the MMP data was measured using the RBA, miscibility development in the rich-gas drives occurred through forward contacts, not in a condensing-gas-drive fashion.

A chronological listing of the lean and rich hydrocarbon MMP correlations described in this section is given in Table 4-1. The developmental basis of each correlation, and whether or not it accounts for varying injection gas compositions and non-hydrocarbon gas impurities is noted.

Table 4-1: Hydrocarbon MMP Correlations

Correlation	Gas[1]	Correlation Basis	Form	Variable Injection Gas Compositions	Non-Hydrocarbon Impurities
Benham et al. (1960)	RG	Empirical critical point calculations of pseudoternary mixtures	Graphical	Yes	No
Blackwell (Stalkup, 1983)	LG	Statistics	Numerical	No, assumes "lean" gas	No
Kuo (1985)	RG	Critical point calculations using EOS generated pseudoternary diagrams	Numerical	Yes	No
Glass (1985)	RG LG	Benham et al. (1960) correlation	Numerical	Yes	No
Firoozabadi & Aziz (1986)	LG	Statistics & EOS simulation data	Numerical	No, assumes "lean" gas	No
Nouar & Flock (1988)	LG	EOS critical point calculations of pure ternary systems	Graphical & numerical	No, assumes 100% C_1	No
Eakin & Mitch (1988)	RG[2] LG	Statistics	Numerical	Yes	Yes

1. RG=Rich-gas; LG=Lean-gas.
2. Developed using liquid-extraction data (not CGD).

4.2 Nitrogen MMP Correlations

Glasø (1985) published a numerical correlation for predicting the MMP of nitrogen vaporizing-gas-drives. The correlation is based on Benham et al.'s (1960) data. Glasø found that the Benham et al. correlation could be used to predict N_2 MMP's, provided that N_2 was represented by a 72%-C_1/28%-C_3 hydrocarbon mixture for calculation purposes. The correlation was adjusted using an empirically derived temperature correction factor, and the MMP was correlated as a function of temperature and the molecular weight of heavy-ends (C_{7+}) in the reservoir oil.

Nouar and Flock (1988) developed a nitrogen vaporizing-gas-drive correlation that is identical in development to their lean-gas correlation described in Section 4.1. The only difference being that the C_1 light fraction was replaced by N_2. The ternary systems considered contained no C_1, and the correlation would appear to be applicable to predict the MMP of a nitrogen VGD of a methane-depleted oil. However, as mentioned by the authors, most oils contain appreciable amounts of methane.

Glasø (1988) published a second correlation for predicting the MMP of nitrogen VGD's. The correlation was derived empirically using 18 experimentally measured MMP's. The MMP was correlated as a function of the amount of light (C_1) and intermediate (C_2-C_6) components in the reservoir oil, temperature, and oil API gravity.

Hudgins, Llave, and Chung (1988) published a correlation for predicting nitrogen MMP's. The correlation was derived empirically using 14 experimentally measured MMP's. The MMP was correlated as a function of the amount of light (C_1) and intermediate (C_2-C_5) fractions in the reservoir oil, the molecular weight of heavy-ends (C_{7+}) in the reservoir oil, and temperature.

Nouar, Flock, and Dranchuk (1990b) published a correlation for predicting the MMP of nitrogen gas drives. The correlation is based on Soave-EOS calculations of the critical conditions for various pure four-component systems at selected temperatures. Each quaternary system consisted of a mixture of injected gas (N_2) and a ternary oil mixture containing a light (C_1), an intermediate (C_3, C_4), and a heavy (C_{12}, C_{13}, or C_{14}) fraction. Unlike the Nouar and Flock (1988) N_2 correlation, this method does account for the presence of light-ends in the reservoir oil. The MMP was correlated as a function of temperature, molecular weights of intermediate (C_2-C_6) and heavy-ends (C_{7+}) in the oil, and the amount of intermediate (C_2-C_6) and heavy-ends (C_{7+}) in the oil.

The Firoozabadi and Aziz and the Eakin and Mitch correlations described in the hydrocarbon correlation section were also intended for predicting MMP's of nitrogen drives. Some of the important characteristics of the N_2 correlations described in this section are summarized in Table 4-2.

Table 4-2: Nitrogen MMP Correlations

Correlation	Correlation Basis	Form	Nitrogen Impurities
Glasø (1985)	Benham et al. (1960) correlation with N_2 = 72%-C_1/28%-C_3	Numerical	No
Firoozabadi & Aziz (1986)	Statistics & EOS simulation data	Numerical	No
Nouar & Flock (1988)	EOS critical point calculations of pure ternary systems	Graphical & numerical	No
Glasø (1988)	Statistics	Numerical	No
Eakin & Mitch (1988)	Statistics	Numerical	Yes
Hudgins, Llave & Chung (1988)	Statistics	Numerical	No
Nouar, Flock & Dranchuk (1990b)	EOS critical point calculations of pure quaternary systems	Computer program	No

4.3 Carbon Dioxide MMP Correlations

Holm and Josendal (1974) published a correlation for predicting the MMP of CO_2 drives. The method is based on the Benham et al. (1960) rich-gas correlation, which Holm and Josendal found could be used to predict CO_2 MMP's, provided that CO_2 was represented by a 59%-C_1/41%-C_3 hydrocarbon mixture for calculation purposes. Using Benham et al. data for the assumed mixture, the MMP was correlated as a function of temperature and molecular weight of the heavy (C_{5+}) fraction in the reservoir oil. Later, Mungan (1981) extended Holm and Josendal's correlation for use with higher molecular weight oils.

The National Petroleum Council (1976) empirically correlated CO_2 MMP's with oil API gravity and temperature. The MMP was considered constant for each of 3 API gravity ranges, and a simple correction factor was presented for temperatures larger than 49°C. Similarly, Cronquist (1978) empirically correlated CO_2 MMP's with temperature, molecular weight of the heavy (C_{5+}) fraction in the reservoir oil, and the amount of light ends (C_1 and N_2) in the reservoir oil.

Dunyushkin and Namiot (1978) published a correlation which was based on experimentally measured critical pressure data of several CO_2/alkane binary systems over a wide range of temperatures. The critical pressure of each binary system represents the first-contact miscibility pressure of the CO_2/alkane mixture. The critical pressures were then correlated with temperature and the molecular weight of the alkane. The MMP of a CO_2/oil mixture can be estimated by determining the critical pressure of the CO_2/alkane binary mixture in which the molecular weight of the alkane represented the molecular weight of the heavy (C_{5+}) fraction in the reservoir oil.

Lee (1979) of the Petroleum Recovery Institute (PRI) presented two CO_2 MMP correlations. The first correlation (PRI-1) is based on the observation that liquid or dense-gas CO_2 has a higher extraction capacity for hydrocarbons than does gaseous CO_2. Consequently, the MMP of a CO_2 drive was thought to be related to CO_2 density. The PRI proposed that the vapor pressure curve of CO_2, extended beyond the critical point using the Hougen et al. (1959) correlation, could be used as an MMP correlation. The MMP (i.e. CO_2 vapor pressure) was presented as a function of temperature. A correction was included so that if the predicted MMP was below the bubble-point of the oil, the bubble-point was to be taken as the predicted MMP. This correction was based on a similar recommendation by Yellig and Metcalfe (1980) in the 1978 unpublished version of their work. A second PRI correlation (PRI-2) was derived empirically using available literature MMP data. The MMP was correlated as a function of temperature only, with the previously discussed bubble-point correction.

Yellig and Metcalfe (1980) produced a CO_2 correlation based on 14 experimental MMP's. The MMP was correlated as a function of temperature alone, and the bubble-point correction was recommended if the predicted MMP was less than the oil bubble-point pressure. The Petroleum Recovery Institute (Lee, 1979) put the Yellig and Metcalfe correlation in equation form, using the original unpublished 1978 Yellig and Metcalfe paper.

Johnson and Pollin (1981) used 25 experimental MMP's and correlated MMP with temperature; reservoir oil API gravity, density, and average molecular weight; the critical temperature and pressure of the injected gas; and injected gas composition and average molecular weight. Impurities in the injection gas (only if N_2 or C_1) were accounted for by adjusting the critical temperature of the injection gas to account for these impurities.

Holm and Josendal (1982) presented a second empirical correlation in which CO_2 density (at MMP conditions) was correlated with the extractable hydrocarbons contained in the oil (C_5-C_{30} fraction). Holm and Josendal proposed evaluating the MMP of a mixture by first determining the required CO_2 density at the MMP based on their correlation. The MMP could then be estimated at the reservoir temperature by using the graphical correlation of Vukalovich and Altunin (1968), where CO_2 density was presented in terms of temperature and pressure.

Similar to Lee (1979), Orr and Jensen (1984) indicated that CO_2 MMP's could be predicted using the extrapolated vapor pressure curve of CO_2. The Newitt et al. CO_2 vapor pressure correlation was recommended for estimating MMP's as a function of temperature.

Glasø (1985) presented a correlation using a procedure very similar to that of Holm and Josendal (1974). Glasø used the Benham et al. (1960) correlation, with CO_2 gas taken to be equivalent to a constant injection gas mixture of 58%-C_1/42%-C_3. The produced MMP correlation requires the molecular weight of the oil heavy (C_{7+}) fraction and temperature as input parameters.

Alston, Kokolis, and James (1985) presented an empirically derived correlation for estimating the MMP of pure and impure CO_2 floods. The MMP was correlated with temperature, molecular weight of the oil heavy (C_{5+}) fraction, and the amount of volatile (C_1 and N_2) and intermediate (C_2-C_4, CO_2, and H_2S) fractions within the oil. The effects of CO_2 impurities were correlated with the critical temperature of the impure CO_2 mixture. The Yellig and Metcalfe bubble-point correction was also recommended.

Two correlations were presented for predicting MMP changes due to the presence of CO_2 injection gas impurities. Sebastian, Wenger, and Renner (1985) proposed a correction factor for MMP of an impure CO_2 stream based on the mole-averaged pseudocritical temperature of impure CO_2 mixtures. The MMP of an impure CO_2 stream can be estimated by multiplying the MMP of the pure CO_2 stream by this correction factor. Kovarick (1985) similarly presented an empirical correlation for impure CO_2 streams. The pure CO_2 MMP was also correlated with the impure CO_2 MMP using a relationship involving the pseudocritical temperature of the injection gas mixture.

Orr and Silva (1987) proposed an empirical correlation that parallels the Holm and Josendal (1982) correlation. The modified form of the correlation accounts for component distribution within the C_5-C_{30} fraction, whereas Holm and Josendal "lumped" these heavy-ends together. This modification requires a detailed oil heavy-ends (C_{5+}) compositional analysis. The density of CO_2 at the MMP was correlated against a heavy-ends (C_{5+}) composition parameter using data obtained by Silva and Orr (1987). The MMP of a CO_2/oil mixture at a given temperature is estimated as the pressure required to yield that CO_2 density. The effects of contaminants in CO_2 can be estimated by calculating the pressure required to give a mixture density equal to that required for pure CO_2.

Enick, Holder, and Morsi (1988) presented a correlation based on similar principles as the Dunyushkin and Namiot (1978) correlation. The critical pressures (or FCMP's) of pure and impure CO_2/normal-alkane binary mixtures were calculated using the PR-EOS. The MMP of an actual system could be estimated by determining the FCMP of the CO_2/alkane mixture where the molecular weight of the alkane equalled the molecular weight of the heavy-ends (C_{5+}) in the oil. The correlation accounts for impurities since it was developed using selected impure CO_2 gases. An empirical low-temperature/high-molecular-weight correction factor was included, based on experimental observations which the PR-EOS critical pressure calculations did not follow.

The Eakin and Mitch (1988) correlation described in the hydrocarbon MMP correlation section was also generated for predicting MMP's of CO_2 gas drives. Some of the important characteristics of each of the CO_2 correlations discussed in this section are summarized in Table 4-3.

Table 4-3: Carbon Dioxide MMP Correlations

Correlation	Correlation Basis	Form	CO_2 Gas Impurities
Holm & Josendal (1974)	Benham et al. (1960) correlation with CO_2 = 59%-C_1/41%-C_3	Graphical	No
National Petroleum Council (1976)	Statistics	Numerical	No
Cronquist (1978)	Statistics	Numerical	No
Dunyushkin & Namiot (1978)	CO_2/alkane FCMP calculations	Graphical	No
PRI-1 (Lee, 1979)	Extrapolated CO_2 vapor pressure curve	Numerical	No
PRI-2 (Lee, 1979)	Statistics	Numerical	No
Yellig & Metcalfe (1980)	Statistics	Graphical	No
Mungan (1981)	Benham et al. correlation with CO_2 = 59%-C_1/41%-C_3	Graphical	No
Johnson & Pollin (1981)	Statistics	Numerical	Yes[1]
Holm & Josendal (1982)	CO_2 density statistics	Graphical	No
Orr & Jensen (1984)	Extrapolated CO_2 vapor pressure curve	Numerical	No
Glass (1985)	Benham et al. correlation with CO_2 = 58%-C_1/42%-C_3	Numerical	No
Alston et al. (1985)	Statistics	Numerical	Yes
Sebastian et al. (1985)[2]	Statistics	Numerical	Yes
Kovarik (1985)[2]	Statistics	Numerical	Yes
Orr & Silva (1987)	CO_2 density statistics	Numerical	Yes
Enick et al. (1988)	CO_2/alkane FCMP calculations	Graphical	Yes
Eakin & Mitch (1988)	Statistics	Numerical	Yes

1. Only if impurity is nitrogen or methane.
2. Only predicts MMP changes due to CO_2 impurities, not actual MMP's.

4.4 MMP Correlation Accuracy Checks

Most of the MMP correlations discussed in the literature were evaluated by the presenting author(s) by comparing correlation predicted MMP's with experimentally measured values. Some of the experimental MMP data used by each author was often taken from other studies and usually measured by the slim-tube technique. Only Benham et al. (1960), who used the PVT cell, and Eakin and Mitch (1988), who used the RBA apparatus, presented correlations which were evaluated using MMP data that was not measured using a slim-tube.

Published accuracy values for the rich-gas, lean-gas, nitrogen, and carbon dioxide MMP correlations respectively, are listed in Tables 4-4 through 4-7. The correlation accuracy check performed by the correlation author(s), as well as any accuracy checks presented in subsequent studies are presented. Inspection of Tables 4-4 through 4-6 indicates that rich-gas, lean-gas, and nitrogen MMP's have been predicted quite accurately using most of these correlations. The maximum average prediction error was 8.5% for 16 rich-gas MMP's predicted by the Glasø (1985) correlation. However, with the exception of the Benham et al. rich-gas correlation, no independent accuracy checks were performed for any of the rich, lean, or nitrogen MMP correlations listed. Also, the largest number of experimental MMP's used to evaluate any of these correlations was 30, the number used in the Eakin and Mitch (lean-gas) correlation. These 30 MMP's were used in the development of the correlation, and do not represent an independent evaluation.

The accuracy checks for CO_2 MMP correlations listed in

Table 4-4: Accuracy of Rich Hydrocarbon MMP Correlations

Correlation	Accuracy Check in Original Work		Accuracy Check(s) in Subsequent Studies	
	# of MMP's	Avg. Dev.	# of MMP's	Avg. Dev.
Benham et al. (1960)	1	5%	10[1] 10[2] 24[3]	4.0% 2.3 MPa 7.2%
Kuo (1985)	24	4.1%	N/A	N/A
Glass (1985)	16	8.5%*	N/A	N/A
Eakin & Mitch (1988)	28	2.8%*	N/A	N/A

Table 4-5: Accuracy of Lean Hydrocarbon MMP Correlations

Correlation	Accuracy Check in Original Work		Accuracy Check(s) in Subsequent Studies
	# of MMP's	Avg. Dev.	
Blackwell (Stalkup, 1983)	9	0.5 MPa	N/A
Glass (1985)	5	6.5%*	N/A
Firoozabadi & Aziz (1986)	11	1.6%*	N/A
Nouar and Flock (1988)	11	7.5%	N/A
Eakin & Mitch (1988)	30	4.7%*	N/A

Table 4-6: Accuracy of Nitrogen MMP Correlations

Correlation	Accuracy Check in Original Work		Accuracy Check(s) in Subsequent Studies
	# of MMP's	Avg. Dev.	
Glass (1985)	0	-	N/A
Firoozabadi & Aziz (1986)	2	2.9%*	N/A
Nouar & Flock (1988)	0	-	N/A
Glass (1988)	18	2.5%	N/A
Eakin & Mitch (1988)	10	5.9%*	N/A
Hudgins, Llave & Chung (1988)	14	2.0%	N/A
Nouar, Flock & Dranchuk (1990b)	4	3.5%	N/A

* Determined in current study.

1. Yarborough and Smith (1970).
2. Stalkup (1983).
3. Kuo (1985).

Table 4-7: Accuracy of Carbon Dioxide MMP Correlations

Correlation	Accuracy Check Presented in Original Work		Accuracy Checks Presented in Subsequent Studies	
	# of MMP's	Average Prediction Error[1]	# of MMP's	Average Prediction Error[1]
Holm & Josendal (1974)	9	6.6%*	40[2] 4[3] 19[7]	(23%) 8.3% 1.9 MPa
National Petroleum Council (1976)	N/A	N/A	40[2]	(27%)
Cronquist (1978)	48	2.1 MPa	19[7]	2.3 MPa
Dunyushkin & Namiot (1978)	18	14.9%*	40[2]	(28%)
PRI-1 (Lee, 1979)	49	9.2%	N/A	N/A
PRI-2 (Lee, 1979)	49	10.9%	N/A	N/A
Yellig & Metcalfe (1980)	40	7.0%* (13%)	49[4] 4[3] 19[7]	7.9% (10.5%) 31.0% 4.0 MPa
Mungan (1981)	N/A	N/A	N/A	N/A
Johnson & Pollin (1981)	25	(6.0%)	19	≈15%[5]
Holm & Josendal (1982)	18*	N/A	33	15.0% (19.9%)
Orr & Jensen (1984)	N/A	N/A	33[6]	15.3% (20.6%)
Glasø (1985)	28	8.25%	N/A	N/A
Alston et al. (1985)	68	6.9% (8.7%)	61[5] 51[6]	15.0% 18.2%*
Sebastian et al. (1985)	61	8% (11%)	27	7.1%*
Kovarik (1985)	11*	5.9% (4.2%)	N/A	N/A
Orr & Silva (1987)	33	8.0%* (9.7%)	N/A	N/A
Enick et al. (1987)	157	(19%)	N/A	N/A
Eakin & Mitch (1988)	28	4.4%*	N/A	N/A

* Determined in current study.

1. Std. Deviation in brackets.
2. Yellig & Metcalfe (1980).
3. Holm & Josendal (1982).
4. Lee (1979).
5. Sebastian et al. (1985).
6. Orr & Silva (1987).
7. Stalkup (1983)

Table 4-7 indicate that the CO_2 correlations were evaluated by the presenting author(s) using a data set that was generally much larger than for most of the rich, lean, or nitrogen gas correlations. For example, the Enick et al. CO_2 correlation was evaluated by Enick et al. using 157 experimental MMP's, and the correlation standard deviation was only 19%. This correlation is theoretically based and is relatively independent of this data base. Of the 18 CO_2 correlations listed in Table 4-7, 10 were evaluated also by other authors.

The Enick et al., Alston et al., and Yellig and Metcalfe (1980) CO_2 correlations have each been evaluated by the respective authors using large data sets with good MMP predictions. Both the Alston et al. and Yellig and Metcalfe (1980) correlations were evaluated in subsequent studies using large MMP data sets, with average prediction errors less than 20%. MMP predictions using these three correlations would seem acceptable for preliminary studies.

4.5 Line of Investigation

Very little work was has been presented with regards to the accuracy of the hydrocarbon and nitrogen MMP correlations discussed in this study. The accuracy of each correlation was usually supported by the presenting author(s) by making MMP predictions for selected gas/oil systems for which MMP data was available. However, with the exception of Kuo (1985), the study in which each correlation was presented made no comparison between the predictive accuracy of the proposed correlation and the accuracy of any other existing correlation. This observation led to a direction of investigation in the current study: to evaluate the presented hydrocarbon and nitrogen MMP correlations with regard to their accuracy and general applicability. This would require compiling a large data set of gas/oil MMP and compositional data from the literature. The MMP predictive accuracy of each correlation would then be evaluated using this MMP data base.

One of the more obvious limitations of performing this type of comparative study is that the MMP correlations would be evaluated using experimental data obtained using different measurement techniques and experimental procedures. The large majority of experimental MMP studies found during the literature review used the slim-tube technique to measure MMP's, and some indication of measured MMP variations due to inconsistent slim-tube apparatus specifications and operating procedures was felt important to aid in evaluating the correlations. This measurement variation would qualitatively indicate the optimal prediction error that could be expected from any correlation evaluated using the MMP data base.

To evaluate properly how sensitive an experimentally measured MMP value is to specific slim-tube operating conditions would require an extensive amount of experimental work. This would involve performing a series of displacements (a minimum of 4 or 5) for each of a large number of live oils at a specific temperature using constant operating conditions. Each series of tests would then have to be repeated at varying temperatures using several different injection rates, slim-tube dimensions, and slim-tube packing materials. The costly and time restrictive nature of slim-tube tests likely explains why such a study has not yet been performed, and why no specific slim-tube testing procedure has been established.

To quantify some slim-tube MMP variations due to different operating conditions, a series of slim-tube displacements on selected gas/oil systems was considered. It was decided to perform a number of slim-tube displacements using nitrogen as the injection gas and two previously studied synthetic oils. Slim-tube apparatus and operating conditions used to measure these MMP's in the original studies were specified in each case. The MMP for each of these mixtures in the current study, using experimental procedures different from those of the original study, was measured to provide some estimate of MMP dependence on operating conditions. A series of slim-tube displacements for two additional nitrogen systems was also proposed to further aid in evaluating the nitrogen correlations. Nitrogen displacements were selected mainly because the N_2 MMP data set was found to be noticeably smaller than the hydrocarbon MMP data set.

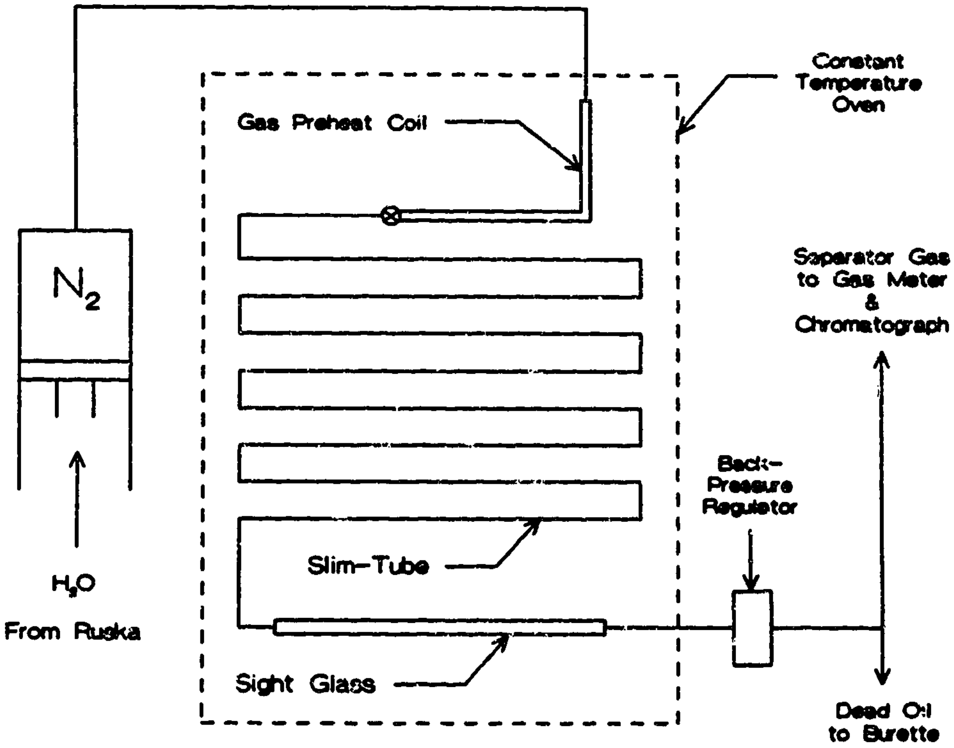
5. Experimental Investigation

5.1 Introduction

A simplified schematic of the slim-tube apparatus used in the current study is presented in Figure 5-1. The basic components of the system include a high-pressure floating-piston cylinder from which the injection gas is displaced into the sand-packed slim-tube. A Ruska positive-displacement pump is used to inject the displacing fluid into the slim-tube at a continuous rate. Prior to a displacement experiment, the slim-tube is completely saturated with live oil. A sight glass is situated at the downstream end of the slim-tube, and allows for an observation of the gas/oil transition zone at the displacement operating pressure and temperature. Both the slim-tube and sight glass are contained in a constant temperature oven.

A back-pressure regulator is located at the slim-tube outlet, and is required to maintain the displacement pressure (downstream) at a constant value (within ± 0.05 MPa). The live oil displaced by the injected gas is flashed to atmospheric conditions after passing through the back-pressure regulator. The produced dead oil is collected in a graduated burette, and the evolved gas passes through a condenser and into a gas metering apparatus, and finally to a gas chromatograph for analysis.

Figure 5-1: Simplified Slim-Tube Schematic



5.2 Selected Slim-Tube Packing and Dimensions

Yellig and Metcalfe (1980) studied the effects of temperature on slim-tube experiment displacement efficiency. Johnson and Pollin (1981) later studied the effects of displacement rate and slim-tube column characteristics (packing, length, and diameter) on the displacement efficiency of slim-tube experiments. Varying these parameters was found to influence the fraction of oil recovered during a displacement. As a result, it was concluded that setting a minimum recovery level (i.e. 90%) at some pore volume of gas injected (i.e. 1.2 PV) as a criteria for miscibility is an unreliable indicator. However, Johnson and Pollin noted that the pressure at which the recovery vs pressure curve breakover point was observed (for a series of displacements) was relatively independent of rate and system effects. Both Yellig and Metcalfe (1980) and Johnson and Pollin (1981) concluded that the best definition of a gas/oil MMP from slim-tube data is the pressure at which a sharp break occurs in the slope of the recovery (at 1.2 PV gas injected) vs pressure curve. A review of the literature indicates that this MMP criteria has been accepted as the industry standard for slim-tube displacements performed over the last few years.

Inspection of the literature indicates that a gas injection rate of 0.1 PV/hr and a 12 meter slim-tube with an OD of 0.635 cm, packed with 100 mesh sand is representative of the experimental conditions used by many researchers. Nouar and Flock (1983) systematically studied how slim-tube recoveries were affected by varying system lengths and injection rates. It was found that increasing the displacement length resulted in increased displacement efficiencies of miscible displacements, but had little influence on the displacement efficiency of immiscible displacements. Also, an increased injection rate was found to decrease the displacement efficiency of immiscible displacements, but had little effect on the displacement efficiency of miscible displacements. As a result, increasing both the tube length and injection rate resulted in a more obvious breakover point on the recovery vs pressure curve. Nouar and Flock recommended using a long displacement length and fast injection rate for slim-tube tests. Hudgins, Llave, and Chung (1988) experimentally supported the findings of Nouar and Flock (1983).

Following the recommendations of both Nouar and Flock and Hudgins et al., a 24.4 meter by 0.635 cm (OD) stainless steel slim-tube and a displacing fluid injection rate of approximately 0.2 PV/hour (30 cc/hr) were chosen for the current study. The tube was packed with 100 mesh Ottawa sand, based on discussions with technical services of D.B. Robinson (DBR) and Associates, of Edmonton, Alberta. The selected packing material was identified as being a current industry standard.

The tube was packed in a vertical position, making use of a long stairwell. As the sand was placed into the tube, an air operated vibrator was positioned at varying locations along the tube to aid in achieving a uniform sand pack. The ends of the tube were capped with 250 mesh sintered steel filters. After being packed, the tube was coiled so that it could be placed inside the slim-tube oven.

5.3 Slim-Tube Pore-Volume Measurement

Discussion with DBR and Associates indicated that until the last few years, slim-tube pore volumes were generally calculated using the given tube dimensions, and the weight and density of sand placed into the tube. This method was then replaced with the gas expansion method, and finally by the toluene injection method. The gas expansion method involves pressuring a certain volume of gas in a chamber to a selected pressure. The pressurized volume of gas is brought into communication with the slim-tube, which has been evacuated for a minimum of 24 hours. The increased gas volume then results in a drop in pressure of the gas. The volume of mercury required to be injected into the gas chamber to bring the gas pressure back up to the original pressure represents the volume of the slim-tube.

Using toluene (a cleaning solvent) to measure the pore volume of the tube involves a procedure identical to the gas expansion method. A selected volume of toluene is pressurized in a chamber to a set pressure, and then brought into contact with the evacuated slim-tube. The volume of mercury required to be injected into the toluene chamber to bring the system to the original pressure then represents the volume of the slim-tube. The toluene technique is the preferred method since the pore volume is measured using a liquid. The only difficulty with this method is that the tube contents must be completely clean and dry prior to a measurement. After being cleaned with toluene, it was found that passing heated N_2 at 70°C for 36 hours at a pressure drop of 3 MPa would completely dry the 24.4 meter sand-packed tube.

Listed in Table 5-1 are the bulk volume, pore volume, and corresponding porosity measurements for the slim-tube packed in this study. Each experimental measurement was made at a pressure of 7 MPa, and was repeated at least twice. These values were found repeatable within ± 0.6%. Note the large discrepancy (≈8%) between the calculated pore volume and either the gas expansion or toluene measured pore volume. The latter two experimentally measured values agree within 0.6%. The toluene measured value was taken to represent the pore volume of the slim-tube.

A second tube of identical dimensions was packed using the same procedure, in the event that a leak developed in the first tube. The pore-volume values calculated and measured for this tube followed the same trend as for the first tube. The calculated pore volume was 7% too low, assuming that the experimentally measured value represented the true pore volume.

Table 5-1: Slim-Tube Bulk and Pore Volume Values			
Measurement Technique	Bulk Volume (cm^3)	Pore Volume (cm^3)	Porosity (%)
Calculated using listed dimensions, sand density, & sand volume.	403.3	144.2	36.1
Gas Expansion Method	413.1	156.6	37.9
Toluene Injection Method	not measured	157.5	38.1

The change in pore volume with changing pressure was estimated by measuring the slim-tube pore volume at 21 and 35 MPa, in addition to the previously measured value at 7 MPa. Table 5-2 contains the estimated pore volumes at each of these pressures. It was difficult to get repeatable pore volume measurements at the two higher pressures (21 and 35 MPa), most likely due to system errors which increase with pressure. However, the results can be used to illustrate the small pressure dependency of tube pore volumes. The slim-tube pore volume was taken as 157.5 cm^3, and was assumed constant for each displacement. This assumption of a constant pore-volume

Table 5-2: Slim-Tube Pore Volume vs. Pressure	
Pressure (MPa)	Pore Volume (cm^3)
7.0	157.5
21.0	160.4
35.0	162.2

slim-tube is consistent with literature MMP studies. Communications with DBR and Associates indicated that they also make this assumption when performing slim-tube tests.

5.4 Selection of Live Oils

The compositions of the four live oils selected for the current study are given in Table 5-3. A series of slim-tube nitrogen displacements was performed using each of these mixtures. The first oil selected was studied previously by Nouar (1987), and was used in verifying the Nouar, Flock, and Dranchuk (1990b) N_2 correlation. The oil was a mixture containing 30 mol% C_1, 35 mol% C_3, and 35 mol% C_{10}, and is referred to as System A. Evaluating the MMP of System A under virtually identical slim-tube length (24.4 m), injection rate (30 cc/hr), and temperature (60°C) conditions as used by Nouar, but with a different porous media (100 mesh Ottawa sand vs 100-150 mesh glass beads), could provide some indication as to the influence of the porous medium on slim-tube results.

The second system selected was identical to System A, with the N_2 displacement being performed at 70°C, rather than 60°C. These conditions were selected based on inspection of the temperature dependency of the N_2 MMP correlations. For example, the Eakin and Mitch (1988) and the Firoozabadi and Aziz (1986) N_2 correlations predict an increase in the MMP for System A as the temperature is increased from 60°C to 70°C. The other N_2 correlations predict a decrease in the MMP.

Table 5-3: Selected Live Oil Mixtures

System	Composition (mol%)			Displacement Temperature (°C)
	C_1	C_3	C_{10}	
A	30.0	35.0	35.0	60
A	30.0	35.0	35.0	70
B	49.9	27.2	22.9	60
C	24.9	51.1	24.0	60

The third system selected was studied previously by Glasø (1988). The oil was 49.9 mol% C_1, 27.2 mol% C_3, and 22.9 mol% C_{10} mixture, and is referred to as System B. Glasø measured the MMP of System B using a 12 m by 0.386 cm (ID) stainless steel tube packed with 50-100 mesh sand, and a gas injection rate of 0.11 cm/s. The selected conditions for this study involve a tube twice as long (24 m) with an 18% larger ID (0.457 cm) packed with approximately 33% smaller sand grains (100 mesh), from which oil is displaced at roughly a 36% faster rate (≈0.15 cm/s). Performing a series of slim-tube displacements on System B could allow for an indication of MMP measurement variations due to relatively large apparatus changes and different operating conditions.

The final system selected, System C, was basically an arbitrary selection of a synthetic oil containing a large fraction of an intermediate component. System A contains roughly equal mole fractions of light, intermediate, and heavy components. System B contains approximately twice as many light-ends as either intermediate or heavy-ends. System C, a mixture containing 24.9 mol% C_1, 51.1 mol% C_3, and 24.0 mol% C_{10}, was chosen to have approximately twice as many intermediates as either light or heavy-ends. The displacement temperature was chosen to be 60°C, as was the case for Systems A and B.

5.4.1 Mixing and Handling of Live Oils

The four oils studied were all combinations of methane, propane, and decane (normal decane). Decane (99% minimum purity) was purchased from Fischer Scientific (Edmonton), and the propane (99.5% minimum purity) and methane (99.5% minimum purity) were supplied by Matheson Ltd. (Edmonton). The three-component mixtures were prepared by Matheson Ltd. to within ± 0.3 mol% of the specified values. Each mixture was shipped in a medium pressure storage cylinder, at a confining pressure well below the bubble-point pressure of the mixture.

Water was injected into the storage cylinder to raise the confining pressure and bring the mixture to a single-phase liquid state. This was done in stages, with the cylinder and contents being shaken for approximately 10 minutes after each water injection stage to maximize the volume of gas dissolved into solution at each pressure increment. This sequence was followed until it was evident that the mixture was a single-phase liquid. A bubble-point check was then performed by withdrawing water from the storage cylinder, and observing the pressure drop per increment of water removed. For each of the four mixtures, the bubble-point was clearly evident.

Once the bubble-point of the mixture was established, the confining pressure was increased to approximately 4 MPa above the bubble-point. The live oil was then always subjected to this confining pressure in the storage cylinder. For each slim-tube displacement, oil was transferred from the storage cylinder to a high-pressure floating-piston cylinder by injecting water into the bottom of the storage cylinder. The live oil was then injected into the slim-tube from the floating-piston cylinder.

5.5 Experimental Procedure

5.5.1 Saturating Tube with Live Oil

There are no standard conditions in which a slim-tube is cleaned and then saturated with live oil in preparation for a displacement. Communications with DBR and Associates indicated that two pore volumes of toluene should be used to clean the slim-tube after each run, and that two pore volumes of live oil should then be used to displace the toluene from the slim-tube. The slim-tube could then be considered completely saturated with live oil.

The slim-tube was evacuated for at least two hours after each run, and then saturated with toluene at a rate of 10 cc/hr while maintaining a vacuum at the downstream end. This sequence was found to reduce the amount of air remaining in the slim-tube, as compared to evacuating the slim-tube for 24 hours, disconnecting the vacuum, and then filling with toluene. Once the tube was completely toluene saturated, an additional one to two pore volumes of toluene was cycled through the slim-tube and back-pressure regulator at a rate of 30 cc/hr, at the expected displacement pressure. The slim-tube was assumed to be completely clean at this point.

Toluene was displaced from the slim-tube by injecting 1.8 to 2.0 pore volumes of live oil into the slim-tube at a rate of 10 cc/hr. The 10 cc/hr injection rate was selected after observing oil formation volume factor (FVF) measurements. Measured oil FVF's generally stabilized after 1.2 to 1.3 pore volumes of live oil were injected, indicating that virtually all of the toluene had been removed from the slim-tube at this point. Injecting approximately two pore volumes of oil at this rate was assumed to result in a completely oil saturated slim-tube.

The formation volume factor (FVF) of each live oil was measured using the slim-tube apparatus. Each FVF was evaluated by measuring the dead oil volume produced through the back-pressure regulator, per 10 cc's of live oil injected. These measurements were made at room temperature, using either the slim-tube or a similar unpacked tube, and after the tube was oil saturated. A FVF vs pressure profile was generated for each oil by repeating the above procedure at different pressures.

5.5.2 Displacement Procedure

Prior to performing each displacement, the oil-saturated slim-tube was heated to the desired test temperature. A 35 cc volume of injection gas (N_2) contained in a preheat coil within the oven was also heated to test conditions, and a valve separated the live oil and injection gas. Once the desired test temperature was reached, the displacing fluid was injected into the slim-tube at a rate of 30 cc/hr. The effluent produced through the back-pressure regulator was flashed to atmospheric conditions, and the separator gas flow rate and dead oil liquid volumes (± 0.02 cc) were recorded every 20 minutes.

The gas/oil transition zone was observed through the visual sight glass for each displacement. After breakthrough of the transition zone, the amount of dead oil produced decreased rapidly until virtually no production was observed. Each displacement was terminated after 1.2 pore volumes of displacing fluid were injected.

5.5.3 Recovery Calculations

The amount of N_2 injected into the slim-tube during each displacement was calculated using the real gas law:

$$V = \frac{Z * T}{Z_r * T_r} * V_r$$

where:

T = test temperature, K

T_r = room temperature, K

Z = N_2 compressibility at T and test pressure

Z_r = N_2 compressibility at T_r and test pressure

V = injected gas volume at T (accounts for thermal expansion)

V_r = injected gas volume at T_r

The compressibility values of nitrogen were obtained from Sage and Lacey (1950).

The live oil recovery of each displacement was calculated by multiplying the produced dead oil volume (at 1.2 PV injected N_2) by an appropriate FVF. For each displacement pressure, the FVF was read from the FVF vs pressure plot generated for the specific live oil. The displacement efficiency was then determined by dividing the calculated oil recovery by the pore volume of the slim-tube apparatus, or

$$\% Recovery = \frac{(Dead\ Oil\ Volume) * FVF}{Pore\ Volume} * 100.$$

Note that the pore volume used in the recovery calculations included the 157.5 cm^3 of sand-packed tube, plus an additional 7.6 cm^3 of unpacked volume (mainly sight glass volume), for a combined pore volume of 165.1 cm^3.

To determine the MMP, the recovery (in %) vs displacement pressure profile for each system was plotted. Displacement pressures were selected such that two displacements were performed both above and below the MMP of each oil. The MMP was taken to represent the breakover point on these plots (discussed in following section). A minimum of approximately four days was required for each displacement experiment conducted using the measurement procedure outlined in this section.

5.6 Experimental Results

In Figure 5-2, the recovery vs pressure profile of System A at 60°C measured in this study, and the recovery profile measured by Nouar (1987) are shown. The two profiles are similar in shape, but the Nouar (1987) measured recovery values are approximately 6% larger than those measured in the current study. This separation of the two curves does not affect significantly the measured MMP, which was taken as the recovery curve breakover point. Note that the curve breakover point was calculated for each of the systems evaluated in this study by performing a least-squares fit of recovery data measured both above and below the MMP. As illustrated in Figure 5-2, the MMP was taken as the pressure where the resulting two asymptotic lines intersect.

The MMP measured for System A in this study was 32.30 MPa, only 3.1% larger than the 31.34 MPa value measured by Nouar (1987). Some of this small difference in MMP measurements can be explained by the range of uncertainty in picking the breakover point on the recovery profile plots. Inspection of Figure 5-2 indicates that the curve breakover point uncertainty is a maximum of about ±0.5 MPa for System A

Figure 5-2

System A: Recovery at T = 60°C

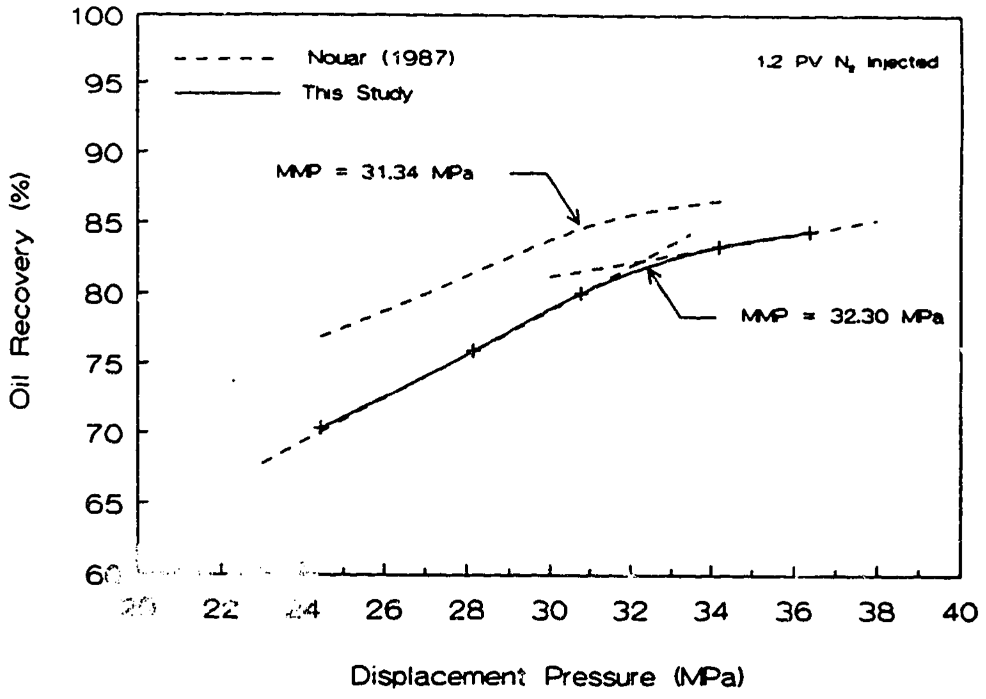
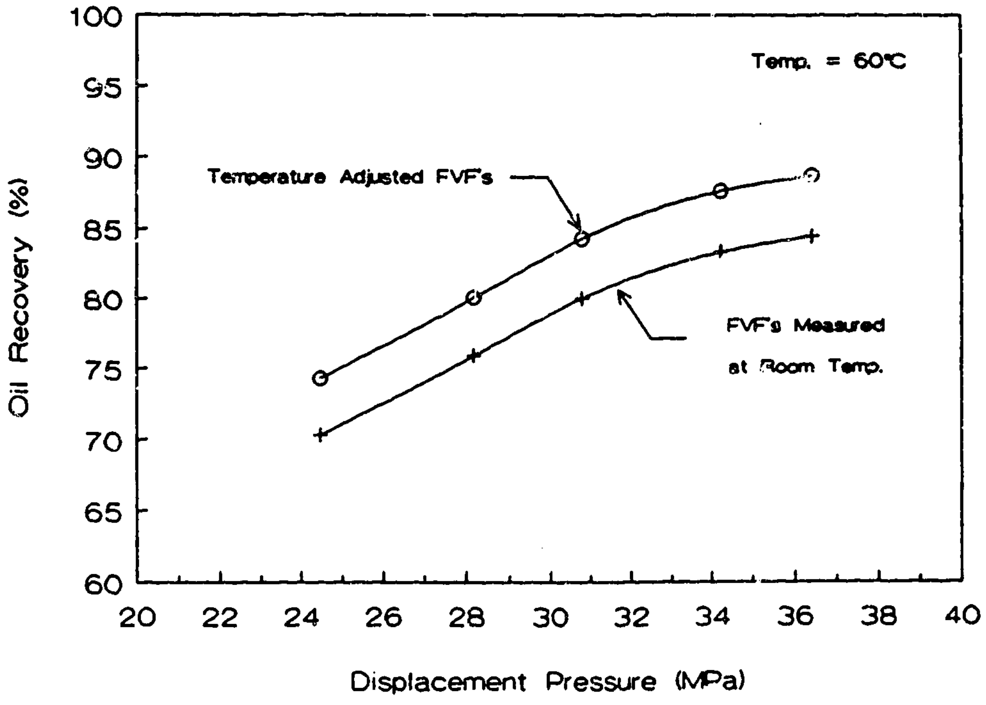


Figure 5-3

System A: Adjusted FVF Values



at 60°C.

The difference between the absolute recovery values measured by Nouar (1987) and those of the current study can be explained by considering how the oil FVF's were obtained in each case. Recovery values in this study were calculated using FVF data that was measured experimentally at room temperature, and the effect of an increase in temperature to test conditions was neglected. The reasoning behind this assumption is that although the FVF of an oil is temperature dependent, each displacement used in measuring an MMP is performed at a constant temperature. The FVF change with changing pressure is assumed dominant, and the temperature influence is assumed constant and independent of pressure. It is important to note that this assumption is consistent with industry procedures in measuring slim-tube MMP's. In contrast, Nouar (1987) did not measure oil FVF's, but calculated these values. The exact procedure followed by Nouar is unclear, but it was stated by Nouar (1987) that FVF's were calculated at 60°C for each displacement pressure, which explains the increased recovery values.

The recovery profile of System A, using FVF values that were adjusted to account for oil expansion as the mixture temperature is increased to 60°C, is illustrated in Figure 5-3. The experimentally measured FVF values (at 20°C) were adjusted using data published by Sage and Berry (1971) for a C_1-C_3-C_{10} mixture that was within 1 mol% of System A's composition. Sage and Berry measured volume changes for the ternary mixture as a result of both pressure and temperature variations. Using this information, the experimentally measured FVF values were increased from between +5.71% at the lowest displacement pressure, to +4.98% at the highest displacement pressure. As shown in Figure 5-3, the effect of increasing the FVF values to account for increased temperature affects the absolute recovery values for a displacement, but does not noticeably change the recovery profile shape. The correction basically amounts to a vertical shift of the recovery profile, and the corresponding measured MMP is essentially unchanged. This adjustment does, however, bring the recovery values measured by Nouar (1987) and those of the current study into relatively close agreement, although the recovery vs pressure profiles are still slightly different.

Recall that the Nouar (1987) measurements were made under identical slim-tube dimension and injection rate conditions, but with a different porous medium than was used in the current study. The agreement between the MMP value measured in Nouar's study and in the current study indicates that, for the mixture studied, the change in porous media had essentially no effect on MMP measurements.

In the discussion on slim-tube pore-volume measurement (Section 5.3) it was indicated that a 7% difference was observed between the measured (157.5 cm^3) and calculated (144.2 cm^3) pore volume for the tube used in this study. The effect of calculating recovery values based on a 144.2 cm^3 tube, and on a 157.5 cm^3 tube, is illustrated in Figure 5-4. Again, the recovery curve is essentially shifted upwards, and the influence of an incorrectly measured pore volume on MMP measurements would appear to be negligible.

The recovery profile of System A at a displacement temperature of 70°C and the profile measured at 60°C, are both illustrated in Figure 5-5. For the 10°C temperature increase, the measured MMP decreased 7.7% to 29.80 MPa, illustrating an increased solubility of N_2 in the oil with increasing temperature. The N_2 MMP correlations which predict the MMP to increase with increasing temperature for this mixture do not appear to account properly for miscibility development of System A with N_2. It may be observed also that the N_2 displacement efficiency at 70°C was improved over that at 60°C. The efficiencies of the immiscible displacements (displacement pressure < MMP) were improved more than the efficiencies of the miscible displacements (displacement pressure $\geq$ MMP).

The recovery profile of System B measured in the current study, and the profile measured by Glasø (1988), are illustrated in Figure 5-6. As with System A, the recovery profile measured in the current study is below that measured by another researcher. However, the MMP values are again in relatively close agreement, differing by 5.7%. The MMP measured by Glasø (1988) was 31.5 MPa, and that of the current

Figure 5-4
System A: Tube PV Influence on Recovery

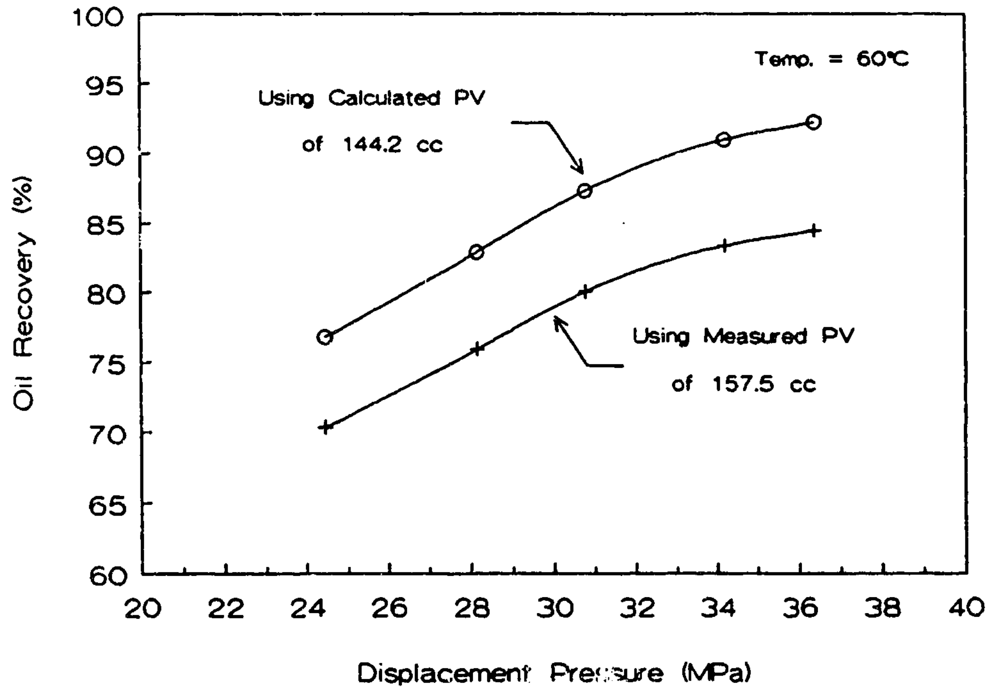


Figure 5-5
System A: Recovery at T = 70°C

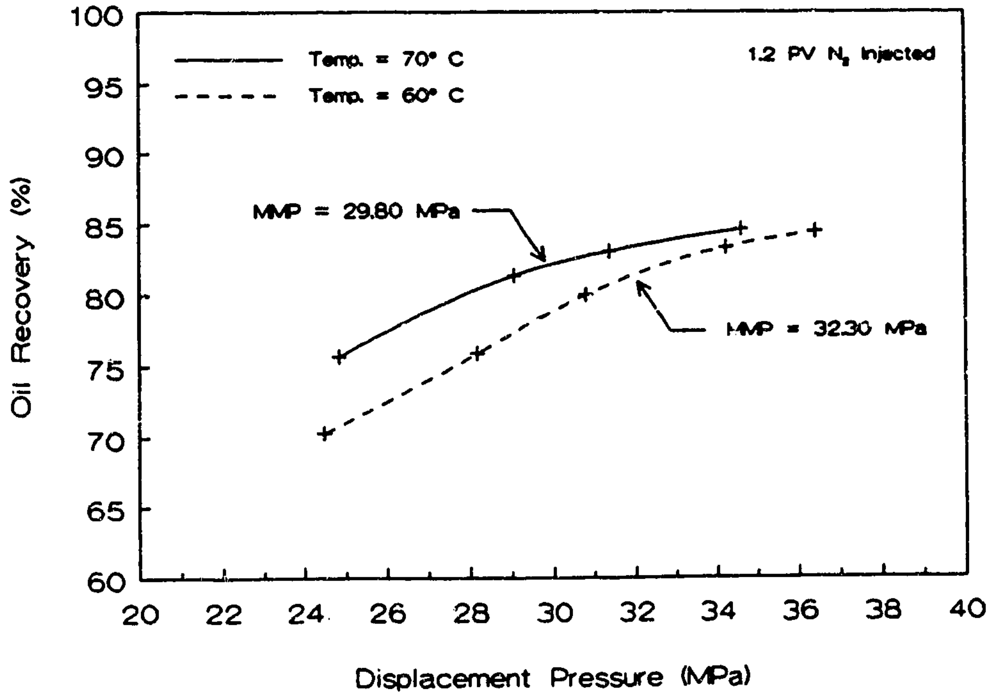


Figure 5-6

System B: Recovery at T = 60°C

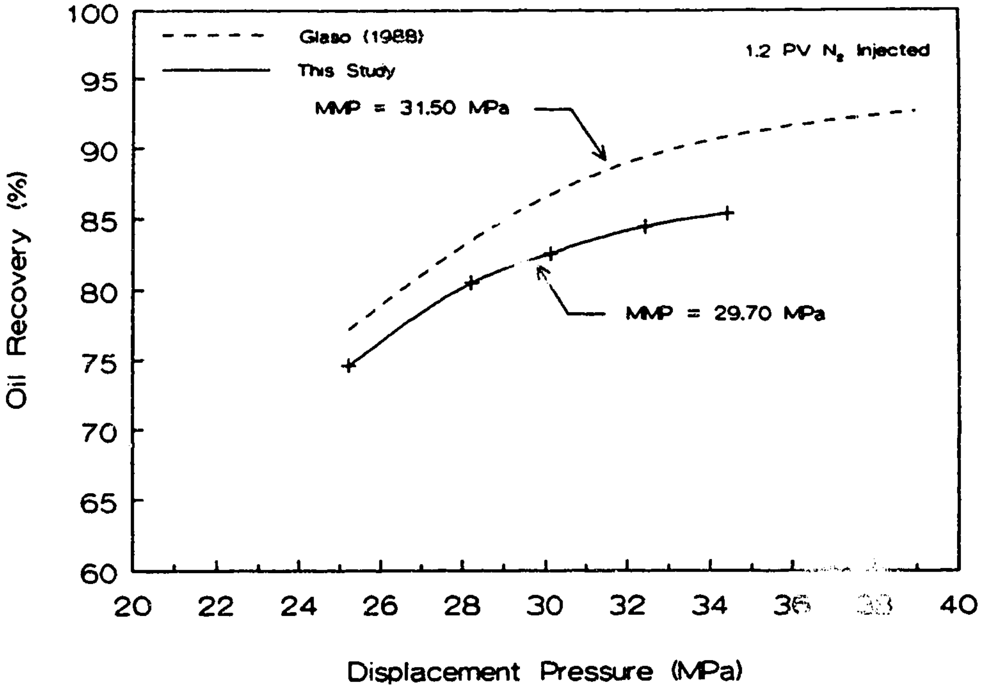
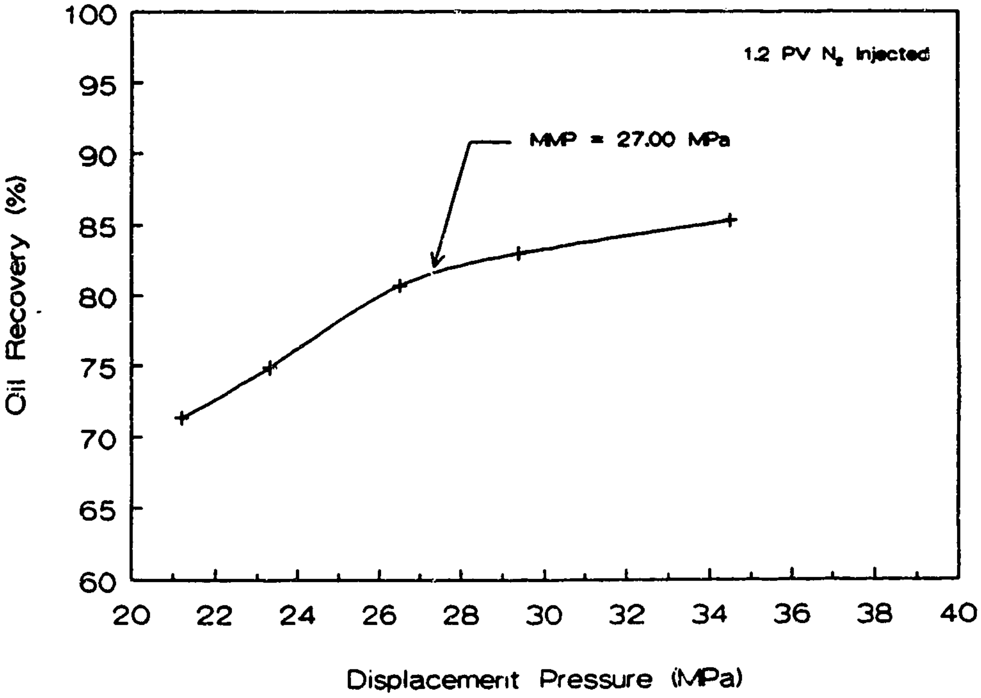


Figure 5-7

System C: Recovery at T = 60°C



study was 29.7 MPa.

The increased recovery levels of Glasø's (1988) measurements for System B can be explained partially by different FVF measuring procedures. Glasø apparently measured FVF's using a PVT apparatus, indicating that they were determined at each displacement pressure and temperature. As previously discussed, the FVF's in the current study were measured at room temperature. The resulting larger FVF values used by Glasø likely accounts for the increased recovery levels.

Also, Glasø's System B measurements were made under much different conditions than those of this study (see Section 5.4). Glasø used a considerably shorter slim-tube, packed with a different porous medium, from which oil was displaced at a lower rate. The influence of these relatively large experimental differences is reflected in the recovery curve profile shapes measured in the two studies. Although the two profiles are much different in shape, the MMP's agree within 5.7%. This indicates that the breakover point on the slim-tube recovery vs pressure plot appears to be relatively independent of experimental operating conditions.

The recovery profile of System C at 60°C is shown in Figure 5-7, and the MMP was found to be 27.0 MPa. The breakover point observed for this oil was the most clearly identifiable of the four systems evaluated. For this particular series of displacements, the uncertainty in the measured MMP would appear to be no more than ±0.25 MPa, or roughly half that of Systems A and B. The uncertainty in MMP measurements is clearly dependent on the particular shape of the recovery vs pressure profile, and the method of determining the breakover point.

5.6.1 Sight Glass Observations

Sight glass observations of the gas/oil transition zone for the two System A series of displacements and the System B displacements, were not found to be helpful in evaluating the minimum miscibility conditions of these oils. The visual observations were found to be helpful in defining when a displacement was obviously immiscible, as gas bubbles were clearly evident at the displacement front. However, as the displacement pressure approached the MMP, the observed phase behavior became more complex. It was very difficult to identify transition zone behavior as being either miscible or immiscible for the displacements performed close to the MMP (as determined from the recovery profiles). As the displacement pressure was increased above the MMP, the sight glass observations became easier to evaluate. Displacements performed well above the MMP were clearly miscible based on these visual observations.

Unfortunately, continual difficulties were encountered with the sight glass prior to the displacements for System C. Each System C displacement was performed with the sight glass removed, so observations of the phase behavior of the gas/oil transition zone were not made.

5.6.2 Characteristic Recovery Profiles

As mentioned earlier, the dead oil recovery level was measured every twenty minutes for each displacement performed in this study. The System C dead oil recovery as a function of nitrogen pore volumes injected, for both a miscible and an immiscible displacement, is illustrated in Figure 5-8. The displacement at 23 MPa was performed 4 MPa below the MMP (see Figure 5-7), and the displacement at 29 MPa was conducted 2 MPa above the MMP. From an inspection of Figure 5-8 it can be seen that the recovery profiles are virtually identical for the early stages of each displacement. The increased recovery of the 29 MPa run is due to improved miscibility between the N_2 and the live oil. The resulting delay in gas breakthrough time improved the ultimate recovery of the displacement. The recovery behavior illustrated in Figure 5-8 is indicative of that observed for each of the systems studied.

5.6.3 Repeatability of Experiments

A repeat displacement was performed for System C at a pressure of 23 MPa to evaluate the repeatability of measurements made in this study. The experiment was conducted independently by a University Lab Technician, using measurement procedures as described in the current study. The

Figure 5-8
Immiscible & Miscible Displacement Data

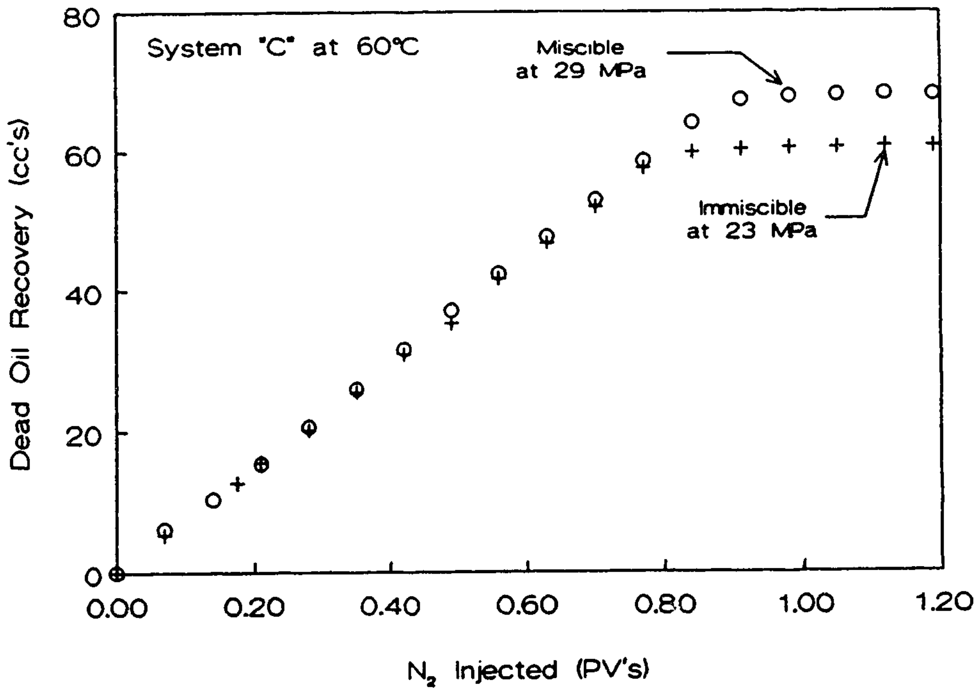
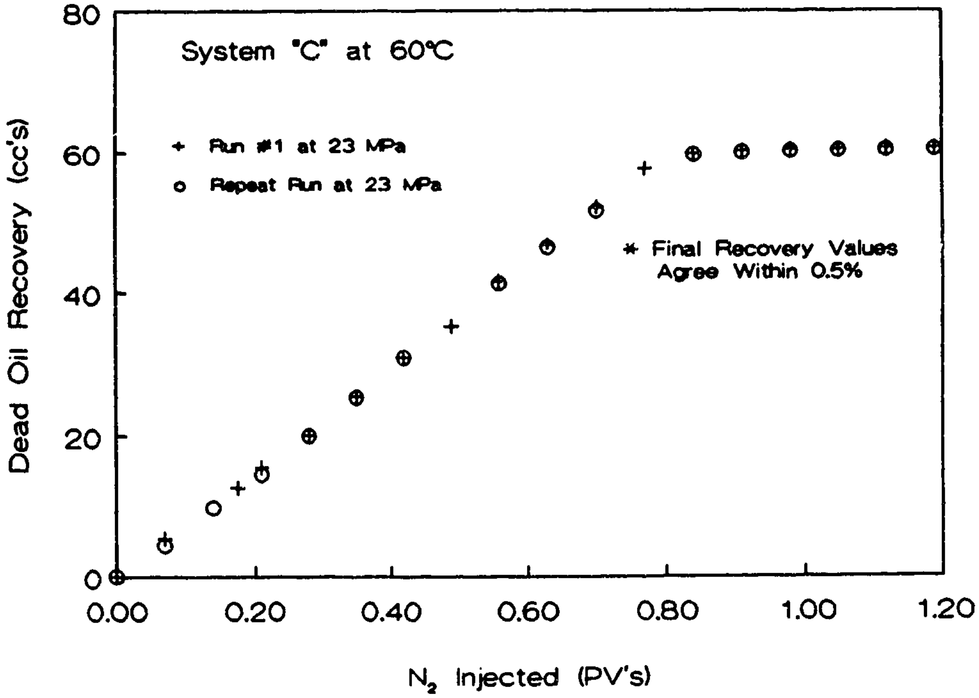


Figure 5-9
Repeatability of Slim Tube Measurements



results of the original and repeat displacements are illustrated in Figure 5-9. Note that the two experiments resulted in virtually identical recoveries. The dead oil recovery of the initial 23 MPa run was 59.80 cc's, while that of the repeat run was 59.67 cc's. These two values agree within 0.2%, indicating that the experiments can be considered repeatable.

The 0.2% repeatability check is most likely not representative of the actual repeatability of slim-tube experiments. A review of the literature indicates that slim-tube recoveries are generally considered repeatable within 1 2%.

6. MMP Correlation Investigation

6.1 Introduction

A data set of experimentally measured MMP's and corresponding gas/oil compositional information was constructed to evaluate the reliability of the lean-gas, rich-gas, and nitrogen MMP correlations discussed in Sections 4.1 and 4.2. A detailed description of each of these correlations (converted to SI units) is presented in Appendix A. A total of 174 MMP measurements were obtained from the literature, and two MMP's were measured in the current study (see Section 5). Table B-1 in Appendix B contains the compositional information for each of these 176 "systems." For the purpose of this study, a system refers to a particular gas/oil/temperature combination for which an MMP has been measured experimentally. For each system listed in Table B-1, gas and oil compositional information is given in terms of the mol% of CO_2, N_2, C_1, C_2, C_3, C_4, C_5, C_6 and C_{7+} fractions. The molecular weight of the oil C_{7+} fraction is also given, and the gas compositional data includes H_2S as a separate component. The system temperature, experimentally measured MMP, the MMP measurement method, the MMP evaluation criteria (if measured using the slim-tube apparatus), and the data reference source are also listed in Table B-1. For the majority of the 176 systems, the gas/oil compositional data were not directly stated in the referenced work as listed in Table B-1 (see discussion in Appendix B).

The 176 experimentally measured MMP's were split into 8 different groupings, depending on the displacement mechanism, gas composition, and oil composition of each gas/oil mixture. The three main groups considered were a rich-gas MMP data set (systems 1 through 26), a lean-gas MMP data set (systems 27 through 44), and a nitrogen MMP data set (systems 45 through 70). There was no ambiguity in distinguishing which were nitrogen gas injection systems, as these injection gases were composed of 100% N_2. There exists some potential for uncertainty in the hydrocarbon gas systems, with regards to whether a system should be classified as a lean-gas or a rich-gas. Recall that a VGD generally results from a combination of a lean injection gas (mainly C_1) and a light oil (high C_2-C_6 fraction). A CGD generally results from a combination of a rich injection gas (high C_2-C_4 fraction) and a medium oil (low C_2-C_6 fraction). There exists no precise definitions of "lean" or "rich" gases, as these terms are completely dependent on the displacement mechanism, and this mechanism is a function of both the gas and oil compositions. The systems classified in this study as lean-gas drives were VGD's (as indicated or implied by the referenced authors), and the rich-gas drives were CGD's (also as indicated by the referenced authors).

A fourth data group was constructed, made up of 11 impure nitrogen/oil systems (systems 71 through 81). This data group was used to test the accuracy of the nitrogen correlations for predicting the MMP of impure nitrogen gas streams. The remaining four data groups were all comprised of Eakin and

Mitch (1988) RBA MMP measurements of mixtures of numerous injection gases with either a light or a medium oil. Eakin and Mitch took a considerable number of MMP measurements, which included combinations of lean-gases/light-oils, lean-gases/medium-oils, enriched-gases/light-oils, enriched-gases/medium-oils, impure-gas-streams (i.e. CO_2)/light-oils, and impure-gas-streams/medium-oils.

After studying the description of the RBA MMP measurement procedure, it was clear that the CGD mechanism cannot be simulated using the apparatus described by Eakin and Mitch. Accordingly, incorporating any of Eakin and Mitch's enriched-gas data into the CGD data set was not considered acceptable because these MMP's were measured through a process involving forward contacts. The development of miscibility most likely occurred through the liquid extraction mechanism, as described by Novosad and Costain (1987a,b), or by the VGD mechanism. In either case, this data could not be used to evaluate the accuracy of the rich CGD MMP correlations.

An attempt was made to incorporate some of the Eakin and Mitch data into the lean-gas data set. Based on gas/oil compositional information, this would likely have been valid in several instances. However, much of the Eakin and Mitch lean-gas MMP data were measured using lean-gases enriched with varying amounts of CO_2, H_2S, and intermediate molecular weight hydrocarbons. Difficulties were encountered in deciding which of these systems fit the compositional patterns of the classically described VGD data set (systems 27 through 44), and it was decided to treat this data separately. The Eakin and Mitch data set was divided into four main groups: mainly hydrocarbon gases mixed with a light oil (systems 82 through 113), mainly hydrocarbon gases mixed with a medium oil (systems 114 through 144), mainly non-hydrocarbon impurities mixed with a light oil (systems 145 through 160), and mainly non-hydrocarbon impurities mixed with a medium oil (systems 161 through 176).

6.2 Treatment of Non-Hydrocarbons

An inconsistency was observed regarding how the various MMP correlations treat the presence of CO_2, H_2S, and N_2 non-hydrocarbon components in either the reservoir oil or the injection gas. Each correlation that specifically indicated how to include non-hydrocarbon fractions for calculation purposes made the same basic recommendations: that N_2 be treated as a light-end and lumped with C_1; and that CO_2 and H_2S be treated as intermediates, and lumped with the C_2-C_4, C_2-C_5, or C_2-C_6 fraction (depending on the particular correlation intermediate pseudocomponent selection). It was not intended for non-hydrocarbons to be grouped in this manner in either of Glasø's nitrogen correlations (1985 or 1988), or the Glasø (1985) hydrocarbon correlation. The Hudgins et al. (1988) nitrogen correlation did not include N_2 as a light end, and Benham et al. (1960) did not indicate how to treat any non-hydrocarbon components for calculation purposes in their correlation.

A series of calculations using suitable systems presented in Table B-1 were performed for each of the three Glasø correlations and the Hudgins et al. (1988) correlation to determine the effect of including N_2 as a light-end, and CO_2 and H_2S as intermediates on each correlation's accuracy. No such calculations were performed using the Benham et al. (1960) correlation. It is this author's opinion that the graphical nature of the Benham et al. (1960) correlation, and the fact that many predictions must be extrapolated from the published curves, make this type of precise comparison very difficult.

For the Glasø (1985) hydrocarbon correlation, calculations were made using both the rich-gas data set (systems 1-26) and lean-gas data set (systems 27-44). The results are presented in Tables C-1 and C-2 in Appendix C. For both data sets, including N_2 as a light-end, and CO_2 and H_2S as intermediates for calculation purposes, slightly improved the predictive accuracy of the Glasø hydrocarbon correlation.

The same calculations were performed for the Glasø (1985), Glasø (1988), and Hudgins et al. (1988) nitrogen correlations using the nitrogen MMP data set (systems 45-70). The results are presented in Tables C-3 through C-5 respectively. In each case, including N_2 as a light-end, and

CO_2 and H_2S as intermediates, slightly improved the predictive accuracy of the correlations, or had no affect at all. Based on these results, N_2 fractions, and CO_2 and H_2S fractions, were included as light-ends and intermediates respectively for calculating MMP values using each of the presented lean-gas, rich-gas, or nitrogen MMP correlations.

The input parameters required by each of the correlations evaluated in this study are summarized in Table B-2 of Appendix B. A listing of any Table B-1 systems which were used in the empirical development of each correlation (if applicable) is also listed in Table B-2.

6.3 Uncertainty in MMP Measurements

When using a "consistent MMP measurement technique" MMP data base to evaluate an MMP correlation, the optimal expected accuracy for any correlation would be the uncertainty present in individual MMP measurements. When different measurement and evaluation techniques are used for MMP's contained in the data base, the optimal expected correlation accuracy could then be expected to be representative of the influence different techniques have on MMP measurements.

Yellig and Metcalfe (1980) indicated that slim-tube MMP's measured in their study could be determined within ± 0.35 to ± 0.70 MPa. At a pressure of 20 MPa, this would correspond to a maximum uncertainty of 3.5%. Inspection of the literature showed that most slim-tube researchers indicated a range of

MMP uncertainty similar to that stated by Yellig and Metcalfe. The experimental results of this study also support this generalized slim-tube MMP measurement uncertainty range.

Novosad et al. (1989) reported that RBA MMP's could be determined with an uncertainty of about 0.20 MPa, or with roughly twice the precision as slim-tube MMP's. Christiansen and Haines (1987), Eakin and Mitch (1988), and Novosad et al. (1989) each compared slim-tube and RBA MMP measurements made for identical gas/oil mixtures. An excellent correlation was found, with the maximum measurement difference being approximately 6.5%.

No study was found in the literature which quantified variations in MMP measurements due to different slim-tube apparatus specifications. However, the limited experimental results of this study indicate that relatively small MMP measurement differences could be anticipated due to different slim-tube apparatus specifications. For example, the MMP measurement confirmation displacement experiments performed for System A (Figure 5-2) indicated that a measurement variation of roughly 3% was observed for two series of experiments using very similar slim-tube apparatus and operating conditions. The experiments performed for System B (Figure 5-6) illustrated that a measurement variation of roughly 6% was recorded for significantly different slim-tube apparatus and operating conditions.

Based on the above discussion, the following generalizations can be made: that slim-tube and RBA MMP's have a maximum uncertainty of about 3.5% (higher at low pressures, lower at high pressures); that slim-tube and RBA measurements have been found to agree within 6.5%; and that slim-tube apparatus differences can result in roughly a 6% change in MMP measurements. Accordingly, for the data listed in Table B-1, any correlation MMP prediction within approximately ± 6% of the experimentally measured value can probably be considered acceptable.

6.4 Rich-Gas MMP Correlation Predictions

The four rich-gas MMP correlations presented in the literature are the Benham et al. (1960), Glasø (1985), Kuo (1985), and Eakin and Mitch (1988) correlations. Each of these correlations is described in detail in Appendix A, and a sample calculation for each is presented in Appendix D. These correlations were evaluated using systems 1 through 26 of Table B-1, which were reported to be rich CGD mixtures.

The MMP values predicted by each correlation for each of the 26 systems are presented in Table C-6 in Appendix C, and the results are summarized in Table 6-1. The prediction deviation, the average prediction deviation, the average predicted/actual MMP ratio, and the estimated standard deviation for each correlation are presented in Table 6-1, and were calculated using equations 1 through 4, respectively.

Table 6-1: Rich-Gas Correlation Accuracy Determination				
Correlation	# of MMP's Evaluated	Average Deviation (%)	Average Predicted/Actual Ratio	Standard Deviation (%)
Benham et al. (1960)	24	13.0	0.98	20.4
Glass (1985)	26	22.2	1.06	28.9
Kuo (1985)	26	9.7	0.99	13.8
Eakin & Mitch (1988)	15	37.7	1.35	48.1

$$Deviation = \frac{Predicted\ MMP}{Experimental\ MMP} - 1 \tag{1}$$

$$Average\ Deviation = \frac{\left[\sum_{1}^{n} |Deviation|\right]}{n} \tag{2}$$

$$Standard\ Deviation = \sqrt{\frac{\sum (Deviation)^2}{n-1}} \tag{3}$$

$$Average\left(\frac{Predicted}{Actual}\right) Ratio = \frac{\sum_{1}^{n} Deviation}{n} \tag{4}$$

where,

n = number of experimental MMP's evaluated

Refer to Table C-6 in Appendix C for more detailed calculation results, and for correlation predictions for specific rich-gas systems. Insufficient gas compositional information was available for the Eakin and Mitch (1988) correlation predictions for 11 systems, and two system MMP's could not be predicted using the Benham et al. (1960) correlation because predictions fell too far off the graphical correlation for an accurate extrapolation to be made.

The MMP predictions using the Benham et al. (1960) and Glasø (1985) hydrocarbon correlations are illustrated in Figures 6-1 and 6-2 respectively. The correlation predicted MMP's are plotted vs the experimentally-measured MMP in each of these figures. A unit-slope line, indicating a perfect match between predicted and actual MMP's, and ± 20% deviation lines are also presented for illustrative purposes. Recall that the Glasø hydrocarbon correlation was developed using Benham et al. data, but was presented using slightly different input parameters. Basic agreement between the two correlations would be expected, and such agreement can be seen in Figures 6-1 and 6-2. For 24 systems the Benham et al. correlation had an average prediction error of 13.0%, and for 26 systems the Glasø correlation had an average prediction error of 22.2%. The two systems (17 and 19) for which MMP predictions were not possible using the Benham et al. correlation were the two in which the Glasø correlation had

Figure 6-1: Benham et al. (1960)
Predicted vs Actual Rich Gas MMP's

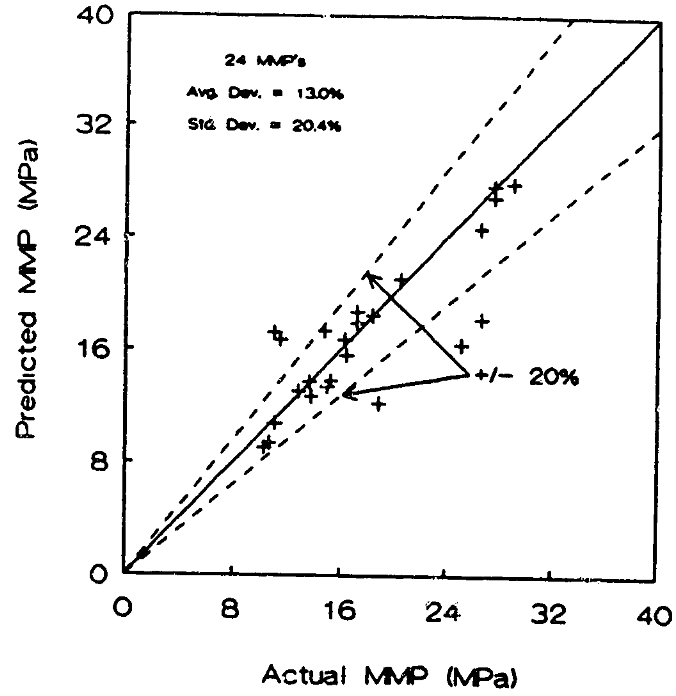
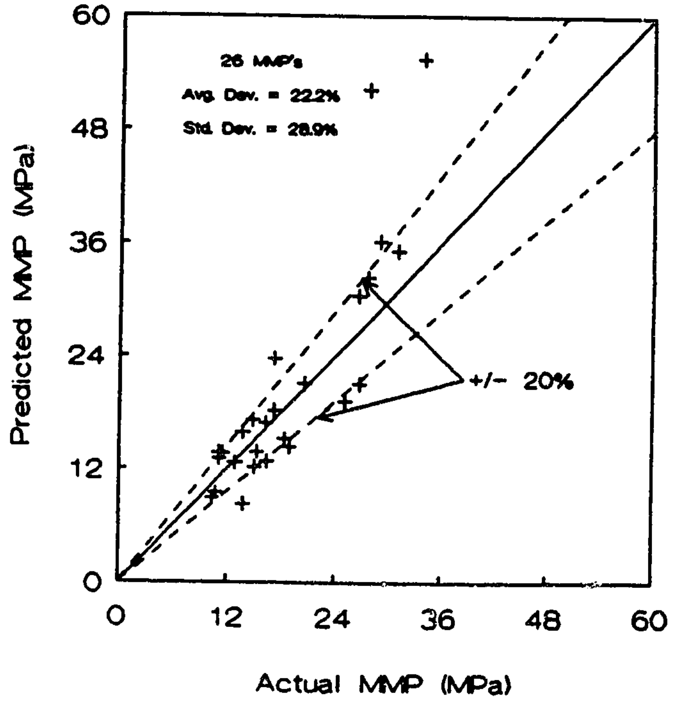


Figure 6-2: Glaso LG/RG (1985)
Predicted vs Actual Rich Gas MMP's



the largest prediction error. When these two systems are ignored, the average prediction error for the Glasø correlation becomes 17.9%, which is more similar to that of Benham et al., but still roughly 5% higher.

The somewhat surprising observation illustrated in Figures 6-1 and 6-2 is that generally, neither the Benham et al. nor Glasø correlations were found to overpredict MMP values. An overprediction was expected based on the limiting tie-line "zero-slope" assumption (see Section A.1.1). This was not found to occur, as about an equal number of MMP's were overpredicted and underpredicted by both correlations.

The Kuo (1985) correlation was found to result in quite accurate MMP predictions, as illustrated in Figure 6-3. The average prediction error was 9.7%, and only one out of 26 MMP predictions was more than 20% in error. The system for which this large prediction error occurred (system 1) was at a temperature of 40.6°C, which is roughly 15°C lower than any of the other 25 systems illustrated in Figure 6-3. The Kuo correlation was developed using PR-EOS phase envelope calculations over the temperature range of 54 to 127°C. The single large Kuo correlation prediction error (system 1) likely can be explained by this low temperature value falling below the correlation development range.

The predicted vs actual MMP values using the Eakin and Mitch (1988) correlation are presented in Figure 6-4. Only 15 MMP predictions were possible because of incomplete gas

Figure 6-3: Kuo (1985)
Predicted vs Actual Rich Gas MMP's

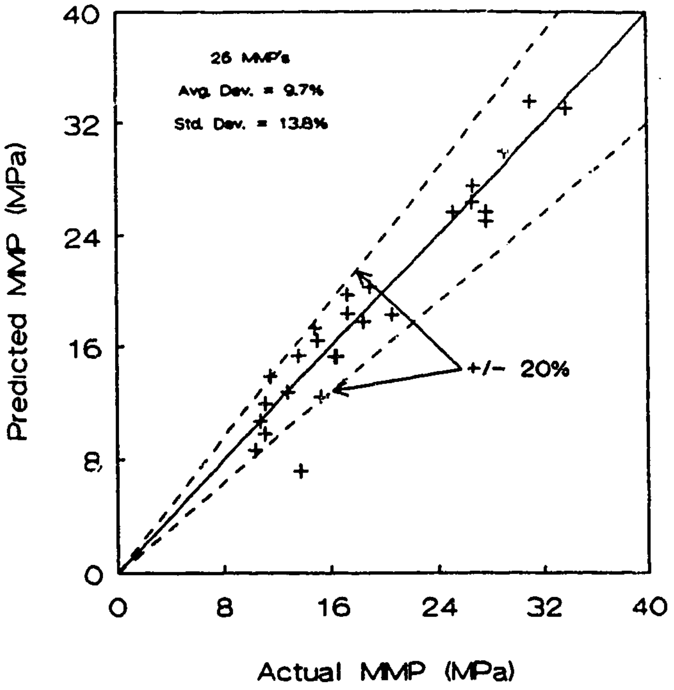
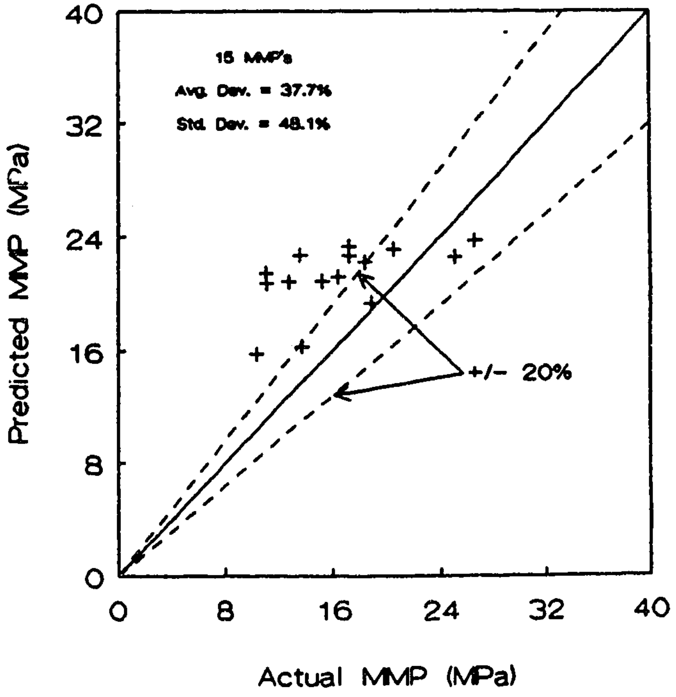


Figure 6-4: Eakin & Mitch (1988)
Predicted vs Actual Rich Gas MMP's



compositional data (for systems 16 through 26). The Eakin and Mitch correlation was found to be the poorest of the four rich-gas correlations, with an average prediction error of 38%, and a tendency to overpredict MMP's by about 35%. This large inaccuracy likely can be explained by the developmental basis of the Eakin and Mitch (1988) correlation. The correlation was developed using RBA data, so miscibility most likely developed (for the rich-gas drives studied by Eakin and Mitch) through the liquid extraction mechanism. The authors did not indicate this limitation of the correlation.

Based on the 26 systems evaluated, the Kuo (1985) and Benham et al. (1960) correlations appear to be the most suitable for predicting the MMP of rich CGD's. Both of these correlations are independent of any data set, with the Kuo correlation being noticeably superior. The Kuo correlation was developed over a broader range of conditions than the Benham et al. correlation, and does not have the limiting assumption of a zero-slope limiting tie-line, which likely explains the improved accuracy of the correlation. The good accuracy of the Kuo correlation strongly supports the applicability of using EOS vapor/liquid equilibria calculations for MMP predictions.

6.5 Lean-Gas MMP Correlation Predictions

The five lean-gas MMP correlations presented in the literature are the Blackwell (Stalkup, 1983), Glasø (1985), Firoozabadi and Aziz (1986), Eakin and Mitch (1988), and Nouar and Flock (1988) correlations. Each of these correlations is described in Appendix A, and a sample calculation for each is presented in Appendix D. The lean-gas correlation predictions for the 18 lean VGD systems (27 through 44) are presented in Table C-7 of Appendix C, and the calculation results are summarized in Table 6-2.

Table 6-2: Lean-Gas Correlation Accuracy Determination

Correlation	# of MMP's Evaluated	Average Deviation (%)	Average Predicted/Actual Ratio	Standard Deviation (%)
Blackwell (Stalkup, 1983)	14	19.0	1.03	23.4
Glasø (1985)	14	13.1	1.05	16.5
Firoozabadi & Aziz (1986)	18 (8)[1]	5.7 (10.7)	1.03 (1.08)	11.5 (17.8)
Nouar & Flock (1988)	18	11.0	0.99	14.3
Eakin & Mitch (1988)	18	17.4%	0.92	20.7

1. Bracketed values indicate calculation results with data points used in correlation development removed.

Note that MMP predictions were not possible for 4 lean-gas systems using the Glasø hydrocarbon correlation. These 4 injection gases were composed of 100% C_1, and the Glasø correlation cannot accommodate pure C_1 injection gases. The

Blackwell correlation requires the bubble-point pressure of the oil as an input parameter, and this information was also not published for 4 of the systems. Blackwell correlation predictions could be made only for the remaining 14 systems. The values in brackets in Table 6-2 represent calculations made with any of the lean-gas systems (27 through 44) which were used in a correlations empirical development removed from the analysis. Refer to Table B-2 for a listing of which systems (if any) were used in developing each correlation.

The predicted vs actual MMP results of the Blackwell correlation are illustrated in Figure 6-5. The average prediction error was 19%, and 4 of the 14 MMP values were predicted with errors greater than 20%. The Glasø hydrocarbon correlation results are shown in Figure 6-6, and the average prediction error was 13.1%. However, 3 of the systems with the largest prediction errors were again in the high pressure region, likely extrapolated well beyond the Benham et al. data used to develop the correlation. Four of the 14 MMP predictions had errors in excess of 20%.

Use of the Firoozabadi and Aziz correlation resulted in excellent predictions with an average prediction error of 5.7% for 18 MMP's. Only one of the 18 MMP's had a prediction error larger than 20% (system 45), as indicated in Figure 6-7. Each of the lean-gas correlations had large prediction errors associated with this particular system. It is important to note that 10 of the 18 MMP's illustrated in Figure 6-7 were

Figure 6-5: Blackwell (Stalkup, 1983)
Predicted vs Actual Lean Gas MMP's

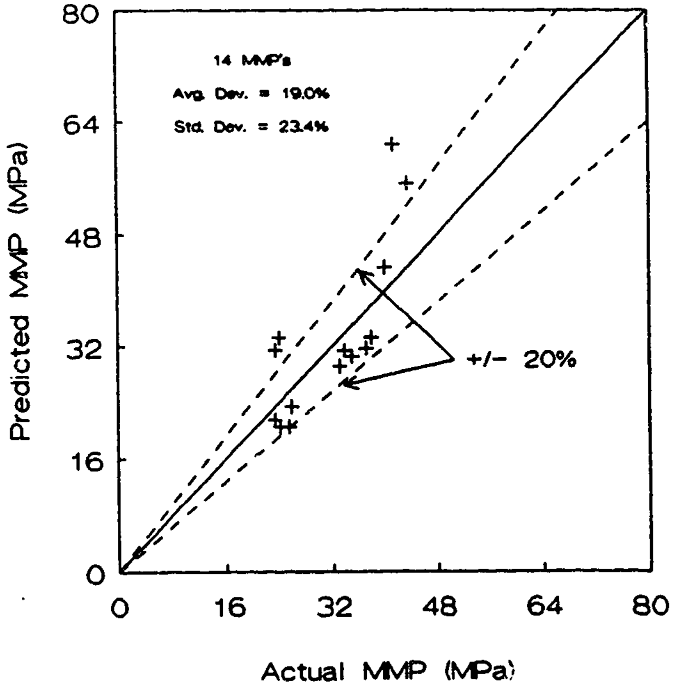


Figure 6-6: Glaso LG/RG (1985)
Predicted vs Actual Lean Gas MMP's

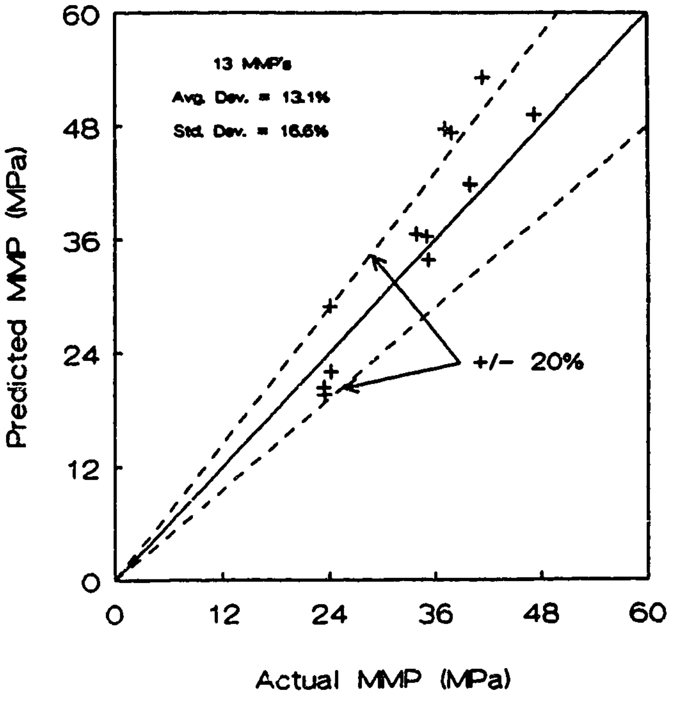


Figure 6-7: Firoozabadi & Aziz (1986)

Predicted vs Actual Lean Gas MMP's

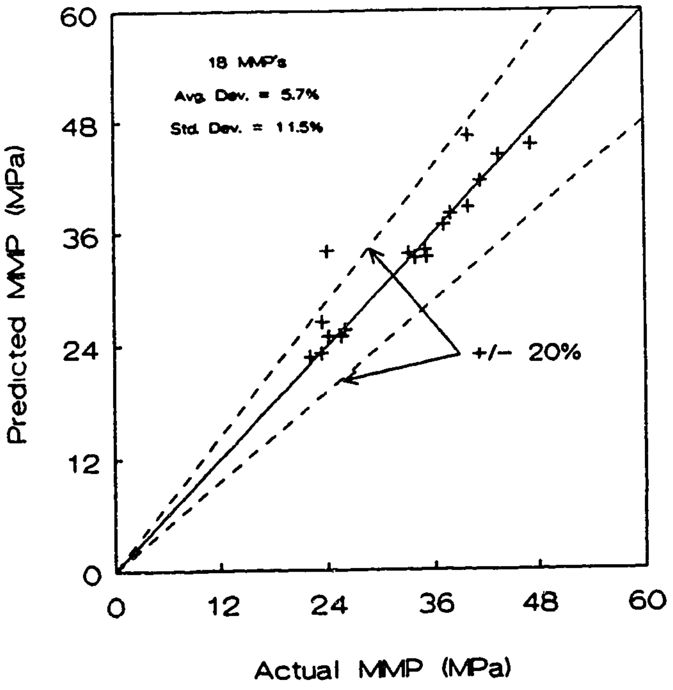
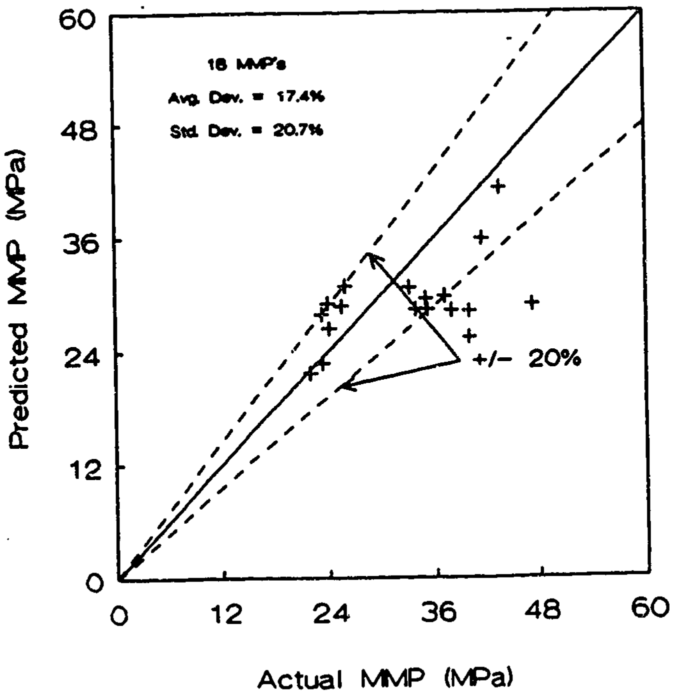


Figure 6-8: Eakin & Mitch (1988)

Predicted vs Actual Lean Gas MMP's



used in the development of the Firoozabadi and Aziz correlation. As indicated in Table 6-2, when these points are disregarded, the average prediction error of the Firoozabadi and Aziz correlation for the remaining 8 MMP's increases to 10.7%, and the standard deviation to 17.8%.

The Eakin and Mitch correlation prediction results are presented in Figure 6-8. As with the rich-gas data set, this correlation also had high prediction errors, with an average prediction deviation of 17.4%. The predictions of the only thermodynamically rigorous lean-gas correlation, the Nouar and Flock (1988) correlation, are illustrated in Figure 6-9. This correlation made relatively good MMP predictions, as the average prediction error for the 18 MMP's was only 11.0%.

The results shown in Figures 6-5 through 6-9 indicate that the Nouar and Flock and Firoozabadi and Aziz correlations are superior in predicting lean VGD MMP values. Also, the Nouar and Flock hydrocarbon correlation, and the Firoozabadi and Aziz correlation, are of about equal accuracy when the MMP data used to develop the Firoozabadi and Aziz correlation is removed from the analysis. The standard deviation of the Nouar and Flock correlation is however, slightly better. A lower standard deviation reflects a better match between a correlation's MMP predictions and actual data. The accuracy of the Nouar and Flock lean-gas correlation supports the applicability of directly calculating mixture critical points by an equation of state to estimate MMP values.

Figure 6-9: Nouar & Flock LG (1988)

Predicted vs Actual Lean Gas MMP's

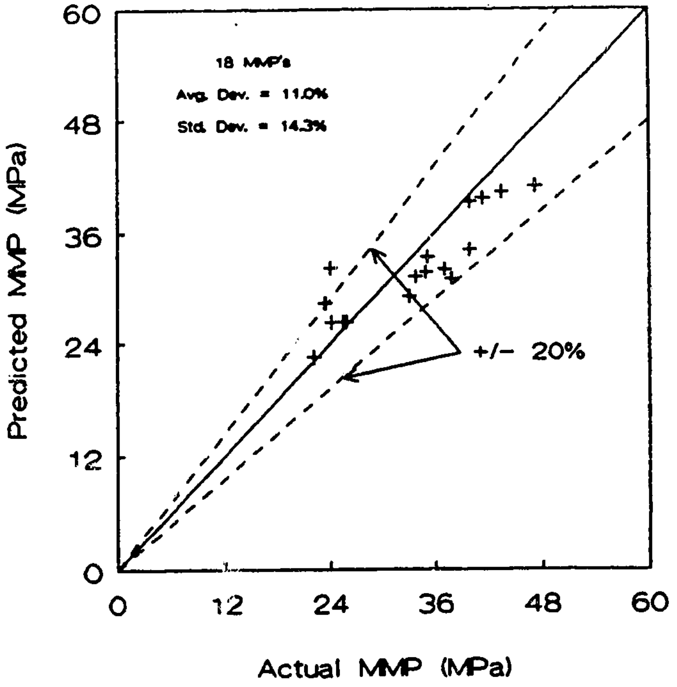
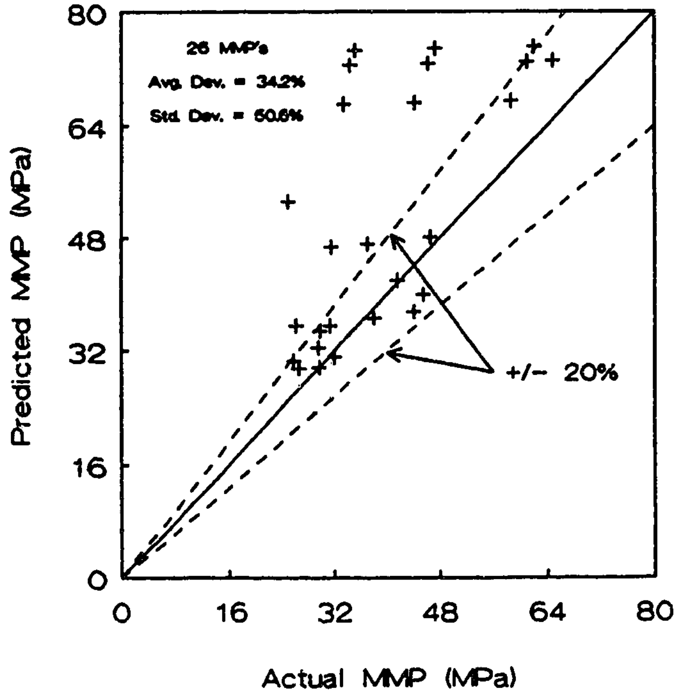


Figure 6-10: Glaso N_2 (1985)

Predicted vs Actual N_2 MMP's



6.6 Nitrogen MMP Correlation Predictions

The seven correlations presented in the literature for predicting the MMP of nitrogen drives are the Glasø (1985), Firoozabadi and Aziz (1986), Hudgins, Llave and Chung (1988), Nouar and Flock (1988), Glasø (1988), Eakin and Mitch (1988), and Nouar, Flock and Dranchuk (1990b) correlations. Each of these correlations is described in Appendix A, and sample calculations are presented in Appendix D. Each nitrogen MMP correlation was evaluated using systems 45 through 70, which represent combinations of live oils and pure nitrogen injection gases. The MMP values predicted by each correlation for these 26 systems are presented in Table C-8 in Appendix C, and the results are summarized in Table 6-3.

As illustrated in Figure 6-10, the Glasø nitrogen (1985) correlation had a very high average prediction error of 34.2%, and 11 of the 26 MMP's evaluated were predicted with errors in excess of 20%. The Firoozabadi and Aziz correlation MMP predictions are shown in Figure 6-11, and 10 of these 26 MMP's were also predicted with errors exceeding 20%. The average prediction error of the Firoozabadi and Aziz correlation was determined to be 17.6%. When the two MMP's used in the correlations empirical development were removed from the analysis, the prediction error increased only slightly to 18.8%.

The Hudgins, Llave and Chung correlation had relatively good MMP predictions, as illustrated in Figure 6-12. For the

Table 6-3: Nitrogen Correlation Accuracy Determination

Correlation	# of MMP's Evaluated	Average Deviation (%)	Average Predicted/Actual Ratio	Standard Deviation (%)
Glass (1985)	26	34.2	1.32	50.6
Firoozabadi & Aziz (1986)	26 (24)	17.6 (18.8)	1.01 (1.00)	24.3 (25.3)
Hudgins, Llave & Chung (1988)	26 (13)	13.9 (25.7)	0.92 (0.85)	21.5 (30.9)
Glass (1988)	26 (11)	12.0 (24.6)	1.09 (1.21)	24.0 (37.7)
Eakin & Mitch (1988)	26	30.2	0.90	35.4
Nouar & Flock (1988)	26	138.2	2.17	-
Nouar, Flock & Dranchuk (1990b)	26	26.4	1.15	43.9

1. Bracketed values indicate calculation results with data points used in correlation development removed.

26 MMP's evaluated, the average prediction error was 13.9%. However, when the 13 MMP's used in the development of the correlation were disregarded, the average prediction error almost doubled, increasing to 25.7%. The Eakin and Mitch correlation predictions are shown in Figure 6-13, and this correlation also had a very high average prediction error. The average prediction deviation was 30.2%, and 16 of the 26 MMP's were predicted with errors exceeding 20%.

Figure 6-11: Firoozabadi & Aziz (1986)
Predicted vs Actual N_2 MMP's

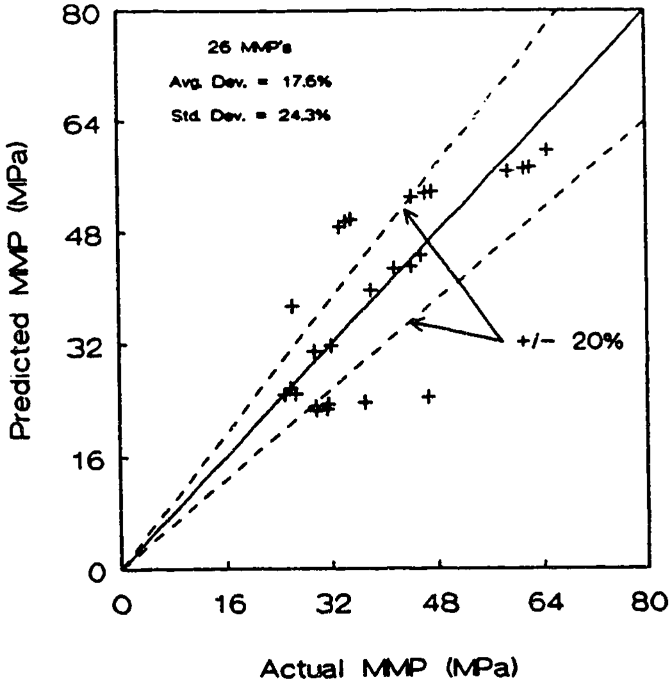
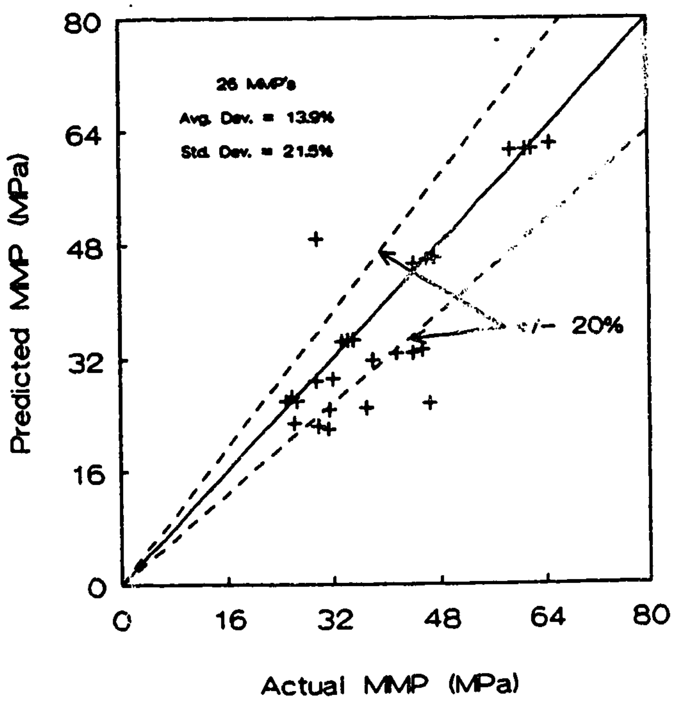


Figure 6-12: Hudgins et al. (1988)
Predicted vs Actual N_2 MMP's



The Nouar and Flock (1988) nitrogen correlation was found to have several MMP prediction errors exceeding 200%, as shown in Figure 6-14. This correlation assumes that all of the light-ends of any gas/oil mixture are nitrogen, and was intended for predicting the MMP of a methane depleted oil. Virtually all of the systems illustrated in Figure 6-14 contained appreciable amounts of C_1, explaining the large correlation errors. However, even for the oils which had a small amount of C_1, prediction errors well in excess of 20% occurred. It is important to note that Nouar and Flock (1988) presented this N_2 MMP correlation as an illustration of the need to consider both C_1 and N_2 as separate components when performing EOS critical point calculations. The method was not actually intended to be a workable MMP correlation, but was presented to support the basic approach of the Nouar et al. (1990b) nitrogen correlation.

Glasø (1988) correlation predictions are shown in Figure 6-15, and relatively accurate MMP predictions were obtained for the systems studied. The average prediction error was 12% for the 26 MMP's. However, 15 of these 26 data points were used to develop the correlation, and when removed from the analysis, the average deviation for the remaining MMP's more than doubled, to 24.6%.

The Nouar, Flock and Dranchuk (1990b) correlation had an average error of 26.4%, as illustrated in Figure 6-16. However, the correlation did have excellent MMP predictions in

Figure 6-13: Eakin & Mitch (1988)
Predicted vs Actual N_2 MMP's

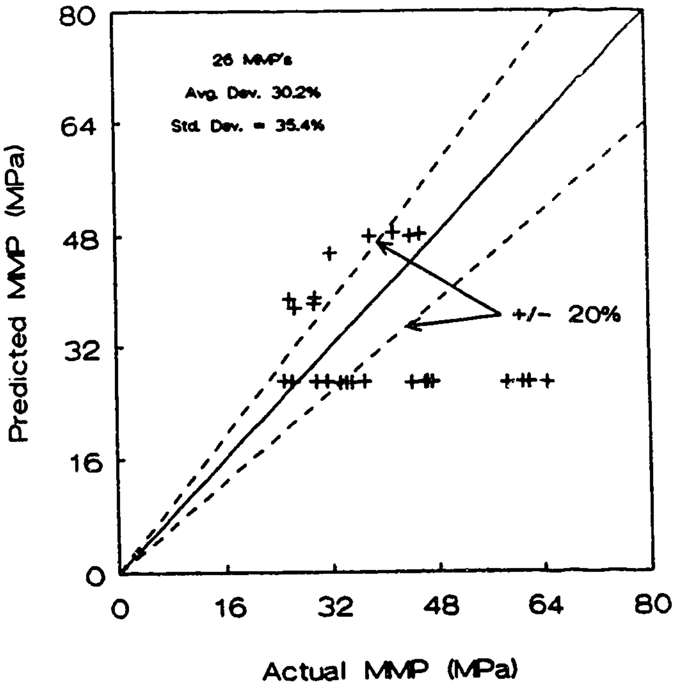


Figure 6-14: Nouar & Flock N_2 (1988)
Predicted vs Actual N_2 MMP's

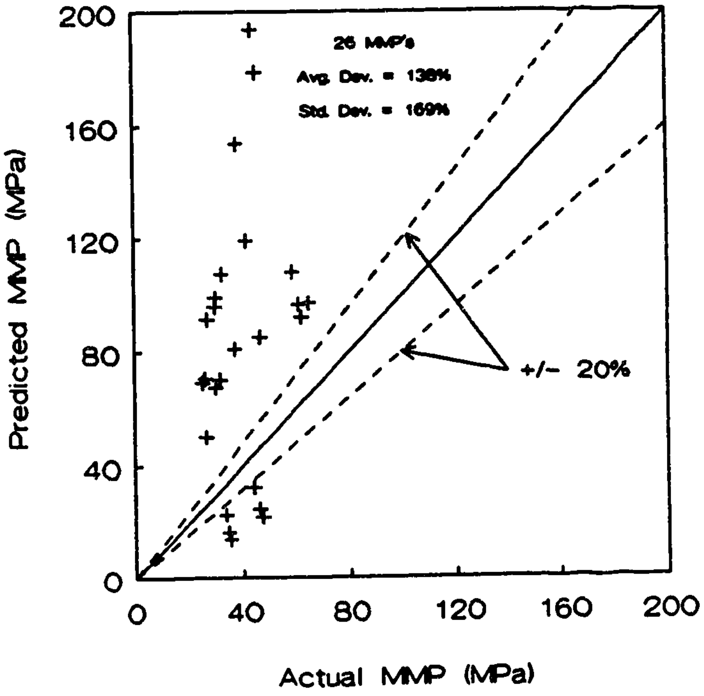


Figure 6-15: Glaso (1988)
Predicted vs Actual N_2 MMP's

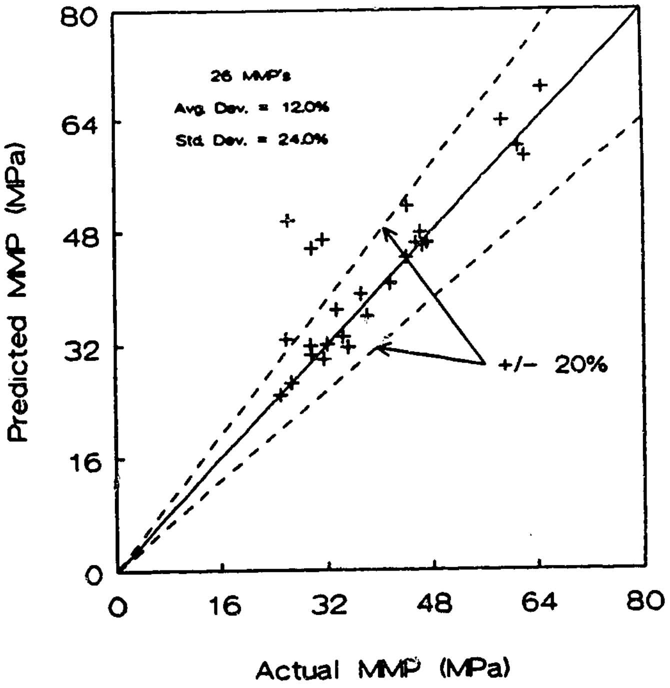
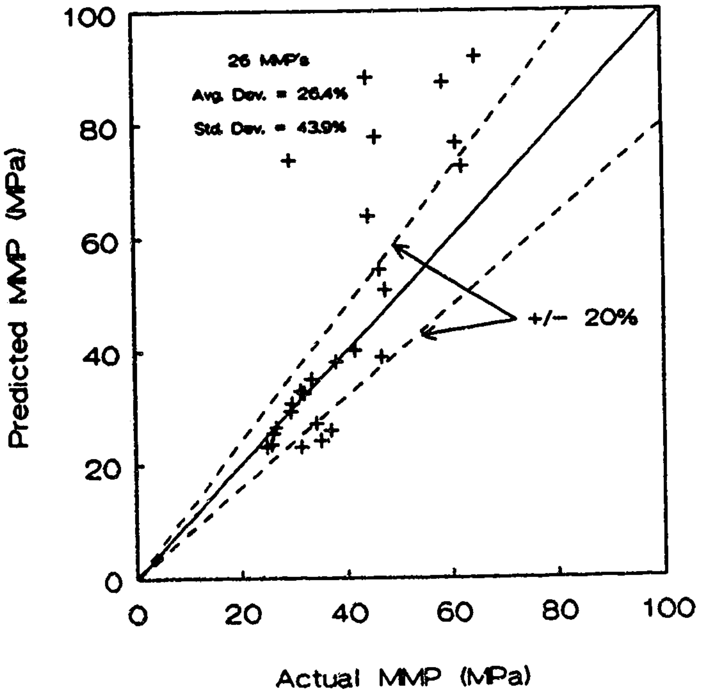


Figure 6-16: Nouar et al. (1990b)
Predicted vs Actual N_2 MMP's



the lower pressure range, as many fell virtually on top of the unit slope line in Figure 6-16. The errors associated with the Nouar et al. correlation were analyzed (see Table C-9), and it was found that for oils having apparent molecular weights in excess of 100 Kg/Kmol, correlation errors were considerable. The prediction error of the Nouar et al. correlation as a function of oil molecular weight, is illustrated in Figure 6-17. Removing the 10 high molecular weight systems (M.Wt. > 100) resulted in the 16 remaining MMP's being predicted with an average prediction error of only 10.3%, as shown in Figure 6-18.

Table C-9 contains a listing of the Nouar et al. correlation MMP predictions for the 26 nitrogen systems, along with the oil molecular weight, mol% of C_1 in the oil, and the mol% of C_2-C_6 in the oil. As a general observation, the higher the amount of C_1 and C_2-C_6 fractions in the oil, the more accurate the Nouar et al. correlation is in predicting MMP values.

The Nouar et al. (1990b) nitrogen correlation was presented for predicting the MMP of a light oil being displaced with nitrogen. Nouar et al. did not indicate what range of oil molecular weight values could be considered as being "light." The results in Figure 6-18 do indicate that the general approach taken by Nouar et al. to develop the correlation is appropriate, even if the correlation range of application is somewhat limited.

Figure 6-17: Nouar et al. (1990b)
Prediction Error vs Oil AMW

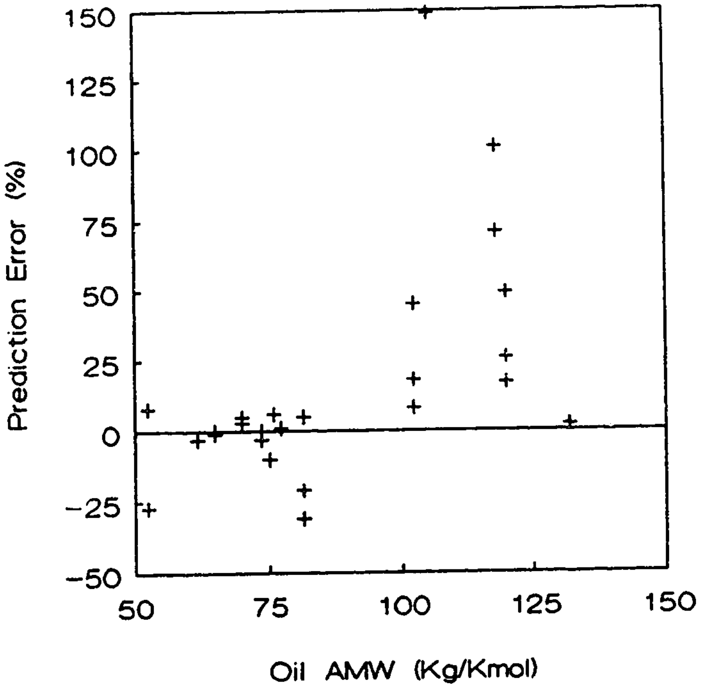
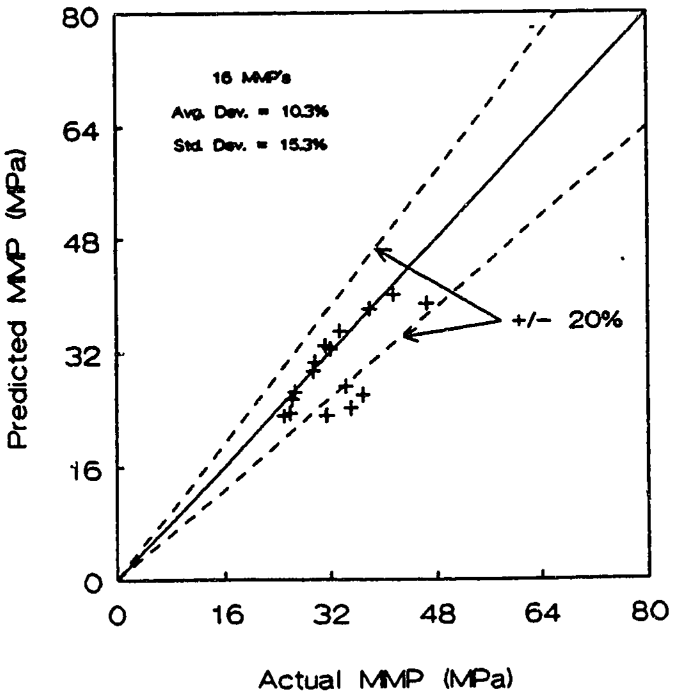


Figure 6-18: Nouar et al. (1990b)
Neglecting Oils with AMW's > 100



The results illustrated in Figures 6-11 through 6-18 indicate that none of the presented nitrogen MMP correlations would appear sufficiently accurate to predict reliable MMP values over a wide range of gas/oil/temperature conditions. The Firoozabadi and Aziz correlation was determined to be the most accurate of the nitrogen correlations (average prediction deviation of ≈ 19%), once the MMP data used in the development of each correlation was disregarded. If consideration is restricted to live oils having an apparent molecular weight below 100 Kg/Kmol, the Nouar et al. correlation was found to predict relatively accurate MMP's, with an average prediction deviation of roughly 10%.

6.6.1 MMP Predictions for Systems A, B & C

The four experimental MMP's measured in this study (System A at 60 and 70°C, and Systems B and C) were included in the analysis of the N_2 correlations presented in the preceding section. The MMP measured for System A at 60°C confirmed the measurement by Nouar (1987), which is listed as System 68 in Table B-1. The System B MMP measured at 60°C confirmed the measurement of Glasø (1988), which is listed as System 50. The MMP's of Systems A and B at 60°C were measured to provide an indication as to the influence varying slim-tube apparatus and operating conditions have on measured MMP values. The MMP's measured for System A at 70°C, and for System C at 60°C, are listed in Table B-1 as Systems 69 and

70, respectively. These two MMP's were measured to add data to the nitrogen MMP data set, which is listed as Systems 45 through 70 in Table B-1.

The MMP predictions for Systems A, B and C, using the Firoozabadi and Aziz (1986), Hudgins et al. (1988), Glasø (1988), and Nouar et al. (1990b) nitrogen correlations are presented in Table 6-4. Recall that previously presented calculation results indicated that these 4 nitrogen MMP correlations were generally found to be the most accurate nitrogen correlations. Table 6-5 lists the same basic calculations shown in Table 6-4. However, instead of using the MMP's listed for Systems A (at 60°C) and B measured in this study, the values measured by Nouar (1987) and Glasø (1988), respectively, are presented.

Although the results listed in Tables 6-4 and 6-5 cannot be used to evaluate meaningfully the nitrogen correlations because of the small size of the data set, they do deserve a couple of observations. Firstly, the Nouar et al. (1990b) correlation had the lowest average prediction deviation for Systems A, B & C, at 8.2%. This result is consistent with the previous finding that light oils MMP's are predicted with relatively good accuracy using the Nouar et al. nitrogen correlation. Each of the four systems listed in Tables 6-4 (and 6-5) consists of a very light live oil. Secondly, the average prediction deviation of each correlation for Systems A through C (Table 6-4) was consistently less than that of

Table 6-4: MMP Predictions for Systems A, B & C

System	MMP (MPa)	Correlation MMP Prediction Deviations			
		Firoozabadi & Aziz (1986)	Glasø (1988)	Hudgins et al. (1988)	Nouar et al. (1990b)
A (60°C)	32.30	-0.29	0.45	-0.32	0.02
B	29.70	-0.21	0.01	-0.17	-0.22
A (70°C)	29.80	-0.24	0.53	-0.25	0.03
C	27.00	0.38	0.84	-0.16	-0.06
Average Deviation		28.3%	45.7%	22.5%	8.2%

Table 6-5: MMP Predictions for Systems 50, 68, A & C

System	MMP (MPa)	Correlation MMP Prediction Deviations			
		Firoozabadi & Aziz (1986)	Glasø (1988)	Hudgins et al. (1988)	Nouar et al. (1990b)
68	31.34	-0.27	0.50	-0.30	0.05
50	31.50	-0.26	-0.05	-0.22	-0.27
A (70°C)	29.80	-0.24	0.53	-0.25	0.03
C	27.00	0.38	0.84	-0.16	-0.06
Average Deviation		28.9%	47.8%	23.2%	10.1%

Systems 68, 50, A (at 70°C), and C (Table 6-5). The only difference between these two sets of MMP measurements is that Table 6-4 measurements were made in this study, while Table 6-5 values contain two measurements made in other studies.

It could be argued that the lower prediction deviations of the measurements presented in Table 6-4 supports the accuracy of the measurements made in the current study. However, the general inaccuracy and developmental nature of the 4 nitrogen correlations listed in Table 6-4 does not allow for this statement to be substantiated.

6.7 Additional Investigation

6.7.1 Adjusted Nouar & Flock Lean-Gas Correlation

A large amount of data analysis was performed in addition to the statistical tests used on each of the rich-gas, lean-gas, and nitrogen MMP correlations presented in this study. This analysis consisted of determining if the prediction errors of each correlation could be related to temperature, or to specific oil and gas compositional characteristics. For each correlation, the MMP prediction deviations were sorted in decreasing magnitude (as shown in Table C-9 for the Nouar et al. correlation), and the standard correlation input parameters (see Table B-2) were studied for any obvious patterns. The presentation (not including all input parameters studied) in Table C-9 in Appendix C illustrates that the Nouar et al. correlation generally predicts more accurate MMP's for lighter oils, as was described earlier.

Unfortunately, the prediction deviation pattern observed for the Nouar et al. correlation was the only result of this additional analysis. Slight deviation trends, involving at most a few systems, were observed for other correlations.

However, the small size of both the data sets and the observed deviation trends made attaching any significance to these patterns unjustifiable.

Many MMP prediction calculations were made using correlations beyond their basic range of application. As an example, calculations were made to determine if any of the lean-gas correlations could be used to predict rich-gas MMP's, or vice versa. An additional goal was to observe deviation trends and determine if a correlation could be adjusted for more accurate use in situations beyond the general range of the correlation's presented application range.

The vast majority of these calculations were of no use as no obvious pattern to prediction deviations was observed for any of the correlations. The single exception was the Nouar and Flock (1988) lean-gas correlation, which was used to calculate the MMP's of the nitrogen systems (systems 45 through 70). These calculations are presented in Table C-8, and the results are illustrated in Figure 6-19. These MMP predictions indicate that the Nouar and Flock lean-gas correlation consistently underpredicted the actual MMP's of the nitrogen systems. This result was expected, as it is generally accepted that N_2 MMP's are usually higher than C_1 MMP's for displacements of the same oil. The average MMP underprediction was calculated to be 22%, as shown in Table C-8. As a general observation, the more C_1 in the reservoir oil, and the lower the molecular weights of the oil

Figure 6-19: Nouar & Flock LG (1988)
Predicted vs Actual N_2 MMP's

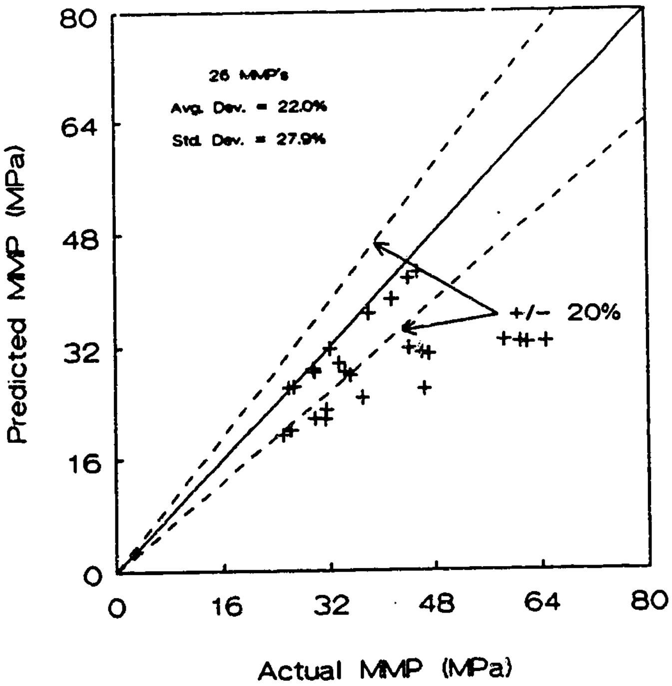
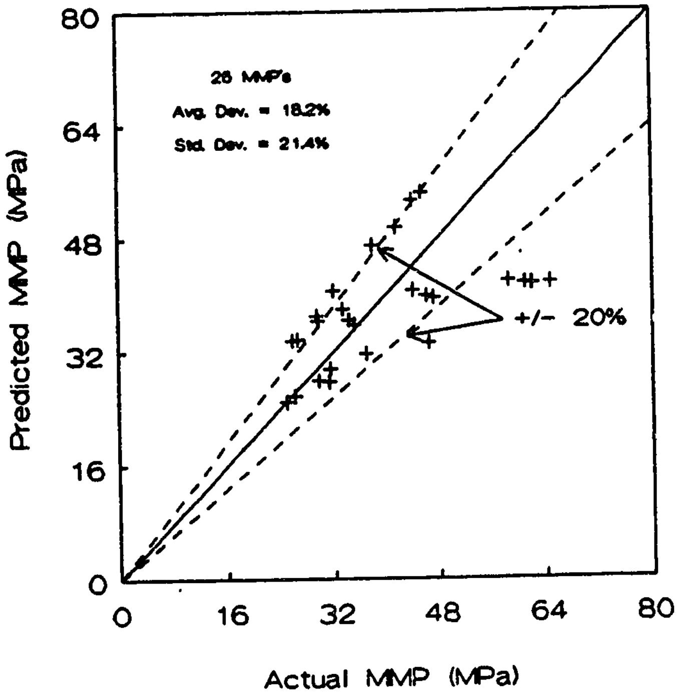


Figure 6-20: Nouar & Flock LG(1988)
(Predicted/0.78) vs Actual N_2 MMP's



intermediate and heavy fractions, the more accurate the Nouar and Flock lean-gas correlation was in predicting the N_2 MMP's.

Adjusting the Nouar and Flock lean-gas correlation for N_2 MMP predictions by simply dividing each correlation prediction by 0.78 (i.e. taking into account the 22% underprediction described above) resulted in a somewhat better fit of the data. These adjusted MMP prediction results are shown in Figure 6-20. The average prediction deviation of the adjusted lean-gas correlation was determined to be 18.2%, and the standard deviation was 21.4%. Surprisingly, this adjusted lean-gas correlation resulted in the lowest standard deviation of any of the nitrogen correlations evaluated using the entire 26 MMP nitrogen data set (see Table 6-3). Also, when any of the data in the set that was used in a correlation's empirical development was disregarded, the adjusted Nouar and Flock lean-gas correlation resulted in the smallest average nitrogen MMP prediction error.

6.7.2 Impure N_2 Injection Streams

With the exception of the Eakin and Mitch correlation, none of the presented nitrogen MMP correlations account for varying injection gas properties. These MMP prediction techniques assume that the injection gas is always composed of pure nitrogen, ignoring the presence of any impurities. Systems 71 through 81 (Table B-1) were used to determine how accurately the 7 nitrogen MMP correlations presented in the literature predict the MMP of impure nitrogen injection streams. Table C-10 (Appendix C) lists the results of these calculations.

An inspection of Table C-10 leads to the conclusion that the presence of the injection gas impurities (ranging from 25% to 34%) cannot be ignored if accurate N_2 MMP predictions are to be made. Only the Eakin and Mitch correlation predicted these MMP values accurately, with an average prediction error of less than 10%. However, the correlation was developed using 10 of these 11 MMP data points, so good accuracy would be expected. The other correlations had average prediction errors in excess of 20%.

Systems 71 through 80 include impurities consisting of CO_2, H_2S, and intermediate molecular weight hydrocarbon gases, and these impurities appear to increase the MMP. This observation is based on the fact that use of each of the N_2 correlations which were shown to be somewhat reliable in Section 6.6 resulted in consistently underpredicted values of the MMP's for these 10 systems. On the other hand, C_1 was the injection gas impurity in System 81, and use of the N_2 MMP correlations resulted in much more accurate predictions for the MMP of this system. It could be speculated that the presence of C_1 impurities in N_2 injection gas streams is of minor consequence, but heavier molecular weight impurities have a large influence on the system MMP.

6.7.3 RBA Light Oil MMP Calculations

Eakin and Mitch (1988) measured 32 MMP's of lean and rich-gases combined with a light oil. The lean and rich injection gases were generally mixed with non-hydrocarbon impurities, and the lean-gas was mixed with heavier molecular weight hydrocarbon gases in several cases. This Eakin and Mitch data is listed as systems 82 through 113 in Table B-1. As mentioned earlier, none of the lean-gas data was included in the lean-gas data set (systems 27 through 44) because many of the injection gas streams did not fit the compositional makeup of what is commonly referred to as a "lean-gas" (i.e. mainly C_1). Systems 82 through 113 had injection gas C_1 fractions ranging from 35.98% to 100%.

MMP calculations were made using the Firoozabadi and Aziz, Nouar and Flock, Eakin and Mitch, Glasø, and Kuo hydrocarbon correlations for each of systems 81 through 113. The calculation results are listed in Table C-11 (Appendix C), and summarized in Table 6-6. It is important to note that these 32 MMP's were measured for a single oil, at two different temperatures, using a variety of different injection gases. Because of this, the Firoozabadi and Aziz and the Nouar and Flock correlations, which do not account for varying gas compositions, predict identical MMP's for each system at a constant temperature.

The surprising result indicated in Table 6-6 is the accuracy of the Firoozabadi and Aziz and the Nouar and Flock

Table 6-6: RBA LG/RG & Light Oil MMP Calculations

Correlation	# of MMP's Evaluated	Average Deviation (%)	Average Predicted/Actual Ratio	Standard Deviation (%)
Glasø (1985)	30	32.5	0.68	34.8
Kuo (1985)	30	31.3	0.76	36.9
Firoozabadi & Aziz (1986)	32	9.0	0.95	11.7
Nouar & Flock (1988)	32	9.4	0.96	11.9
Eakin & Mitch (1988)	32	3.2	1.01	4.2

correlations in predicting the MMP's of Systems 82 through 113. These two correlations had average prediction errors below 10%, likely a direct result of the small influence that varying the injection gas composition had on the MMP of the light oil studied by Eakin and Mitch. It would appear that the development of miscibility for a light oil is a strong function of the oil composition, and relatively independent of gas composition.

The Eakin and Mitch correlation was quite accurate in predicting the MMP's of systems 82 through 113, with an average prediction error of only 3.2%. However, each of these systems was used in the development of the Eakin and Mitch correlation, so a good prediction accuracy value would be expected. Neither of the Glasø or Kuo correlations were suitable in predicting the MMP's of these 32 systems. These two correlations were included to determine if they could predict accurately any of the rich-gas/light-oil MMP's of systems 82 through 113, which was not the case.

6.7.4 RBA Medium Oil MMP Calculations

Systems 114 through 144 (Table B-1) represent Eakin and Mitch (1988) RBA measurements for a variety of lean and rich injection-gas combinations, at two temperatures, using a single medium-weight oil. These injection gases were basically the same gases that were used with the light oil (see systems 82 through 113) discussed in the preceding section. The MMP predictions for these 31 systems, using the Firoozabadi and Aziz, Nouar and Flock, Eakin and Mitch, Glasø, Kuo, and Benham et al. correlations, are listed in Table C-12 (Appendix C).

As indicated in Table C-12, none of the correlations accurately predicted the MMP's of systems 114 through 144, with the exception of the Eakin and Mitch correlation (average prediction deviation of 4.4%). The accuracy of the Eakin and Mitch correlation was expected, as these 31 systems were used in the correlation's empirical development. The lack of success in using the Firoozabadi and Aziz and the Nouar and Flock correlations to predict these MMP's can be explained easily by the observation that these correlations were developed for the classical VGD situation: a lean injection gas and a light oil. Systems 114 through 144 MMP's were measured for a medium oil, which was actually extremely heavy in comparison to all of the systems listed in Table B-1. It is also possible that some (or several) of these 31 systems had miscibility which developed by the liquid extraction mechanism, which is a much different miscibility mechanism than either the Firoozabadi and Aziz or Nouar and Flock correlations were developed for.

6.7.5 RBA CO_2 MMP Calculations

Calculations were made for several non-hydrocarbon/non-nitrogen injection gas streams. These MMP's were measured by Eakin and Mitch (1988) using the RBA, and were included in this study solely to observe how the evaluated correlations perform under these injection gas situations. These injection gases were mainly CO_2 streams, with intermediate molecular weight hydrocarbon and H_2S contaminants. This data is listed as systems 145 through 176 in Table B-1.

The MMP calculations for systems 145 through 160 using the Firoozabadi and Aziz, Nouar and Flock, Eakin and Mitch, and the Glasø hydrocarbon correlations are listed in Table C-13 (Appendix C). These systems represent the CO_2-based injection gases mentioned above, in combination with a light oil. The calculations for systems 161 through 176 are listed in Table C-14, and represent the CO_2-based injection gases in combination with a medium oil.

The calculations (Table C-13 and C-14) indicate quite clearly that none of the evaluated correlations, with the exception of Eakin and Mitch, can be used to estimate the MMP's of these CO_2 systems. The Eakin and Mitch correlation was developed using these data points, so the correlation accuracy is expected for these systems. The surprising result indicated in Table C-13 is that the Firoozabadi and Aziz and the Nouar and Flock correlations predict MMP values "relatively well" for the light oil (systems 145 through 160). The average prediction errors of these correlations for systems 145 through 160 was found to be 16.2 and 17.3%, respectively. This likely indicates that even for CO_2 displacements, when the reservoir oil is light, oil composition appears to be a controlling factor regarding the development of multiple-contact miscibility.

Summary and Conclusions

The limited experimental results of this study indicate that when the recovery vs pressure profile method is used to determine the MMP, slim-tube MMP measurements are relatively insensitive to apparatus specifications and operating conditions.

As a general observation, none of the MMP correlations evaluated in this study would appear sufficiently accurate for anything but preliminary MMP calculation purposes. Experimental MMP measurement methods where the experiment truly simulates the actual miscible reservoir mechanism would likely be required for the final MMP determination. However, the following generalizations can be made:

1. Both of the theoretically based Kuo rich-gas, and the Nouar and Flock lean-gas MMP correlations have been found to be quite successful in predicting MMP's, proving superior to other similar empirical correlations. These correlations were determined to have average prediction errors of roughly 10% for the data studied. The success of these two correlations supports the applicability of EOS calculated phase envelopes (Kuo correlation) and EOS critical point calculations (Nouar and Flock correlation) for MMP predictions.
2. The Firoozabadi and Aziz correlation predicted lean-gas MMP's with prediction errors of roughly 10%, proving to be the only empirical correlation which accurately

predicted these MMP's.

3. The inability of the Eakin and Mitch correlation to predict accurately VGD MMP values not used in the correlation's empirical development underscores an important fact about scientific research. The correlation was developed using considerably more data than was used in developing any of the other correlations. However, Eakin and Mitch concentrated on correlating MMP deviations resulting from gas composition changes, while oil composition would appear to be the major factor influencing the VGD MMP. The Eakin and Mitch correlation was determined to be one of the least accurate VGD MMP correlations presented. The Firoozabadi and Aziz correlation was developed using only a few MMP values and proved to be relatively accurate, illustrating that a few well chosen data points are better than a considerable number of poorly selected data points.
4. None of the nitrogen MMP correlations had accuracy values approaching those of the superior hydrocarbon correlations. The best method was the empirical approach of Firoozabadi and Aziz, which had an average prediction error of approximately 19%. If consideration is restricted to light oils (apparent molecular weights below 100 Kg/Kmol), the Nouar et al. thermodynamically rigorous correlation was found to be quite accurate, with an average prediction error of roughly 10%.

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Appendix A

Hydrocarbon and Nitrogen MMP Correlations

The correlations discussed in this section were generated for predicting the MMP of hydrocarbon or nitrogen gas floods. They have been split into two main groups: theoretically and empirically based correlations. Correlations described as being theoretically based are founded on determining the critical conditions of selected gas/oil mixtures. The empirically based correlations were all generated largely by relating experimentally measured MMP's to various parameters describing the injected gas composition, reservoir oil composition, and the reservoir pressure and temperature. Each numerical correlation has been converted to SI units for inclusion in this section.

Defining two specific correlations as being either theoretically or empirically based was somewhat arbitrary. The Benham et al. (1960) graphical correlation is based upon critical point calculations of selected gas/oil mixtures, but relies on an empirical correlation (not an EOS) to calculate mixture critical points. The Flock & Robinson (1989) "Hydrocarbon and CO_2 Miscible Fluid Displacement" short course notes indicated that the empirical critical point correlation used by Benham et al. is of equivalent accuracy as any EOS method. Consequently, the Benham et al. correlation was felt to be more theoretical than empirical, and was classified accordingly. The Glasø (1985) hydrocarbon correlation was developed by doing a best-fit of Benham et al. data, and was arbitrarily classified as being empirical in nature.

A.1 Theoretically Based Correlations

A.1.1 Benham, Dowden, and Kunzman Correlation

Benham, Dowden, and Kunzman (1960) studied the conditions necessary for condensing-gas-drive miscible displacement of reservoir fluids by rich injection gases. Unlike the case of a vaporizing-gas-drive, where the displacing fluid composition has no effect on the MMP (when phase behavior is illustrated using a pseudoternary approximation), the composition of the displacing fluid is a controlling factor in the development of miscibility in condensing-gas-drives.

Benham et al. suggested that for the case of a condensing-gas-drive, by considering only regions close to the critical point and associated limiting tie-line, the character of the intermediate fraction will be close to that of the injection gas. They proposed a pseudoternary approximation of condensing-gas displacements using intermediates of character equal to that of the injection mixture and heavy fractions having a character equal to that in the reservoir fluid. Benham et al. chose three pseudocomponents where C_1 represented the light fraction, C_2-C_4 the intermediate fraction, and C_{5+} the heavy-ends.

Benham et al. calculated the critical pressure and temperature of various mixtures of five different reservoir fluids and various rich hydrocarbon gases. The gases consisted of methane combined with mixtures of ethane/propane or propane/butane. The modified Kurata-Katz (Davis et al., 1954) empirical method was used to evaluate the critical pressure and temperature of each mixture. The limiting tie-line associated with the critical mixture was assumed to be parallel to the C_1-C_{5+} edge of the pseudoternary diagram, so the minimum enrichment corresponded to the mole percentage of the C_2-C_4 fraction of the critical mixture. This assumption has been referred to as a "zero-slope" limiting tie-line, assuming that the ternary diagram is a "right" triangle.

The maximum permissible methane concentration in the displacing fluid for a miscible displacement of reservoir fluids was then correlated as a function of temperature, pressure, C_{5+} molecular weight of the reservoir fluid, and C_2-C_4 molecular weight of the displacing fluid. The final correlation of results was presented as Figures 6 through 16 of Benham et al. (1960). Stalkup (1983) presented simplified crossplots of Benham et al.'s correlation which were used for calculation purposes in this study. Benham et al. did not indicate how to account for the presence of non-hydrocarbons such as CO_2, H_2S or N_2 in either the reservoir oil or displacing fluid.

The Benham et al. correlation was developed over the following range of conditions: temperatures of 21 to 127°C;

pressures from 6900 to 20700 KPa; molecular weights of C_2-C_4 fraction in the injection gas from 39 to 49; and molecular weights of the C_{5+} fraction in the reservoir oil from 182.6 to 241.

A.1.2 Kuo Correlation

Kuo (1985) proposed a pseudoternary representation of condensing-gas displacements using C_1 as the light fraction, C_2-C_4 as the intermediate fraction, and C_{5+} as the heavy fraction. Non-hydrocarbon CO_2 and H_2S components were treated as intermediates, and N_2 as a light fraction. Various mathematical combinations of four different reservoir fluids and three injection gases were used in developing the correlation. The injection gases consisted of methane with various combinations of ethane, propane, and butane.

The Peng-Robinson equation of state was used to determine the critical point and limiting tie-line of the selected gas/oil mixtures. This was accomplished by calculating the dew-point and bubble-point curves for each gas/oil mixture over a specified range of pressures and temperatures. An estimation of the maximum allowable amount of lean component (C_1) in the injection gas to develop miscibility with the reservoir fluid was then made for each system studied.

The calculated maximum allowable methane concentration in the injection gas was correlated against temperature, pressure, molecular weight of the C_{5+} fraction in the reservoir fluid, and the molecular weight of the C_2-C_4 fraction in the injection gas. The correlation was presented graphically as a series of figures, and in equation form as follows:

$$\log(y_{\%C1}) = [A+B*(1.8T+32)]*\log(1.8T+32) + C*\log(MMP/6.8947575) + D*\log(MW_{C5+}) + (E+F*MW^{C2\text{-}C4})*\log(MW^{C2\text{-}C4})$$

where: MMP = KPa
T = temperature, °C
MW_{C5+} = molecular weight of C_{5+} fractions in the reservoir fluid
$y_{\%C1}$ = maximum allowable mol% methane in the injection gas
$MW^{C2\text{-}C4}$ = molecular weight of C_2 to C_4 fractions in the displacing gas

and,

A = 0.19899861 C = 0.58347828 E = 0.57821035
B = -0.00055769 D = -0.62406453 F = 0.00058948

Based on the development conditions, the approximate range of application of the Kuo correlation is: temperatures of 54 to 127°C; pressures of 10.3 to 27.6 MPa; molecular weights of the C_2-C_4 fraction in the injected gas from 35 to 48; and molecular weights of the C_{5+} fraction in the reservoir oil from 160 to 300.

A.1.3 Nouar and Flock Lean-Gas Correlation

Nouar and Flock (1988) published a predictive method for the determination of the MMP of lean hydrocarbon vaporizing-gas-drives. Nouar and Flock calculated the critical point composition and limiting tie-line slope over a range of temperature and pressure combinations for a series of pure three component systems. The ideal ternary systems consisted of a light (C_1), intermediate (C_3, C_4, C_5, or C_6), and heavy (C_8, C_{10}, C_{12}, or C_{15}) fraction.

Two equations describing the Gibbs criteria that have to be satisfied by a critical composition at some fixed pressure and temperature, and a third equation, which describes the slope of the limiting tie-line in terms of partial derivatives of the molar Gibbs free energy, were used by Nouar and Flock. The pressure at which the conditions in these three equations are satisfied was taken to represent the MMP for the selected oil and temperature. The Gibbs free energy was constructed from the Soave (1972) equation of state.

Five temperatures were selected, varying from 30 to 90°C, and sixteen ternaries were considered at these temperatures. For each system at a fixed temperature, the critical point composition and slope of the limiting tie-line were calculated at seven pressures, ranging from the critical pressure of the light/intermediate binary to the critical pressure of the light/heavy binary.

For each system and temperature, the generated data were correlated by Nouar and Flock into two equations. The first was a linear relationship relating the critical point mole fraction of the light component (X_{LC}) to the critical point mole fraction of the intermediate component (X_{IC}) and the intermediate mole fraction of the critical point of the light/intermediate binary (x_{ic}),

$$X_{LC} = 1 - x_{ic} + b_1 (X_{IC} - x_{ic})$$

where b is a correlating coefficient. The second equation is a quadratic relationship between the slope of the limiting tie-line (a) and the same correlating variables discussed above,

$$a = -[1 + a_1 (X_{IC} - x_{ic}) + a_2 (X_{IC} - x_{ic})^2]$$

where a_1 and a_2 represent correlating coefficients. For a specified ternary system at a fixed temperature, the coefficients a_1, a_2, b_1, and x_{ic} were tabulated. The mole fraction of the light component at the critical point and the slope of the limiting tie-line were both evaluated as a function of the mole fraction of the intermediate component at the critical point.

Using the above results and given the mole fractions of the intermediate (x_I^{oil}) and light (x_L^{oil}) components in the live oil, a cubic equation in terms of the mole fraction of the intermediate component of the critical point (X_{IC}) was presented:

$$C_0 + C_1 X_{IC} + C_2 X_{IC}^2 + C_3 X_{IC}^3 = 0 \qquad (5)$$

where:

$$C_0 = X_I^{oil} - (1 - a_1 x_{ic} + x_{ic}^2)\,(X_L^{oil} - 1 + x_{ic} + b_1 x_{ic}) \tag{6}$$

$$C_1 = 1 + b_1(1 - a_1 x_{ic} + x_{ic}^2) - (a_1 - 2a_2 x_{ic})\,(x_L^{oil} - 1 + x_{ic} + b_1 x_{ic}) \tag{7}$$

$$C_2 = b_1(a_1 - 2a_2 x_{ic}) - a_2(x_L^{oil} - 1 + x_{ic} + b_1 x_{ic}) \tag{8}$$

$$C_3 = a_2 b_1 \tag{9}$$

Given correlation variables a_1, a_2, b_1, and x_{ic} for a particular ternary system (Table 2 in Nouar and Flock, 1988), along with the oil compositional data (x_I^{oil} and x_L^{oil}), equations 6 through 9 can be solved, and the results substituted into equation 5. The value of X_{IC} satisfying equation 5 verifies that the point representing the composition of the oil satisfies the equation of the limiting tie-line. The critical pressure corresponding to the calculated value of X_{IC} represents the MMP for the VGD of the specified oil by methane. For the selected ternary system and temperature, a graphical representation relating X_{IC}, the molecular weight of the intermediate component, and the molecular weight of the heavy component, to the MMP was developed. The MMP is then read from the appropriate curve (Figures 3 through 22 of Nouar and Flock, 1988) at the calculated value of X_{IC}.

For the case of actual multicomponent reservoir oils at one of the temperatures studied by Nouar and Flock, the MMP can be predicted by equating the reservoir fluid to the idealized ternary systems previously discussed. The reservoir oil components are grouped into an intermediate (C_2-C_6, CO_2 and H_2S) and heavy (C_{7+}) pseudocomponent, and the molecular weight of each is calculated using a mole weighted average. Inspection of the ideal ternary systems for which miscibility conditions have been correlated will then yield up to four ternary systems which circumscribe the actual reservoir oil based on the molecular weight of the intermediate and heavy components. The MMP's of these "circumscribing" ternaries can be calculated, and the MMP of the actual reservoir oil can be estimated by interpolating the ternary MMP's on the basis of the molecular weights of the intermediate and heavy components.

When the reservoir temperature does not correspond to any of the temperatures for which tabulated data is available (30, 45, 60, 75, and 90°C) an interpolation (or extrapolation) scheme may be used. This would involve the calculation of the MMP by the above procedure at two temperatures selected from the above range to bracket the reservoir temperature. A linear interpolation may then be used to determine the MMP at the desired temperature. The approximate range of conditions over which the Nouar and Flock lean-gas correlation is applicable include: temperatures from 30 to 90°C; molecular weights of the reservoir oil intermediate (C_2-C_6) fraction from 44 to 86; and molecular weights of the reservoir oil heavy (C_{7+}) fractions from 114 to 212.

A.1.4 Nouar and Flock Nitrogen Correlation

Nouar and Flock (1988) published a predictive method for the determination of the MMP of VGD's with pure nitrogen as the displacing fluid. The correlation development is identical to the lean VGD correlation presented by the same authors and discussed in the preceding section. The only difference being that the light component of the pure three-component systems used to develop the correlation was represented by N_2, rather than C_1.

The correlation usage and details are identical to those previously discussed in Section A.1.3. At a fixed temperature and for a pure ternary system studied by Nouar and Flock, the coefficients a_1, a_2, b_1, and x_{ic} can be read from Table 3 of Nouar and Flock (1988). This information is substituted into equations 6 through 9 (see Section A.1.3), allowing for the mole fraction of the intermediate component at the critical point (X_{IC}) to be calculated using equation 5. The critical pressure corresponding to the calculated value of X_{IC} is then obtained by referring to the appropriate figure (Figures 3 through 22 of Nouar and Flock, 1988). This pressure represents the MMP of the ternary system at the conditions studied.

As with the Nouar and Flock lean-gas correlation, actual complex reservoir fluid MMP's are determined by calculating the MMP's of selected ternaries which circumscribe the reservoir fluid on the basis of the molecular weights of the intermediate (C_2-C_6) and heavy (C_{7+}) fractions. The reservoir fluid MMP is then obtained by interpolating (or extrapolating) between the MMP's of the selected ternaries to the molecular weights of the intermediate and heavy fractions of the reservoir fluid.

Inspection of the pure three-component systems selected by Nouar and Flock in development of the correlation indicates some possible limitations of this pseudoternary approach to representing nitrogen gas drives. Since no C_1 is present in the ternaries used, the method is applicable for the prediction of the MMP of a vaporizing-gas-drive by nitrogen of a methane-depleted oil. However, as mentioned by the authors, most oils contain an appreciable amount of methane in solution. The range of conditions over which the Nouar and Flock nitrogen correlation can be considered appropriate are the same as those applicable for their lean-gas correlation.

A.1.5 Nouar, Flock, and Dranchuk Correlation

Nouar, Flock, and Dranchuk (1990a,b) studied N_2 VGD's through the use of quaternary (four component) systems. The phase behavior of a quaternary system is represented by a tetrahedron, with each apex of the tetrahedron corresponding to one of the four pure components. Nouar et al. investigated the miscibility conditions of pure four-component mixtures consisting of N_2 and a ternary oil mixture comprised of a light (C_1), intermediate (C_3 or C_4), and heavy (C_{12}, C_{13}, or C_{14})

hydrocarbon. Six separate quaternary systems were studied. As an example, for the N_2-C_1-C_3-C_{10} system, one face of the tetrahedron will correspond to the hydrocarbon ternary system C_1-C_3-C_{10}, while the other three faces correspond to the N_2-C_3-C_{10}, N_2-C_1-C_{10} and N_2-C_1-C_3 ternary systems, respectively.

The addition of one component in going from a ternary to a quaternary system changes the system phase behavior characteristics. The quaternary system will have a bubble-point surface and a dew-point surface, rather than the bubble and dew-point curves previously described for ternary systems. Also, the critical point of a ternary system is replaced with a critical curve, and the limiting tie-line is replaced by a ruled surface. The ruled surface is generated by determining the particular quaternary limiting tie-line passing through each point of the critical point curve. Refer to Nouar et al. (1990a,b) for a representation of the phase behavior of quaternary systems.

The MMP for a nitrogen vaporizing-gas-drive was defined by Nouar et al. as the minimum pressure, at the prescribed temperature, at which the point representing the oil composition lies on the ruled surface generated by the quaternary limiting tie-lines. Most reservoir oils contain a negligible amount of nitrogen, so Nouar et al. restricted consideration to the intersection of the above ruled surface with the hydrocarbon face of the tetrahedron. The intersection of this ruled surface with the hydrocarbon face of the tetrahedron results in a curve which was referred to by Nouar et al. as the limiting curve. This curve was selected to separate oils that may be miscibly displaced by nitrogen through a multiple-contact process from those that may not. The MMP was taken as the pressure, at the prescribed temperature, at which the limiting curve passes through the point representing the oil composition.

Nouar et al. (1990b) determined limiting curves at various pressures (17.5 MPa to 70.0 MPa) and temperatures (30, 60, and 90°C). The limiting curves generated were correlated in terms of the mole fraction of the reservoir light (C_1) and intermediate (C_2-C_6) components, and the corresponding molecular weights of these component groups. A computer program (published by Nouar et al., 1990b) utilizing the results of this correlation was designed to calculate the MMP of a nitrogen VGD of a multicomponent oil. The program requires the reservoir temperature, oil compositional data in terms of the mole fraction of the light fractions (C_1 and N_2), intermediate fractions (C_2-C_6, CO_2, and H_2S), and heavy-ends (C_{7+}), as well as the apparent molecular weight of the intermediate and heavy fractions.

For a particular multicomponent system at one of the temperatures studied by Nouar et al., the program determines the quaternary systems which circumscribe the actual reservoir oil based on the molecular weight of the intermediate and heavy components. The MMP's of these circumscribing ternaries are then calculated. The MMP of the actual reservoir oil is determined by interpolating the circumscribing quaternary MMP's on the basis of the molecular weights of the intermediate and heavy components. If the temperature does not fall on one of the values studied by Nouar et al., the program will perform either a linear interpolation or extrapolation using suitable temperature values.

The Nouar et al. (1990b) correlation was developed over the following range of conditions: temperatures from 30 to 90°C; molecular weights of the reservoir oil intermediate (C_2-C_6) fraction from 44 to 58; and molecular weights of the oil heavy (C_{7+}) fraction from 170 to 198.

A.2 Empirical Hydrocarbon and Nitrogen Correlations

A.2.1 Blackwell Correlation

Blackwell produced an empirical correlation intended for estimating the MMP of lean hydrocarbon VGD's. The correlation was first published by Stalkup (1983), and was derived from experimental MMP measurements for nine oils. Blackwell found that correlating parameters which represented the reservoir oil composition, the reservoir oil saturation pressure, and the reduced temperature of the reservoir fluid could be used to predict the MMP of a lean hydrocarbon VGD. The Blackwell correlation was given as:

$$MMP = \frac{P_s(X+4.09068)}{(2.252354*X)}$$

where:

$$X = \frac{W_i * W_1 * T_r^{1/3}}{W_{7+}}$$

and:

MMP = KPa
P_s = oil saturation pressure at reservoir temperature, kPa
W_1 = kg C_1+N_2 per kg-mole oil
W_i = kg $C_2-C_6+CO_2+H_2S$ per kg-mole oil
W_{7+} = kg C_{7+} per kg-mole oil
T_r = reduced temperature of reservoir oil
= T/T_{pc}
T = reservoir temperature, K
T_{pc} = pseudocritical temperature of the reservoir oil, K

Blackwell's correlation does not differentiate between different lean hydrocarbon injection gases, but rather, treats all lean-gases as if they will have identical effects on a reservoir oil. The Blackwell correlation was developed over the following range of conditions: temperatures from 60 to 129°C; pressures from 22.4 to 32.8 MPa; saturation pressures from 4.1 to 27.8 MPa; and molecular weights of the oil heavy (C_{7+}) fraction from 149 to 216.

A.2.2 Glasø Lean and Rich-Gas Correlation

The graphical correlation that was developed by Benham et al. (1960) for predicting the minimum enrichment of an injected gas necessary to initiate a multiple-contact miscible displacement for condensing-gas-drives was put into equation form by Glaso (1985). The correlation was a result of curve fitting Benham et al. data, and the absolute deviation of the fit was stated as being generally less than one percent.

While using the curve fit equations to predict MMP's of published gas/oil systems, Glasø found that oil paraffinicity (k-factor) has an effect on MMP values. The five oils used by Benham et al. had a k-factor of 11.95. In order improve the deviation between calculated and measured MMP's, Glasø found it necessary to correct an oil's C_{7+} molecular weight to a k-factor of 11.95, thereby accounting for varying paraffinicity. Oil with a K-factor less than 11.95 represents oil with a relatively high content of aromatic compounds and has correspondingly higher MMP's. In order to correct the molecular weight of the oil according to the method proposed, the specific gravity of the C_{7+} stock-tank-oil is required. The equation for calculating the K-factor reported by Whitson (1983) was selected by Glasø.

The original correlation published by Benham et al. (1960) was intended specifically for condensing-gas-drives. Glasø (1985) extended this method to the case of vaporizing-gas-drives, and presented numerical equations with slightly different variables than those proposed in the original graphical correlation. The following series of equations were presented by Glasø:

$$
\begin{aligned}
MMP_{MW^{C2\text{-}C6}=34} = {} & 43636.9-175.196\,(MW_{C7+}) \\
& -[322.296-1.276\,(MW_{C7+})]\,y_{C1} \\
& +[7.770*10^{-12}\,(y_{C1})^{5.258}e^{319.8\,(y_{C1})\,(MW_{C7+})^{-1.703}}] \\
& *(1.8T+32)
\end{aligned}
\tag{10}
$$

$$
\begin{aligned}
MMP_{MW^{C2\text{-}C6}=44} = {} & 37941.8-132.641\,(MW_{C7+}) \\
& -[577.876-1.882\,(MW_{C7+})]\,y_{C1} \\
& +[11.721*10^{-9}\,(MW_{C7+})^{3.730}e^{13.567\,(y_{C1})\,(MW_{C7+})^{-1.058}}] \\
& *(1.8T+32)
\end{aligned}
\tag{11}
$$

$$
\begin{aligned}
MMP_{MW^{C2\text{-}C6}=54} = {} & 51276.3-177.216\,(MW_{C7+}) \\
& -[506.868-1.475\,(MW_{C7+})]\,y_{C1} \\
& +(33.922*10^{-14}\,(MW_{C7+})^{5.520}e^{21.706\,(y_{C1})\,(MW_{C7+})^{-1.109}}] \\
& *(1.8T+32)
\end{aligned}
\tag{12}
$$

where:

MMP = KPa

$MW^{C2\text{-}C6}$ = molecular weight of C_2 through C_6 in injection gas, kg/kmol

MW_{C7+} = corrected molecular weight of C_{7+} in the stock-tank-oil

= $[2.622/(S.G._{C7+\ oil})]^{6.588}$

$S.G._{C7+}$ = specific gravity of stock-tank-oil.

y_{C1} = methane in injection gas, mol%

T = temperature, °C

Prediction of the MMP by use of injection gases with molecular weight of the C_2 through C_6 other than the values (34, 44, and 54) given in the above equations is obtained by interpolation. For injection gases with molecular weights of the C_2 through C_6 equivalent to 100% ethane ($MW^{C2\text{-}C6} = 30$), Glasø indicated that an additional 1388 KPa should be added to the predicted MMP from equation 10 (for $MW^{C2\text{-}C6} = 34$).

The mol% C_1 represented in equations 10 through 12 is related to the mechanism of miscible displacement considered. In vaporizing-gas-drives, the minimum required mol% of C_2 through C_6 in the injection gas for multiple-contact miscibility is assumed to equal that existing at the critical composition. This corresponds to a limiting tie-line parallel to the C_1-C_{7+} line in the ternary diagram (using C_1, C_2-C_6, and C_{7+} pseudocomponents) that intersects the reservoir fluid composition. In condensing-gas-drive miscibility, the mol% methane in the injection gas is equal to the amount actually present in the injection gas.

To estimate the mechanism of miscibility for the purpose of using the correlation, the actual reservoir fluid and injection gas composition are plotted on a ternary diagram. A line parallel to the C_1 through C_{7+} line is drawn from the reservoir fluid composition. If the composition of the gas lies on the left of this line, the process is considered a vaporizing-gas-drive. Otherwise, a condensing process is assumed.

During this study's verification of Glasø's correlation, it was found that to get MMP predictions to match results published in Glasø's (1985) work, two of the equations had to be modified (typographic errors). Equation 10 was originally published in the Appendix of Glasø's paper (as equation 1) using an exponent of (-1.073), while the correct value was determined to be (-1.703). Also, the Whitson (1983) equation presented by Glasø for correcting the molecular weight of the C_{7+} fraction to a k-factor of 11.95 was incorrectly published in Glasø's work. The exponent (6.588) was omitted in the Appendix of the mentioned work. The same basic range of conditions that were applicable to the original Benham et al. correlation likely can be assumed to be applicable to Glasø's extension.

A.2.3 Firoozabadi and Aziz Correlation

Firoozabadi and Aziz (1986) generated an empirical correlation for estimating the minimum miscibility pressure of nitrogen or lean hydrocarbon vaporizing-gas-drives. The authors used MMP information available in the literature on eight reservoir fluids, and experimentally measured MMP's of four other reservoir fluids. Eleven lean-gas and two nitrogen injection systems were used to develop the correlation, in combination with some PR-EOS simulation data.

Similar to Blackwell's correlation, the authors found that three parameters seem to affect the multiple-contact miscibility of a reservoir fluid with nitrogen or lean-gas: the amount of intermediates, the volatility, and the reservoir temperature. Firoozabadi and Aziz (1986) chose to represent the intermediates in the reservoir fluid by the C_2 through C_5, CO_2, and H_2S fraction. The volatility of the oil is accounted for by the molecular weight of the C_{7+} components of the oil.

The Firoozabadi and Aziz correlation was published as follows:

$$MMP = [9433-188*10^3X+1430*10^3X^2]*6.894757$$

where:

$$X = \frac{(\%C_2-C_5)}{(MW_{C7+})(1.8T+32)^{0.25}}$$

and:

MMP = KPa

$\%C_2$-C_5 = mol% of intermediate fraction C_2 through C_5, CO_2, and H_2S in the reservoir oil

MW_{C7+} = molecular weight of heavy fraction (C_{7+}) in the reservoir oil

T = temperature, °C

As with Blackwell's correlation, the Firoozabadi and Aziz correlation does not take into account any variance in the composition of the injected gas, but specifies that it is applicable to "lean" or nitrogen gases only.

The Firoozabadi and Aziz correlation was developed over the following range of conditions: Temperatures from 60 to 171°C; pressures from 23.4 to 43.4 MPa; and molecular weights of the oil heavy (C_{7+}) fraction from 183 to 250.

A.2.4 Glasø Nitrogen Correlation (1985)

Glasø (1985) generated a correlation for estimating the MMP's of nitrogen gas drives. At normal reservoir temperatures and for light reservoir fluids, Glasø noted that the MMP of nitrogen/oil mixtures tends to decrease with increasing temperature because the solubility of nitrogen in oil increases with temperature. Also, the MMP increases with increasing temperature for relatively heavy oils, but the effect of temperature on the MMP is less pronounced than with light oils. Glasø related this temperature effect on the MMP of N_2/oil mixtures to the API gravity of the oil.

Nine MMP data points based on slim-tube displacement tests were used to develop the correlation for nitrogen gas drives. The equations are based on the $MW^{C2-C6}=34$ equation Glasø generated for hydrocarbon gas/oil systems (equation 10), with an equivalent 72 mol% methane/28 mol% ethane mixture. Recall that equation 10 was generated by a curve fit of Benham et al.'s (1960) correlation. The effect of temperature (T) on the MMP for oil with a C_{7+} fraction molecular weight (MW_{C7+}) greater than 160 or less than 160 was correlated by Glasø as follows:

$$\Delta MMP_{MW_{C7+}>160} = [3400.0-20.80(1.8T+32)]*6.894757 \qquad \textbf{(13)}$$

$$\Delta MMP_{MW_{C7+}<160} = [4731.5-39.77(1.8T+32)]*6.894757 \qquad \textbf{(14)}$$

where T represents reservoir temperature in °C, and ΔMMP represents (in KPa) the difference in the nitrogen/oil miscibility pressure from that of a lean hydrocarbon gas/oil system at a specific temperature.

Using equation 10 developed by Glasø for hydrocarbon gas/oil MMP prediction with y_{C1} = 72, combined with equations 13 and 14 resulted in the following:

$$\begin{aligned} MMP_{MW_{C7+}>160} = {} & 43878.2-83.358 MW_{C7+} \\ & +(7.77*10^{-12}*MW_{C7+}^{5.258} e^{23025 MW_{C7+}^{-1.703}}-143.41) \\ & *(1.8T+32) \end{aligned} \tag{15}$$

$$\begin{aligned} MMP_{MW_{C7+}<160} = {} & 53055.2-83.358 MW_{C7+} \\ & +(7.77*10^{-12} MW_{C7+}^{5.258} e^{23025 MW_{C7+}^{-1.703}}-274.20) \\ & *(1.8T+32) \end{aligned} \tag{16}$$

From fluid properties and displacement test data used in the development of the N_2 correlation, Glasø found that no effect on MMP was evident if the amount of reservoir fluid intermediates (C_2-C_6) exceeded 28 mol%. Equations 15 and 16 are appropriate for predicting the N_2 MMP in such cases. Equation 17 was developed for reservoir oil with intermediates less than 28 mol%:

$$\begin{aligned} MMP_{\%C_2-C_6<28\%} = {} & 64562-83.358*MW_{C7+} \\ & +(7.77*10^{-12} MW_{C7+}^{5.258} e^{23025 MW_{C7+}^{-1.703}}-143.41) \\ & *(1.8T+32)-684.65(\%C_2-C_6) \end{aligned} \tag{17}$$

where

$\%C_2$-C_6 = mol% C_2-C_6 in the reservoir fluid

No range of conditions over which the correlation is appropriate were stated.

A.2.5 Glasø Correlation (1988)

Glasø (1988) published an empirically based N_2 MMP correlation based on literature MMP data and slim-tube tests performed on reservoir fluid and three-component hydrocarbon mixtures. Four reservoir fluids and three pure three-component systems were studied, along with 9 other MMP's listed in the literature.

The correlation parameters selected by Glasø (1988) were the reservoir temperature, and the amount of methane and intermediates in the reservoir fluid. The effect of the correlation parameters on MMP was related to the API gravity of the oil. For oil with API gravity less than 45, or greater than 45, the following MMP correlation equations were proposed by Glasø:

$$MMP_{API<45} = [725.0-3.85(\%C_1)-9.22(\%C_2-C_6)+0.63(T)]*100$$

$$MMP_{API>45} = [873.8-9.17(\%C_1)-1.71(\%C_2-C_6)+1.25(T)]*100$$

where:

MMP = KPa
$\%C_1$ = mol% C_1 in the reservoir fluid
$\%C_2-C_6$ = mol% C_2 through C_6 in the reservoir fluid
T = temperature, °C

The Glasø (1988) nitrogen correlation was developed over the following range of conditions: pressures from 25.0 to 61.7 MPa; temperatures from 60 to 137°C; and molecular weights of the oil heavy C_{7+} fraction from 140 to 232.

A.2.6 Eakin and Kitch Correlation

Eakin and Mitch (1988) generated an empirical correlation for measuring the miscibility pressures for N_2, CO_2, H_2S, lean hydrocarbon, and enriched hydrocarbon gas drives. Two recombined samples of reservoir fluid (a light gravity oil and a medium gravity oil), were used in developing the correlation. Five gases were selected as solvents and tested with and without enhancers added. These base solvents were nitrogen, flue gas, carbon dioxide, a rich natural gas and a lean natural gas. Four other solvents were tested without addition of enhancers. These were methane, hydrogen sulphide, and two multicomponent mixtures. Three liquid enhancers were selected to add to the base solvents to determine their effectiveness in reducing the MMP. These enhancers were a natural gas liquid, an ethane-rich refinery gas, and hydrogen sulphide. A total of 105 MMP were measured using the RBA.

Eakin and Mitch found that the data could be represented by the following equation which needs only the solvent composition, oil C_{7+} fraction molecular weight, and the solvent pseudoreduced temperature:

$$\begin{aligned}\ln\left(\frac{MMP}{P_c}\right) = {} & (0.1697-0.06912/T_r)\,y_{C1}(MW_{C7+})^{1/2} \\ & +[2.3865-0.005955(MW_{C7+})/T_r]\,y_{C2+} \\ & +(0.1776-0.01023/T_r)\,y_{N2}(MW_{C7+})^{1/2} \\ & +[0.01221(MW_{C7+})-0.00058(MW_{C7+})^{3/2}/T_r]\,y_{CO2} \\ & +[101.429/(MW_{C7+})+0.003750(MW_{C7+})/T_r]\,y_{H2S}\end{aligned}$$

where:

MMP = KPa

P_c = solvent pseudocritical pressure, KPa

T_r = solvent pseudoreduced temperature

= T/T_c

T = reservoir temperature, K

T_c = solvent pseudocritical temperature, K

MW_{C7+} = molecular weight of the C_{7+} fractions in the reservoir fluid

y_{C1} = mole fraction of C_1 in the solvent

y_{C2+} = mole fraction of C_{2+} in the solvent

y_{N2} = mole fraction of N_2 in the solvent

y_{CO2} = mole fraction of CO_2 in the solvent

y_{H2S} = mole fraction of H_2S in the solvent

The Eakin and Mitch correlation was developed over the following range of conditions: pressures from 6.8 to 41.5 MPa; temperatures from 82 to 116°C; and molecular weights of the oil heavy (C_{7+}) fraction from 216 to 231.

A.2.7 Hudgins, Llave, and Chung Correlation

Hudgins, Llave and Chung (1988) used experimental and literature MMP data to correlate variables found to affect N_2 MMP's. Slim-tube displacement tests were conducted using three live oils that were recombined from a stock-tank-oil. A total of 14 MMP's were used to develop the correlation.

The MMP for nitrogen displacement was found to be a weak function of temperature, increasing only slightly with increasing temperature. The concentration of methane and the C_2 through C_5 components in the reservoir fluid were found to be significant factors in determining the miscibility pressure of nitrogen floods. The following empirical correlation was presented by Hudgins, Llave and Chung (1988):

$$MMP = 5568\,e^{-R_1} + 3641\,e^{-R_2}$$

where:

$$R_1 = \frac{792.06\,(C_2 - C_5)}{(MW_{C7+})\,(1.8\,T + 32)^{0.25}}$$

and

$$R_2 = \frac{2.158 * 10^6\,(C_1)^{5.632}}{(MW_{C7+})\,(1.8\,T + 32)^{0.25}}$$

The units are MMP in KPa, T in °C; C_1 is the mole fraction of methane in the reservoir oil, and C_2-C_5 is the mole fraction of ethane through pentane (including CO_2 and H_2S) in the oil. The Hudgins, Llave and Chung correlation was developed over the following range of conditions: pressures from 25.2 to 64.8 MPa; temperatures from 60 to 149°C; and molecular weights of the oil heavy (C_{7+}) from 140 to 195.

Appendix B

MMP Data Set

Every experimentally measured MMP which was found during the literature review, and for which sufficient gas and oil compositional information (required for correlation calculations) was published, is summarized in Table B-1. For each of these 176 MMP's, the gas and oil compositions are listed in terms of the mol% of CO_2, N_2, C_1, C_2, C_3, C_4, C_5, C_6, and C_{7+} fractions. The mol% of H_2S in the injection gas is also presented. Only three of the 176 systems contained any H_2S in the oil, and H_2S was lumped with CO_2 in these cases for presentation in Table B-1. The molecular weight of the oil C_{7+} fraction (MW_{C7+}), the MMP experimental measurement method, and the data reference source are also listed for each system.

In situations where literature compositional analysis included $i\text{-}C_3/n\text{-}C_3$ and $i\text{-}C_4/n\text{-}C_4$ fractions, they were combined into C_3 and C_4 fractions respectively for presentation in Table B-1. Also, if literature compositional analysis extended beyond the C_7 hydrocarbons, these fractions were lumped into a single C_{7+} fraction in Table B-1. For systems 16 through 25, complete gas compositional data was not published. Summarized information (sufficient for use in all but one of the relevant correlations) was given, and is listed for each of these systems.

If an experimental MMP measurement was made using the slim-tube, the MMP criteria was indicated as being based on the recovery vs pressure profile of a series of displacements (recovery usually at 1.2 PV of gas injected), or as a specific recovery level (i.e. 90% or 95%) at some gas injection level (usually 1.2 PV of gas injected). Unfortunately, a large number of slim-tube studies did not indicate the specific criteria used to measure the MMP. The MMP criteria was indicated as N/A (not available) in these cases.

Table B-2 summarizes the input parameters required for each of the correlations, as well as the systems (if any) listed in Table B-1 which were used in developing each correlation.

TABLE B-1: MMP DATA SET

| SYSTEM
#
Oil Compositional Data (mol%) CO2	N2	C1	C2	C3	C4	C5	C6	C7+	MWC7+
1	0.91	0.00	20.58	6.51	4.18	4.89	4.93	3.07	54.93	243
2	5.36	0.45	26.96	6.21	4.87	4.26	3.88	3.50	44.51	242
3	5.36	0.45	26.96	6.21	4.87	4.26	3.88	3.50	44.51	242
4	0.00	0.00	15.77	1.54	2.20	4.79	4.36	4.73	66.61	263
5	0.06	0.17	41.79	0.75	0.30	0.32	0.04	0.00	56.57	302
6	0.06	0.17	41.79	0.75	0.30	0.32	0.04	0.00	56.57	302
7	0.06	0.17	41.79	0.75	0.30	0.32	0.04	0.00	56.57	302
8	0.39	0.13	32.52	5.53	4.25	3.76	3.67	5.97	43.78	215
9	0.39	0.13	32.52	5.53	4.25	3.76	3.67	5.97	43.78	215
10	6.75	0.36	24.22	9.39	6.35	5.52	3.69	2.66	41.06	248
11	0.40	0.20	27.52	2.32	2.45	3.02	2.92	6.88	54.29	139
12	0.47	0.37	32.04	8.36	10.05	6.61	3.30	3.65	35.15	173
13	0.47	0.37	32.04	8.36	10.05	6.61	3.30	3.65	35.15	173
14	0.31	0.51	35.74	10.20	7.36	5.28	3.06	4.11	33.43	187
15	0.00	1.75	34.25	10.68	9.77	5.91	5.62	2.58	29.44	207
16	0.82	0.98	29.49	8.66	4.43	4.43	3.79	3.48	43.92	170
17	0.82	0.98	29.49	8.66	4.43	4.43	3.79	3.48	43.92	170
18	0.13	0.37	8.83	4.68	3.34	3.82	3.33	5.52	69.98	173
19	0.13	0.37	8.83	4.68	3.34	3.82	3.33	5.52	69.98	173
20	1.37	1.28	47.97	11.59	7.35	4.34	2.26	1.90	21.94	177
21	1.37	1.28	47.97	11.59	7.35	4.34	2.26	1.90	21.94	177
22	0.76	1.82	23.68	8.16	7.73	6.03	3.63	3.74	44.45	186
23	1.34	3.13	35.05	7.10	6.55	4.87	3.07	1.87	37.02	201
24	1.34	3.13	35.05	7.10	6.55	4.87	3.07	1.87	37.02	201
25	0.04	0.05	24.86	5.05	3.30	2.11	1.50	2.05	61.04	261
26	0.04	0.05	24.86	5.05	3.30	2.11	1.50	2.05	61.04	261
27	3.60	0.25	56.86	9.37	5.48	4.07	2.59	1.26	16.59	184
28	0.32	0.58	54.50	8.09	5.82	2.95	2.59	2.39	22.76	209
29	0.00	0.00	50.39	8.82	5.91	4.17	2.23	1.36	27.12	250
30	1.34	0.46	49.01	7.04	4.93	3.47	2.68	3.34	27.73	250
31	0.49	0.47	42.01	6.05	2.93	1.60	1.00	0.92	44.53	196
32	0.36	0.92	40.60	5.22	3.31	2.57	2.17	1.92	42.93	215
33	0.44	0.18	43.92	10.71	8.81	5.29	3.19	2.55	24.91	231
34	0.32	0.92	41.25	8.68	7.27	4.90	2.89	4.29	29.48	193
35	0.37	0.98	41.79	8.87	7.11	5.22	2.88	4.30	28.48	204
36	0.38	0.69	59.41	8.15	4.99	3.71	1.97	3.17	17.53	191
37	1.19	0.51	45.21	7.09	4.61	4.50	3.56	4.42	28.91	190
38	0.00	0.00	42.70	12.50	10.20	6.20	3.80	3.30	21.30	191
39	0.00	0.80	13.00	13.20	13.30	8.40	6.10	4.50	40.70	197
40	1.34	2.12	32.73	13.09	11.34	7.58	3.55	2.10	26.15	195
41	0.00	0.00	42.70	12.50	10.20	6.20	3.80	3.30	21.30	191
42	0.24	0.25	40.91	10.38	9.01	5.13	3.28	2.21	28.58	183
43	0.00	0.00	53.16	9.06	7.66	4.23	2.48	2.41	21.00	217
44	0.00	0.00	30.00	0.00	35.00	0.00	0.00	0.00	35.00	142
45	0.49	0.47	54.67	8.75	4.87	2.97	2.04	2.23	23.52	232

*Systems 2,3 & 10 include 1.69, 1.69, and 1.26 mol% H2S respectively (included with CO2)

TABLE B-1, cont'd

SYSTEM #	H2S	CO2	N2	C1	C2	C3	C4	C5	C6	C7+
	Gas Compositional Data (mol%)									
1	0.00	0.06	0.92	31.93	[illegible].65	30.12	0.32	0.00	0.00	0.00
2	0.00	0.00	0.00	58.00	0.00	42.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	68.00	0.00	32.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	35.00	0.00	65.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	65.00	0.00	35.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	62.40	0.00	37.60	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	54.30	0.00	45.70	0.00	0.00	0.00	0.00
8	0.00	0.45	0.26	52.88	19.43	13.11	7.70	3.17	3.00	0.00
9	0.00	0.45	0.26	52.88	19.43	13.11	7.70	3.17	3.00	0.00
10	1.20	11.70	0.00	43.00	18.00	16.10	6.20	3.80	0.00	0.00
11	0.00	0.00	0.00	50.50	0.00	49.50	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	59.00	0.00	41.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	60.50	0.00	39.50	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	63.50	0.00	36.50	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	54.50	0.00	45.50	0.00	0.00	0.00	0.00
16	C1=68.5%, and MWI = 38.7-39.8									
17	C1=82.0%, and MWI = 39.8									
18	C1=71.0%, and MWI = 41.9-42.6									
19	C1=81.5%, and MWI = 39.9-41.4									
20	C1=64.5%, and MWI = 35.2-36.9									
21	C1=69.5%, and MWI = 35.2-36.9									
22	C1=51.5%, and MWI = 42.0-43.1									
23	C1=54.5%, and MWI = 40.0-41.6									
24	C1=62.0%, and MWI = 40.0-41.6									
25	C1=39.0%, and MWI = 43.5									
26	C1=50.0%, and MWI = 43.5									
27	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
28	0.00	1.05	0.00	83.21	8.81	4.11	1.40	0.00	0.00	0.00
29	0.00	2.48	0.00	87.83	7.50	1.91	0.26	0.00	0.00	0.00
30	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
31	0.00	0.76	0.50	72.04	12.41	8.60	3.74	1.23	0.35	0.37
32	0.00	1.35	1.40	82.17	8.42	4.53	1.44	0.37	0.16	0.16
33	0.00	0.76	0.29	73.05	13.95	8.17	2.66	0.62	0.24	0.26
34	0.00	0.52	1.02	85.61	8.41	3.60	0.71	0.10	0.02	0.01
35	0.00	0.52	1.02	85.61	8.41	3.60	0.71	0.10	0.02	0.01
36	0.00	0.52	1.02	85.61	8.41	3.60	0.71	0.10	0.02	0.01
37	0.00	1.89	3.53	88.20	3.09	1.66	1.13	0.39	0.08	0.03
38	0.00	0.00	0.00	85.00	15.00	0.00	0.00	0.00	0.00	0.00
39	0.00	0.00	0.00	85.00	15.00	0.00	0.00	0.00	0.00	0.00
40	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
41	0.00	0.00	15.00	72.25	12.75	0.00	0.00	0.00	0.00	0.00
42	0.00	0.63	0.61	68.48	14.71	10.45	3.59	0.90	0.29	0.34
43	0.00	0.00	0.00	87.00	13.00	0.00	0.00	0.00	0.00	0.00
44	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
45	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

TABLE B-1, cont'd

SYSTEM #	TEMP. (C)	MMP (MPa)	MEASUREMENT METHOD	CRITERIA USED (IF SLIM TUBE DATA)	REFERENCE
1	40.6	13.79	PVT		Shelton et al. (1977)
2	86.7	17.24	ST	Recovery Profile	Jacobson (1972)
3	86.7	17.24	ST	Recovery Profile	Jacobson (1972)
4	78.3	10.34	PVT		Benham et al. (1960)
5	55.6	26.65	ST	Recovery Profile	Kuo (1985)
6	55.6	25.07	ST	Recovery Profile	Kuo (1985)
7	55.6	18.86	ST	Recovery Profile	Kuo (1985)
8	76.7	16.45	ST	Recovery Profile	Kuo (1985)
9	96.7	18.38	ST	Recovery Profile	Kuo (1985)
10	104.4	13.69	ST	N/A	Welge et al. (1961)
11	98.9	11.10	ST	N/A	Yarborough et al. (1970)
12	60.0	11.14	ST	N/A	Yarborough et al. (1970)
13	60.0	15.27	ST	N/A	Yarborough et al. (1970)
14	93.3	20.51	ST	N/A	Yarborough et al. (1970)
15	71.1	12.86	ST	N/A	Yarborough et al. (1970)
16	108.3	27.58	ST	N/A	Yarborough et al. (1970)
17	108.3	31.03	ST	N/A	Yarborough et al. (1970)
18	110.0	27.58	ST	N/A	Yarborough et al. (1970)
19	110.0	33.78	ST	N/A	Yarborough et al. (1970)
20	111.7	26.55	ST	N/A	Yarborough et al. (1970)
21	111.7	28.96	ST	N/A	Yarborough et al. (1970)
22	108.3	16.31	ST	N/A	Yarborough et al. (1970)
23	62.2	11.51	ST	N/A	Yarborough et al. (1970)
24	62.2	14.82	ST	N/A	Yarborough et al. (1970)
25	73.9	10.72	ST	N/A	Yarborough et al. (1970)
26	73.9	15.00	ST	N/A	Yarborough et al. (1970)
27	171.1	33.10	ST	N/A	Firoozabadi et al. (1986)
28	93.3	39.99	ST	N/A	Firoozabadi et al. (1986)
29	107.2	41.37	ST	N/A	Firoozabadi et al. (1986)
30	150.6	43.44	ST	N/A	Firoozabadi et al. (1986)
31	91.7	39.99	ST	95% Recovery	Glaso (1985)
32	78.9	47.23	ST	95% Recovery	Glaso (1985)
33	98.9	35.16	ST	95% Recovery	Glaso (1985)
34	103.0	33.80	ST	N/A	Lee et al. (1982)
35	102.0	35.00	ST	N/A	Lee et al. (1982)
36	106.0	37.90	ST	N/A	Lee et al. (1982)
37	125.0	37.13	ST	95% Recovery	Meltzer et al. (1965)
38	60.0	24.13	ST	Recovery Profile	Koch et al. (1958)
39	80.0	23.34	ST	Recovery Profile	Koch et al. (1958)
40	121.1	25.92	ST	N/A	*Deffrenne et al. (1961)
41	60.0	25.51	ST	Recovery Profile	Koch et al. (1958)
42	54.4	23.44	ST	90% Recovery	Williams et al. (1980)
43	60.0	24.03	ST	Recovery Profile	Hutchinson et al. (1961)
44	60.0	22.10	ST	Recovery Profile	Nouar (1987)
45	60.0	38.00	ST	Recovery Profile	Glaso (1988)

* including Dorsey et al. (1975) & Giraud et al. (1971) data

TABLE B-1, cont'd

SYSTEM #	CO2	N2	C1	C2	C3	C4	C5	C6	C7+	MWC7+
	Oil Compositional Data (mol%)									
46	0.49	0.47	54.67	8.75	4.87	2.97	2.04	2.23	23.52	232
47	0.31	0.31	36.22	5.95	3.50	2.98	3.20	3.95	43.59	232
48	0.31	0.31	36.22	5.95	3.50	2.98	3.20	3.95	43.59	232
49	0.12	0.55	42.96	3.93	18.35	3.61	3.10	3.17	24.25	222
50	0.00	0.00	49.90	0.00	27.20	0.00	0.00	0.00	22.90	142
51	0.00	0.00	49.90	0.00	27.20	0.00	0.00	0.00	22.90	142
52	0.00	0.00	40.00	0.00	26.60	0.00	0.00	0.00	33.00	142
53	0.00	0.00	32.90	0.00	25.20	0.00	0.00	0.00	41.90	142
54	0.00	0.00	0.00	0.00	0.00	0.05	2.42	9.24	88.29	140
55	0.00	0.00	9.37	0.79	0.52	0.21	2.21	8.23	78.68	140
56	0.00	0.00	9.37	0.79	0.52	0.21	2.21	8.23	78.68	140
57	0.00	0.00	9.37	0.79	0.52	0.21	2.21	8.23	78.68	140
58	0.00	0.00	22.69	1.90	1.26	0.43	1.91	6.80	65.01	140
59	0.00	0.00	22.69	1.90	1.26	0.43	1.91	6.80	65.01	140
60	0.00	0.00	22.69	1.90	1.26	0.43	1.91	6.80	65.01	140
61	0.00	0.00	38.62	3.24	2.14	0.69	1.56	5.09	48.66	140
62	0.00	0.00	38.62	3.24	2.14	0.69	1.56	5.09	48.66	140
63	0.00	0.00	38.62	3.24	2.14	0.69	1.56	5.09	48.66	140
64	0.40	1.02	54.62	11.47	7.33	4.01	1.96	1.42	17.77	193
65	1.34	2.12	32.73	13.09	11.34	7.58	3.55	2.10	26.15	195
66	0.00	0.00	42.70	12.50	10.20	6.20	3.80	3.30	21.30	191
67	0.00	0.80	13.00	13.20	13.30	8.40	6.10	4.50	40.70	197
68	0.00	0.00	30.00	0.00	35.00	0.00	0.00	0.00	35.00	142
69	0.00	0.00	30.00	0.00	35.00	0.00	0.00	0.00	35.00	142
70	0.00	0.00	24.04	0.00	51.10	0.00	0.00	0.00	24.86	142
71	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
72	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
73	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
74	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
75	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
76	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
77	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
78	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
79	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
80	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
81	0.00	0.00	42.70	12.50	10.20	6.20	3.80	3.30	21.30	191
82	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
83	6.66	0.01	32.98	23.16	8.39	[illegible]	3.10	1.88	19.59	216
84	6.66	0.01	32.98	23.16	8.39	[illegible]	3.10	1.88	19.59	216
85	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
86	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
87	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
88	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
89	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
90	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216

TABLE B-1, cont'd

SYSTEM #	Gas Compositional Data (mol%) H2S	CO2	N2	C1	C2	C3	C4	C5	C6	C7+
46	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
47	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
48	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
49	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
51	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
52	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
53	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
54	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
55	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
56	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
57	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
58	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
59	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
60	0.00	[illegible]	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
61	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
62	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
63	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
64	0.00	[illegible]	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
65	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
66	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
67	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
68	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
69	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
70	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
71	0.00	0.00	75.00	0.00	6.00	16.25	2.75	0.00	0.00	0.00
72	0.00	0.00	75.00	0.00	6.00	16.25	2.75	0.00	0.00	0.00
73	0.00	2.96	75.00	0.00	10.36	6.66	3.33	1.33	0.34	0.03
74	0.00	2.96	75.00	0.00	10.36	6.66	3.33	1.33	0.34	0.03
75	0.00	8.25	66.75	0.00	6.00	16.25	2.75	0.00	0.00	0.00
76	0.00	8.25	66.75	0.00	6.00	16.25	2.75	0.00	0.00	0.00
77	0.00	11.08	80.10	0.00	4.14	2.66	1.33	0.53	0.14	0.01
78	0.00	11.08	80.10	0.00	4.14	2.66	1.33	0.53	0.14	0.01
79	0.00	11.21	66.75	0.00	10.36	6.66	3.33	1.33	0.34	0.03
80	0.00	11.21	66.75	0.00	10.36	6.66	3.33	1.33	0.34	0.03
81	0.00	0.00	66.00	28.90	5.10	0.00	0.00	0.00	0.00	0.00
82	0.00	4.70	0.40	72.50	18.20	3.20	0.80	0.20	0.00	0.00
83	0.00	4.70	0.40	72.50	18.20	3.20	0.80	0.20	0.00	0.00
84	0.00	4.23	0.36	65.25	18.78	9.38	1.82	0.18	0.00	0.00
85	0.00	4.23	0.36	65.25	18.78	9.38	1.82	0.18	0.00	0.00
86	0.00	3.53	0.30	54.38	19.65	18.65	3.35	0.15	0.00	0.00
87	0.00	3.53	0.30	54.38	19.65	18.65	3.35	0.15	0.00	0.00
88	0.00	5.41	0.36	65.25	20.52	5.54	2.05	0.71	0.14	0.01
89	0.00	5.41	0.36	65.25	20.52	5.54	2.05	0.71	0.14	0.01
90	0.00	6.48	0.30	54.38	24.01	9.06	3.93	1.48	0.34	0.03

TABLE B-1, cont'd

SYSTEM #	TEMP. (C)	MMP (MPa)	MEASUREMENT METHOD	CRITERIA USED (IF SLIM TUBE DATA)	REFERENCE
46	133.0	41.50	ST	Recovery Profile	Glaso (1988)
47	60.0	44.00	ST	Recovery Profile	Glaso (1988)
48	93.0	45.50	ST	Recovery Profile	Glaso (1988)
49	91.0	32.00	ST	Recovery Profile	Glaso (1988)
50	60.0	31.50	ST	Recovery Profile	Glaso (1988)
51	100.0	25.00	ST	Recovery Profile	Glaso (1988)
52	60.0	37.00	ST	Recovery Profile	Glaso (1988)
53	60.0	46.50	ST	Recovery Profile	Glaso (1988)
54	137.2	64.81	ST	Recovery Profile	Hudgins et al. (1988)
55	137.2	61.02	ST	Recovery Profile	Hudgins et al. (1988)
56	107.2	58.61	ST	Recovery Profile	Hudgins et al. (1988)
57	148.9	62.05	ST	Recovery Profile	Hudgins et al. (1988)
58	137.2	46.20	ST	Recovery Profile	Hudgins et al. (1988)
59	107.2	44.13	ST	Recovery Profile	Hudgins et al. (1988)
60	148.9	47.23	ST	Recovery Profile	Hudgins et al. (1988)
61	137.2	34.34	ST	Recovery Profile	Hudgins et al. (1988)
62	107.2	33.44	ST	Recovery Profile	Hudgins et al. (1988)
63	148.9	35.16	ST	Recovery Profile	Hudgins et al. (1988)
64	73.3	29.51	ST & PVT	90% Recovery	Peterson (1978)
65	121.1	25.92	ST	N/A	*Deffrenne et al. (1961)
66	60.0	26.68	ST	Recovery Profile	Koch et al. (1958)
67	80.0	29.65	ST	Recovery Profile	Koch et al. (1958)
68	60.0	31.34	ST	Recovery Profile	Nouar (1987)
69	70.0	29.80	ST	Recovery Profile	This Study (System A)
70	60.0	27.00	ST	Recovery Profile	This Study (System C)
71	82.2	40.09	RBA		Eakin et al. (1988)
72	115.6	41.47	RBA		Eakin et al. (1988)
73	82.2	41.47	RBA		Eakin et al. (1988)
74	115.6	41.47	RBA		Eakin et al. (1988)
75	82.2	34.58	RBA		Eakin et al. (1988)
76	115.6	35.61	RBA		Eakin et al. (1988)
77	82.2	40.44	RBA		Eakin et al. (1988)
78	115.6	40.78	RBA		Eakin et al. (1988)
79	82.2	36.65	RBA		Eakin et al. (1988)
80	115.6	38.54	RBA		Eakin et al. (1988)
81	60.0	25.72	ST	Recovery Profile	Koch et al. (1958)
82	82.2	27.50	RBA		Eakin et al. (1988)
83	115.6	30.14	RBA		Eakin et al. (1988)
84	82.2	24.75	RBA		Eakin et al. (1988)
85	115.6	26.58	RBA		Eakin et al. (1988)
86	82.2	22.17	RBA		Eakin et al. (1988)
87	115.6	23.89	RBA		Eakin et al. (1988)
88	82.2	25.79	RBA		Eakin et al. (1988)
89	115.6	27.25	RBA		Eakin et al. (1988)
90	82.2	22.68	RBA		Eakin et al. (1988)

* including Dorsey et al. (1975) & Giraud et al. (1971) data

TABLE B-1, cont'd

SYSTEM	Oil Compositional Data (mol%)									
#	CO2	N2	C1	C2	C3	C4	C5	C6	C7+	MWC7+
91	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
92	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
93	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
94	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
95	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
96	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
97	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
98	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
99	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
100	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
101	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
102	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
103	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
104	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
105	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
106	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
107	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
108	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
109	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
110	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
111	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
112	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
113	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
114	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
115	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
116	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
117	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
118	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
119	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
120	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
121	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
122	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
123	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
124	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
125	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
126	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
127	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
128	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
129	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
130	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
131	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
132	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
133	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
134	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
135	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281

SYSTEM #	Gas Compositional Data (mol%) H2S	CO2	N2	C1	C2	C3	C4	C5	C6	C7+
91	0.00	6.48	0.30	54.38	24.01	9.06	3.93	1.48	0.34	0.03
92	10.00	4.23	0.36	65.25	16.38	2.88	0.72	0.18	0.00	0.00
93	10.00	4.23	0.36	65.25	16.38	2.88	0.72	0.18	0.00	0.00
94	25.00	3.53	0.30	54.38	13.65	2.40	0.60	0.15	0.00	0.00
95	25.00	3.53	0.30	54.38	13.65	2.40	0.60	0.15	0.00	0.00
96	0.00	7.10	0.30	47.97	25.99	11.10	5.00	2.00	0.50	0.04
97	0.00	7.10	0.30	47.97	25.99	11.10	5.00	2.00	0.50	0.04
98	0.00	6.39	0.27	43.17	25.79	16.49	5.60	1.80	0.45	0.04
99	0.00	6.39	0.27	43.17	25.79	16.49	5.60	1.80	0.45	0.04
100	0.00	5.33	0.23	35.98	25.49	24.58	6.50	1.50	0.38	0.03
101	0.00	5.33	0.23	35.98	25.49	24.58	6.50	1.50	0.38	0.03
102	0.00	7.57	0.27	43.17	27.53	12.65	5.83	2.33	0.59	0.05
103	0.00	7.57	0.27	43.17	27.53	12.65	5.83	2.33	0.59	0.05
104	0.00	8.28	0.23	35.98	29.85	14.98	7.08	2.83	0.72	0.06
105	0.00	8.28	0.23	35.98	29.85	14.98	7.08	2.83	0.72	0.06
106	10.00	6.39	0.27	43.17	23.39	9.99	4.50	1.80	0.45	0.04
107	10.00	6.39	0.27	43.17	23.39	9.99	4.50	1.80	0.45	0.04
108	25.00	5.33	0.23	35.98	19.49	8.33	3.75	1.50	0.38	0.03
109	25.00	5.33	0.23	35.98	19.49	8.33	3.75	1.50	0.38	0.03
110	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
111	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
112	0.00	30.00	4.30	45.70	20.00	0.00	0.00	0.00	0.00	0.00
113	0.00	30.00	4.30	45.70	20.00	0.00	0.00	0.00	0.00	0.00
114	0.00	30.00	4.30	45.70	20.00	0.00	0.00	0.00	0.00	0.00
115	0.00	30.00	4.30	45.70	20.00	0.00	0.00	0.00	0.00	0.00
116	0.00	4.70	0.40	72.50	18.20	3.20	0.80	0.20	0.00	0.00
117	0.00	4.70	0.40	72.50	18.20	3.20	0.80	0.20	0.00	0.00
118	0.00	4.23	0.36	65.25	18.78	9.38	1.82	0.18	0.00	0.00
119	0.00	4.23	0.36	65.25	18.78	9.38	1.82	0.18	0.00	0.00
120	0.00	3.53	0.30	54.38	19.65	18.65	3.35	0.15	0.00	0.00
121	0.00	3.53	0.30	54.38	19.65	18.65	3.35	0.15	0.00	0.00
122	0.00	5.41	0.36	65.25	20.52	5.54	2.05	0.71	0.14	0.01
123	0.00	5.41	0.36	65.25	20.52	5.54	2.05	0.71	0.14	0.01
124	0.00	6.48	0.30	54.38	24.01	9.06	3.93	1.48	0.34	0.03
125	0.00	6.48	0.30	54.38	24.01	9.06	3.93	1.48	0.34	0.03
126	10.00	4.23	0.36	65.25	16.38	2.88	0.72	0.18	0.00	0.00
127	10.00	4.23	0.36	65.25	16.38	2.88	0.72	0.18	0.00	0.00
128	25.00	3.53	0.30	54.38	13.65	2.40	0.60	0.15	0.00	0.00
129	25.00	3.53	0.30	54.38	13.65	2.40	0.60	0.15	0.00	0.00
130	0.00	7.10	0.30	47.97	25.99	11.10	5.00	2.00	0.50	0.04
131	0.00	7.10	0.30	47.97	25.99	11.10	5.00	2.00	0.50	0.04
132	0.00	6.39	0.27	43.17	25.79	16.49	5.60	1.80	0.45	0.04
133	0.00	6.39	0.27	43.17	25.79	16.49	5.60	1.80	0.45	0.04
134	0.00	5.33	0.23	35.98	25.49	24.58	6.50	1.50	0.38	0.03
135	0.00	5.33	0.23	35.98	25.49	24.58	6.50	1.50	0.38	0.03

TABLE B-1, cont'd

SYSTEM #	TEMP. (C)	MMP (MPa)	MEASUREMENT METHOD	CRITERIA USED (IF SLIM TUBE DATA)	REFERENCE
91	115.6	24.79	RBA		Eakin et al. (1988)
92	82.2	25.44	RBA		Eakin et al. (1988)
93	115.6	29.44	RBA		Eakin et al. (1988)
94	82.2	25.55	RBA		Eakin et al. (1988)
95	115.6	27.81	RBA		Eakin et al. (1988)
96	82.2	22.17	RBA		Eakin et al. (1988)
97	115.6	23.97	RBA		Eakin et al. (1988)
98	82.2	22.68	RBA		Eakin et al. (1988)
99	115.6	24.66	RBA		Eakin et al. (1988)
100	82.2	20.62	RBA		Eakin et al. (1988)
101	115.6	21.48	RBA		Eakin et al. (1988)
102	82.2	21.65	RBA		Eakin et al. (1988)
103	115.6	23.46	RBA		Eakin et al. (1988)
104	82.2	20.00	RBA		Eakin et al. (1988)
105	115.6	22.51	RBA		Eakin et al. (1988)
106	82.2	23.20	RBA		Eakin et al. (1988)
107	115.6	24.24	RBA		Eakin et al. (1988)
108	82.2	23.41	RBA		Eakin et al. (1988)
109	115.6	24.61	RBA		Eakin et al. (1988)
110	82.2	28.51	RBA		Eakin et al. (1988)
111	115.6	32.13	RBA		Eakin et al. (1988)
112	82.2	27.51	RBA		Eakin et al. (1988)
113	115.6	30.61	RBA		Eakin et al. (1988)
114	84.4	34.37	RBA		Eakin et al. (1988)
115	115.6	35.87	RBA		Eakin et al. (1988)
116	82.2	32.79	RBA		Eakin et al. (1988)
117	115.6	35.87	RBA		Eakin et al. (1988)
118	82.2	30.44	RBA		Eakin et al. (1988)
119	115.6	32.16	RBA		Eakin et al. (1988)
120	82.2	27.23	RBA		Eakin et al. (1988)
121	115.6	28.72	RBA		Eakin et al. (1988)
122	82.2	31.34	RBA		Eakin et al. (1988)
123	115.6	33.12	RBA		Eakin et al. (1988)
124	82.2	26.48	RBA		Eakin et al. (1988)
125	115.6	28.03	RBA		Eakin et al. (1988)
126	82.2	30.44	RBA		Eakin et al. (1988)
127	115.6	33.37	RBA		Eakin et al. (1988)
128	82.2	26.92	RBA		Eakin et al. (1988)
129	115.6	30.23	RBA		Eakin et al. (1988)
130	82.2	21.13	RBA		Eakin et al. (1988)
131	115.6	24.06	RBA		Eakin et al. (1988)
132	82.2	20.62	RBA		Eakin et al. (1988)
133	115.6	23.37	RBA		Eakin et al. (1988)
134	82.2	17.51	RBA		Eakin et al. (1988)
135	115.6	19.69	RBA		Eakin et al. (1988)

TABLE B-1, cont'd

SYSTEM	Oil Compositional Data (mol%)									
#	CO2	N2	C1	C2	C3	C4	C5	C6	C7+	MWC7+
136	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
137	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
138	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
139	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
140	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
141	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
142	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
143	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
144	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
145	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
146	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
147	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
148	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
149	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
150	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
151	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
152	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
153	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
154	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
155	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
156	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
157	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
158	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
159	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
160	6.66	0.01	32.98	23.16	8.39	4.23	3.10	1.88	19.59	216
161	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
162	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
163	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
164	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
165	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
166	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
167	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
168	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
169	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
170	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
171	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
172	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
173	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
174	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
175	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281
176	1.41	0.39	6.35	7.43	7.13	4.62	4.24	2.67	65.76	281

TABLE B-1, cont'd

SYSTEM #	Gas Compositional Data (mol%) H2S	CO2	N2	C1	C2	C3	C4	C5	C6	C7+
136	0.00	7.57	0.27	43.17	27.53	12.65	5.83	2.33	0.59	0.05
137	0.00	7.57	0.27	43.17	27.53	12.65	5.83	2.33	0.59	0.05
138	0.00	8.28	0.23	35.98	29.85	14.98	7.08	2.83	0.72	0.06
139	0.00	8.28	0.23	35.98	29.85	14.98	7.08	2.83	0.72	0.06
140	10.00	6.39	0.27	43.17	23.39	9.99	4.50	1.80	0.45	0.04
141	10.00	6.39	0.27	43.17	23.39	9.99	4.50	1.80	0.45	0.04
142	25.00	5.33	0.23	35.98	19.49	8.33	3.75	1.50	0.38	0.03
143	25.00	5.33	0.23	35.98	19.49	8.33	3.75	1.50	0.38	0.03
144	0.00	6.97	0.31	48.51	26.03	10.46	5.24	1.96	0.52	0.00
145	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
146	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
147	0.00	90.00	0.00	0.00	2.40	6.50	1.10	0.00	0.00	0.00
148	0.00	90.00	0.00	0.00	2.40	6.50	1.10	0.00	0.00	0.00
149	0.00	75.00	0.00	0.00	6.00	16.25	2.75	0.00	0.00	0.00
150	0.00	75.00	0.00	0.00	6.00	16.25	2.75	0.00	0.00	0.00
151	0.00	91.18	0.00	0.00	4.14	2.66	1.33	0.53	0.14	0.01
152	0.00	91.18	0.00	0.00	4.14	2.66	1.33	0.53	0.14	0.01
153	0.00	77.96	0.00	0.00	10.36	6.66	3.33	1.33	0.34	0.03
154	0.00	77.96	0.00	0.00	10.36	6.66	3.33	1.33	0.34	0.03
155	10.00	90.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
156	10.00	90.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
157	25.00	75.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
158	25.00	75.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
159	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
160	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
161	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
162	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
163	0.00	90.00	0.00	0.00	2.40	6.50	1.10	0.00	0.00	0.00
164	0.00	90.00	0.00	0.00	2.40	6.50	1.10	0.00	0.00	0.00
165	0.00	75.00	0.00	0.00	6.00	16.25	2.75	0.00	0.00	0.00
166	0.00	75.00	0.00	0.00	6.00	16.25	2.75	0.00	0.00	0.00
167	0.00	91.18	0.00	0.00	4.14	2.66	1.33	0.53	0.14	0.01
168	0.00	91.18	0.00	0.00	4.14	2.66	1.33	0.53	0.14	0.01
169	0.00	77.96	0.00	0.00	10.36	6.66	3.33	1.33	0.34	0.03
170	0.00	77.96	0.00	0.00	10.36	6.66	3.33	1.33	0.34	0.03
171	10.00	90.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
172	10.00	90.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
173	25.00	75.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
174	25.00	75.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
175	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
176	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

TABLE B-1, cont'd

SYSTEM #	TEMP. (C)	MMP (MPa)	MEASUREMENT METHOD	CRITERIA USED (IF SLIM TUBE DATA)	REFERENCE
136	82.2	20.02	RBA		Eakin et al. (1988)
137	115.6	23.03	RBA		Eakin et al. (1988)
138	82.2	17.00	RBA		Eakin et al. (1988)
139	115.6	22.57	RBA		Eakin et al. (1988)
140	82.2	23.41	RBA		Eakin et al. (1988)
141	115.6	25.41	RBA		Eakin et al. (1988)
142	82.2	24.13	RBA		Eakin et al. (1988)
143	115.6	25.75	RBA		Eakin et al. (1988)
144	103.3	26.21	RBA		Eakin et al. (1988)
145	82.2	21.34	RBA		Eakin et al. (1988)
146	115.6	25.30	RBA		Eakin et al. (1988)
147	82.2	16.65	RBA		Eakin et al. (1988)
148	115.6	21.31	RBA		Eakin et al. (1988)
149	82.2	16.91	RBA		Eakin et al. (1988)
150	115.6	18.86	RBA		Eakin et al. (1988)
151	82.2	19.06	RBA		Eakin et al. (1988)
152	115.6	22.75	RBA		Eakin et al. (1988)
153	82.2	18.03	RBA		Eakin et al. (1988)
154	115.6	21.68	RBA		Eakin et al. (1988)
155	82.2	22.37	RBA		Eakin et al. (1988)
156	115.6	24.03	RBA		Eakin et al. (1988)
157	82.2	21.13	RBA		Eakin et al. (1988)
158	115.6	23.37	RBA		Eakin et al. (1988)
159	82.2	18.57	RBA		Eakin et al. (1988)
160	115.6	18.89	RBA		Eakin et al. (1988)
161	82.2	27.51	RBA		Eakin et al. (1988)
162	115.6	25.55	RBA		Eakin et al. (1988)
163	82.2	17.86	RBA		Eakin et al. (1988)
164	115.6	23.72	RBA		Eakin et al. (1988)
165	82.2	17.42	RBA		Eakin et al. (1988)
166	115.6	20.24	RBA		Eakin et al. (1988)
167	82.2	19.34	RBA		Eakin et al. (1988)
168	115.6	24.06	RBA		Eakin et al. (1988)
169	82.2	16.31	RBA		Eakin et al. (1988)
170	115.6	21.89	RBA		Eakin et al. (1988)
171	82.2	22.74	RBA		Eakin et al. (1988)
172	115.6	25.79	RBA		Eakin et al. (1988)
173	82.2	21.20	RBA		Eakin et al. (1988)
174	115.6	23.82	RBA		Eakin et al. (1988)
175	82.2	6.83	RBA		Eakin et al. (1988)
176	115.6	10.65	RBA		Eakin et al. (1988)

Table B-2: Correlation Input Parameters

Correlation	Gas Types	Input Data[1]	Table B-1 Systems used in Correlation Development (if empirical)
Benham et al. (1960)[2]	RG	T, MW^{C2-C4}, MW_{C5+} & Y_{C1}	None
Blackwell (Stalkup, 1983)	LG	T, W_{C1}, W_{C2-C6}, W_{C7+}, P_s & $T_{c(oil)}$	None (systems not published)
Glasø (1985)	LG RG	T, MW^{C2-C6}, MW_{C7+}, Y_{C1} & SG_{C7+} (if available)	None
Kuo (1985)	RG	T, MW^{C2-C4}, MW_{C5+} & Y_{C1}	None
Glasø (1985)	N_2	T, MW_{C7+} & C_2-C_6	None (systems not published)
Firoozabadi & Aziz (1986)	LG N_2	T, C_2-C_5 & MW_{C7+}	27 through 30, & 34 through 39
Nouar & Flock (1988)	N_2	T, MW_{C2-C6}, MW_{C7+}, C_2-C_6 & C_{7+}	None
Hudgins, Llave & Chung (1988)	N_2	T, MW_{C7+}, C_1 & C_2-C_5	54 through 63, & 64 through 66
Eakin & Mitch (1988)	LG RG N_2	T, MW_{C7+}, Y_{C1}, Y_{C2+}, Y_{N2}, Y_{CO2}, Y_{H2S}, $P_{c(inj)}$ & $T_{c(inj)}$	71 through 80, & 82 through 176
Glasø (1988)	N_2	T, C_1, C_2-C_6 & oil API gravity	45 through 53, 55, 58, 61, 64, 66 & 67
Nouar & Flock (1988)	LG	T, C_2-C_6, C_{7+}, MW_{C2-C6} & MW_{C7+}	None
Nouar, Flock & Dranchuk (1990b)	N_2	T, C_2-C_6, C_{7+}, MW_{C2-C6} & MW_{C7+}	None

1. N_2 included with C_1; CO_2 & H_2S included with C_2-C_n grouping
2. Using Stalkup (1983) crossplots of Benham et al. correlation

* see following page for input parameter definitions

Where: T = displacement temperature (°C or K)

MW^{C2-C4} = molecular weight of injection gas C_2-C_4 fraction (kg/kmol)

MW^{C2-C6} = molecular weight of injection gas C_2-C_6 fraction (kg/kmol)

y_{C1} = injection gas C_1 fraction (mol% or mole fraction)

y_{C2+} = injection gas C_{2+} fraction (mol% or mole fraction)

y_{N2} = injection gas N_2 fraction (mol% or mole fraction)

y_{CO2} = injection gas CO_2 fraction (mol% or mole fraction)

y_{H2S} = injection gas H_2S fraction (mol% or mole fraction)

$P_{c(inj)}$ = injection gas pseudocritical pressure (KPa)

$T_{c(inj)}$ = injection gas pseudocritical temperature (K)

$T_{c(oil)}$ = oil pseudocritical temperature (K)

P_s = oil saturation pressure (KPa)

W_{C1} = kg C_1 per kg-mole oil

W_{C2-C6} = kg C_2-C_6 per kg-mole oil

W_{C7+} = kg C7+ per kg-mole oil

MW_{C2-C6} = molecular weight of oil C_2-C_6 fraction (kg/kmol)

MW_{C5+} = molecular weight of oil C_{5+} fraction (kg/kmol)

MW_{C7+} = molecular weight of the oil C_{7+} fraction (kg/kmol)

SG_{C7+} = specific gravity of oil C_{7+} fraction

C_1 = oil C_1 fraction (mol% or mole fraction)

C_2-C_5 = oil C_2 through C_5 fraction (mol% or mole fraction)

C_2-C_6 = oil C_2 through C_6 fraction (mol% or mole fraction)

C_{7+} = oil C_{7+} fraction (mol% or mole fraction)

Appendix C

Correlation Predicted MMP's

The MMP predictions tabulated in this section for selected gas/oil systems were used to calculate the following parameters for evaluating the feasibility of using each correlation to accurately predict MMP values:

$$Deviation = \frac{Predicted\ MMP}{Experimental\ MMP} - 1$$

$$Average\ Deviation = \frac{\left[\sum_{1}^{n} |Deviation|\right]}{n}$$

$$Standard\ Deviation = \sqrt{\frac{\sum (Deviation)^2}{n-1}}$$

$$Average\left(\frac{Predicted}{Actual}\right) Ratio = \frac{\sum_{1}^{n} Deviation}{n}$$

where,

$$n = number\ of\ experimental\ MMP's\ evaluated$$

These statistical tests were selected based on discussions with Professor W.H. Griffin, of the University of Alberta.

Table C-1: Effect of Including Non-Hydrocarbons In Glaso (1985)
Hydrocarbon Correlation for Rich Gas MMP Predictions

SYSTEM #	MMP (MPa)	MMP PREDICTED -correlation as published (MPa)	DEV.	MMP PREDICTED -including non-hydrocarbons (MPa)	DEV.
1	13.79	7.93	-0.42	8.24	-0.40
2	17.24	18.16	0.05	18.16	0.05
3	17.24	23.66	0.37	23.66	0.37
4	10.34	8.91	-0.14	8.91	-0.14
5	26.65	20.98	-0.21	20.98	-0.21
6	25.07	19.15	-0.24	19.15	-0.24
7	18.86	14.31	-0.24	14.31	-0.24
8	16.45	12.68	-0.23	12.77	-0.22
9	18.38	15.04	-0.18	15.16	-0.18
10	13.69	15.94	0.16	15.85	0.16
11	11.10	13.70	0.23	13.70	0.23
12	11.14	13.12	0.18	13.12	0.18
13	15.27	13.80	-0.10	13.80	-0.10
14	20.51	21.05	0.03	21.05	0.03
15	12.86	12.63	-0.02	12.63	-0.02
Average Deviation =			18.7%		18.4%
Standard Deviation =			22.5%		22.1%

Table C-2: Effect of Including Non-Hydrocarbons In Glaso (1985)
Hydrocarbon Correlation for Lean Gas MMP Predictions

SYSTEM #	MMP (MPa)	MMP PREDICTED -correlation as published (MPa)	DEV.	MMP PREDICTED -including non-hydrocarbons (MPa)	DEV.
28	39.99	42.44	0.06	41.85	0.05
29	41.37	54.52	0.32	53.14	0.28
31	39.99	41.42	0.04	41.96	0.05
32	47.23	51.35	0.09	49.18	0.04
33	35.16	34.38	-0.02	33.78	-0.04
34	33.80	37.11	0.10	36.57	0.08
35	35.00	36.87	0.05	36.27	0.04
36	37.90	48.06	0.27	47.30	0.25
37	37.13	50.77	0.37	47.70	0.28
38	24.13	21.98	-0.09	21.98	-0.09
39	23.34	20.32	-0.13	20.32	-0.13
42	23.44	20.29	-0.13	19.54	-0.17
43	24.03	28.88	0.20	28.88	0.20
Average Deviation =			14.4%		13.1%
Standard Deviation =			18.6%		16.6%

Table C-3: Effect of Including Non-Hydrocarbons In Glaso (1985)
Nitrogen Correlation

		MMP PREDICTED -correlation as published		MMP PREDICTED -including non-hydrocarbons	
SYSTEM #	MMP (MPa)	(MPa)	DEV.	(MPa)	DEV.
45	38.00	36.62	-0.04	36.29	-0.05
46	41.50	41.95	0.01	41.62	0.00
47	44.00	37.50	-0.15	37.29	-0.15
48	45.50	39.91	-0.12	39.69	-0.13
49	32.00	31.10	-0.03	31.10	-0.03
50	31.50	46.70	0.48	46.70	0.48
51	25.00	53.18	1.13	53.18	1.13
52	37.00	47.11	0.27	47.11	0.27
53	46.50	48.07	0.03	48.07	0.03
54	64.81	73.11	0.13	73.11	0.13
55	61.02	72.95	0.20	72.95	0.20
56	58.61	67.48	0.15	67.48	0.15
57	62.05	75.07	0.21	75.07	0.21
58	46.20	72.71	0.57	72.71	0.57
59	44.13	67.24	0.52	67.24	0.52
60	47.23	74.84	0.58	74.84	0.58
61	34.34	72.42	1.11	72.42	1.11
62	33.44	66.96	1.00	66.96	1.00
63	35.16	74.55	1.12	74.55	1.12
64	29.51	32.37	0.10	32.09	0.09
65	25.92	30.54	0.18	30.54	0.18
66	26.68	29.48	0.10	29.48	0.11
67	29.65	29.61	-0.00	29.61	-0.00
68	31.34	35.50	0.13	35.50	0.13
69	29.80	34.77	0.17	34.77	0.17
70	27.00	35.50	0.31	35.50	0.31
Average Deviation =			34.2%		34.2%
Standard Deviation =			50.6%		50.6%

Table C-4: Effect of Including Non-Hydrocarbons In Glaso (1988)
Nitrogen Correlation

SYSTEM #	MMP (MPa)	MMP PREDICTED -correlation as published (MPa)	DEV.	MMP PREDICTED -including non-hydrocarbons (MPa)	DEV.
45	38.00	36.00	-0.05	35.37	-0.07
46	41.50	40.60	-0.02	39.97	-0.04
47	44.00	44.28	0.01	43.88	-0.00
48	45.50	46.36	0.02	45.96	0.01
49	32.00	32.04	0.00	31.72	-0.01
50	31.50	29.97	-0.05	29.97	-0.05
51	25.00	24.97	-0.00	24.97	-0.00
52	37.00	39.15	0.06	39.15	0.06
53	46.50	45.90	-0.01	45.90	-0.01
54	64.81	68.73	0.06	68.73	0.06
55	61.02	60.09	-0.02	60.09	-0.02
56	58.61	63.84	0.09	63.84	0.09
57	62.05	58.63	-0.06	58.63	-0.06
58	46.20	47.82	0.04	47.82	0.04
59	44.13	51.57	0.17	51.57	0.17
60	47.23	46.36	-0.02	46.36	-0.02
61	34.34	33.14	-0.03	33.14	-0.03
62	33.44	36.89	0.10	36.89	0.10
63	35.16	31.68	-0.10	31.68	-0.10
64	29.51	31.94	0.08	31.18	0.06
65	25.92	32.81	0.27	30.76	0.19
66	26.68	26.65	-0.00	26.65	-0.00
67	29.65	30.58	0.03	30.28	0.02
68	31.34	46.89	0.50	46.89	0.50
69	29.80	45.64	0.53	45.64	0.53
70	27.00	49.59	0.84	49.59	0.84
Average Deviation =			12.3%		12.0%
Standard Deviation =			24.3%		24.0%

Table C-5: Effect of Including Non-Hydrocarbons In Hudgins et al. (1988) Nitrogen Correlation

SYSTEM #	MMP (MPa)	MMP PREDICTED -correlation as published (MPa)	DEV.	MMP PREDICTED -including non-hydrocarbons (MPa)	DEV.
45	38.00	31.75	-0.16	31.75	-0.16
46	41.50	32.69	-0.21	32.69	-0.21
47	44.00	32.78	-0.25	32.78	-0.26
48	45.50	33.22	-0.27	33.22	-0.27
49	32.00	29.08	-0.09	29.08	-0.09
50	31.50	24.70	-0.22	24.70	-0.22
51	25.00	25.80	0.03	25.80	0.03
52	37.00	24.94	-0.33	24.94	-0.33
53	46.50	25.52	-0.45	25.52	-0.45
54	64.81	62.20	-0.04	62.20	-0.04
55	61.02	61.41	0.01	61.41	0.01
56	58.61	61.30	0.05	61.30	0.05
57	62.05	61.45	-0.01	61.45	-0.01
58	46.20	45.90	-0.01	45.90	-0.01
59	44.13	45.26	0.03	45.26	0.03
60	47.23	46.11	-0.02	46.12	-0.02
61	34.34	34.54	0.01	34.54	0.01
62	33.44	34.34	0.03	34.34	0.03
63	35.16	34.61	-0.02	34.61	-0.02
64	29.51	28.78	-0.02	28.78	-0.02
65	25.92	26.48	0.02	26.35	0.02
66	26.68	25.88	-0.03	25.88	-0.03
67	29.65	48.76	0.64	48.46	0.63
68	31.34	21.93	-0.30	21.93	-0.30
69	29.80	22.33	-0.25	22.33	-0.25
70	27.00	22.70	-0.16	22.70	-0.16
	Average Deviation =		14.0%		13.9%
	Standard Deviation =		21.6%		21.5%

Table C-6: Rich Gas Correlation Predicted MMP Values

		BENHAM ET AL. (1960)		GLASO (1985)		KUO (1985)		EAKIN & MITCH (1988)	
	MMP	-predicted MMP		-predicted MMP		-predicted MMP		-predicted MMP	
SYSTEM #	(MPa)	(MPa)	DEV.	(MPa)	DEV.	(MPa)	DEV.	(MPa)	DEV.
1	13.79	12.70	-0.08	8.24	-0.40	7.16	-0.48	16.30	0.18
2	17.24	17.90	0.04	18.16	0.05	19.66	0.14	22.64	0.31
3	17.24	18.66	0.08	23.66	0.37	18.31	0.06	23.29	0.35
4	10.34	9.07	-0.12	8.91	-0.14	8.64	-0.16	15.77	0.53
5	26.65	18.19	-0.32	20.98	-0.21	27.50	0.03	23.69	-0.11
6	25.07	16.38	-0.35	19.15	-0.24	25.64	0.02	22.56	-0.10
7	18.86	12.23	-0.35	14.31	-0.24	20.21	0.07	19.32	0.02
8	16.45	15.57	-0.05	12.77	-0.22	15.26	-0.07	21.28	0.29
9	18.38	18.42	0.00	15.16	-0.18	17.71	-0.04	22.19	0.21
10	13.69	13.72	0.00	15.85	0.16	15.35	0.12	22.67	0.66
11	11.10	17.17	0.55	13.70	0.23	9.80	-0.12	21.40	0.93
12	11.14	10.80	-0.03	13.12	0.18	11.92	0.07	20.70	0.86
13	15.27	13.80	-0.10	13.80	-0.10	12.44	-0.19	20.87	0.37
14	20.51	21.00	0.02	21.05	0.03	18.23	-0.11	23.10	0.13
15	12.86	13.10	0.02	12.63	-0.02	12.75	-0.01	20.82	0.62
16	27.58	27.60	0.00	32.36	0.17	24.99	-0.09		
17	31.03			57.06	0.84	33.51	0.08		
18	27.58	26.80	-0.03	35.14	0.27	25.64	-0.07		
19	33.78			55.40	0.64	33.04	-0.02		
20	26.55	24.60	-0.07	30.45	0.15	26.34	-0.01		
21	28.96	27.80	-0.04	36.12	0.25	29.94	0.03		
22	16.31	16.70	0.02	16.82	0.03	15.24	-0.07		
23	11.51	16.70	0.45	13.64	0.19	13.85	0.20		
24	14.82	17.30	0.17	17.14	0.16	17.27	0.17		
25	10.72	9.40	-0.12	9.43	-0.12	10.71	-0.00		
26	15.00	13.40	-0.11	12.19	-0.19	16.40	0.09		
Avg. Pred./Actual Ratio =			0.98		1.06		0.99		1.35
# of MMP's =			24		26		26		15
Average Deviation =			13.0%		22.2%		9.7%		37.7%
Standard Deviation =			20.4%		28.9%		13.8%		48.1%

Table C-7: Lean Gas Correlation Predicted MMP Values

SYSTEM #	MMP (MPa)	FIROOZABADI & AZIZ (1986) -predicted MMP (MPa)	DEV.	NOUAR & FLOCK (1988) -predicted MMP (MPa)	DEV.	EAKIN & MITCH (1988) -predicted MMP (MPa)	DEV.	GLASO (1985) -predicted MMP (MPa)	DEV.	BLACKWELL (STALKUP, 1983) -predicted MMP (MPa)	DEV.
27	33.10	33.76	0.02	28.77	-0.13	30.71	-0.07			29.09	-0.12
28	39.99	38.67	-0.03	34.18	-0.15	28.21	-0.29	41.85	0.05	43.42	0.09
29	41.37	41.45	0.00	39.61	-0.04	35.80	-0.13	53.14	0.28	60.70	0.47
30	43.44	44.29	0.02	40.31	-0.07	41.21	-0.05			55.14	0.27
31	39.99	46.40	0.16	39.24	-0.02	25.50	-0.36	41.96	0.05		
32	47.23	45.43	-0.04	40.94	-0.13	28.89	-0.39	49.18	0.04		
33	35.16	33.43	-0.05	33.42	-0.05	28.41	-0.19	33.78	-0.04		
34	33.80	33.35	-0.01	31.23	-0.08	28.42	-0.16	36.57	0.08	31.37	-0.07
35	35.00	34.14	-0.02	31.77	-0.09	29.54	-0.16	36.27	0.04	30.47	-0.13
36	37.90	37.99	0.00	31.04	-0.18	28.33	-0.25	47.30	0.25	33.20	-0.12
37	37.13	36.82	-0.01	32.07	-0.14	29.78	-0.20	47.70	0.28	31.63	-0.15
38	24.13	24.95	0.03	26.29	0.09	26.43	0.10	21.98	-0.09	20.51	-0.15
39	23.34	23.16	-0.01	28.34	0.21	27.93	0.20	20.32	-0.13	21.50	-0.08
40	25.92	25.68	-0.01	26.29	0.01	30.88	0.19			23.39	-0.10
41	25.51	24.95	-0.02	26.29	0.03	28.76	0.13	21.98	-0.14	20.51	-0.20
42	23.44	26.52	0.13	28.40	0.21	22.77	-0.03	19.54	-0.17	31.42	0.34
43	24.03	34.07	0.42	32.25	0.34	29.07	0.21	28.88	0.20	33.20	0.38
44	22.10	22.78	0.03	22.52	0.02	21.71	-0.02				
Avg. Pred./Actual Ratio =			1.03		0.99		0.92		1.05		1.03
# of MMP's =			18		18		18		14		14
Average Deviation =			5.7%		11.0%		17.4%		13.1%		19.0%
Standard Deviation =			11.5%		14.3%		20.7%		16.5%		23.4%

Table C-8: Nitrogen Correlation Predicted MMP Values

SYSTEM #	MMP (MPa)	GLASO (1985) -predicted MMP (MPa)	DEV.	FIROOZABADI & AZIZ (1986) -predicted MMP (MPa)	DEV.	HUDGINS, LLAVE & CHUNG (1988) -predicted MMP (MPa)	DEV.	EAKIN & MITCH (1988) -predicted MMP (MPa)	DEV.
45	38.00	36.29	-0.05	39.64	0.04	31.75	-0.16	47.92	0.26
46	41.50	41.62	0.00	42.78	0.03	32.69	-0.21	48.43	0.17
47	44.00	37.29	-0.15	43.08	-0.02	32.78	-0.26	47.92	0.09
48	45.50	39.69	-0.13	44.63	-0.02	33.22	-0.27	48.18	0.06
49	32.00	31.10	-0.03	31.72	-0.01	29.08	-0.09	45.46	0.42
50	31.50	46.70	0.48	23.43	-0.26	24.70	-0.22	26.94	-0.14
51	25.00	53.18	1.13	24.82	-0.01	25.80	0.03	27.08	0.08
52	37.00	47.11	0.27	23.69	-0.36	24.94	-0.33	26.94	-0.27
53	46.50	48.07	0.03	24.41	-0.48	25.52	-0.45	26.94	-0.42
54	64.81	73.11	0.13	59.63	-0.08	62.20	-0.04	26.78	-0.59
55	61.02	72.95	0.20	57.02	-0.07	61.41	0.01	26.78	-0.56
56	58.61	67.48	0.15	56.61	-0.03	61.30	0.05	26.70	-0.54
57	62.05	75.07	0.21	57.16	-0.08	61.45	-0.01	26.81	-0.57
58	46.20	72.71	0.57	53.49	0.16	45.90	-0.01	26.78	-0.42
59	44.13	67.24	0.52	52.91	0.20	45.26	0.03	26.70	-0.39
60	47.23	74.84	0.58	53.68	0.14	46.12	-0.02	26.81	-0.43
61	34.34	72.42	1.11	49.51	0.44	34.54	0.01	26.78	-0.22
62	33.44	66.96	1.00	48.75	0.46	34.34	0.03	26.70	-0.20
63	35.16	74.55	1.12	49.75	0.41	34.61	-0.02	26.81	-0.24
64	29.51	32.09	0.09	30.93	0.05	28.78	-0.02	38.13	0.29
65	25.92	30.54	0.18	25.68	-0.01	26.35	0.02	38.78	0.50
66	26.68	29.48	0.11	24.95	-0.06	25.88	-0.03	37.50	0.41
67	29.65	29.61	-0.00	23.16	-0.22	48.46	0.63	39.05	0.32
68	31.34	35.50	0.13	22.78	-0.27	21.93	-0.30	26.94	-0.14
69	29.80	34.77	0.17	22.58	-0.24	22.33	-0.25	26.98	-0.09
70	27.00	35.50	0.31	37.37	0.38	22.70	-0.16	26.94	0.00
Avg. Pred./Actual Ratio =			1.31		1.01		0.92		0.90
# of MMP's =			26		26		26		26
Average Deviation =			34.2%		17.6%		13.9%		30.2%
Standard Deviation =			50.6%		24.3%		21.5%		35.4%

Table C-8: cont'd

		NOUAR & FLOCK (1988) -predicted MMP		GLASO (1988) -predicted MMP		NOUAR ET AL. (1990b) -predicted MMP	
SYSTEM #	MMP (MPa)	(MPa)	DEV.	(MPa)	DEV.	(MPa)	DEV.
45	38.00	153.77	3.05	35.37	-0.07	38.04	0.00
46	41.50	119.22	1.87	39.97	-0.04	40.09	-0.03
47	44.00	193.62	3.40	43.88	-0.00	88.23	1.01
48	45.50	178.69	2.93	45.96	0.01	77.76	0.71
49	32.00	107.50	2.36	31.72	-0.01	32.46	0.01
50	31.50	70.09	1.23	29.97	-0.05	23.09	-0.27
51	25.00	69.07	1.76	24.97	-0.00	23.08	-0.08
52	37.00	81.07	1.19	39.15	0.06	25.97	-0.30
53	46.50	85.08	0.83	45.90	-0.01	38.83	-0.16
54	64.81	97.11	0.50	68.73	0.06	91.78	0.42
55	61.02	96.60	0.58	60.09	-0.02	76.63	0.26
56	58.61	108.07	0.84	63.84	0.09	87.34	0.49
57	62.05	92.14	0.48	58.63	-0.06	72.46	0.17
58	46.20	24.63	-0.47	47.82	0.04	54.49	0.18
59	44.13	32.37	-0.27	51.57	0.17	63.80	0.45
60	47.23	21.62	-0.54	46.36	-0.02	50.88	0.08
61	34.34	16.12	-0.53	33.14	-0.03	27.20	-0.21
62	33.44	22.59	-0.32	36.89	0.10	34.98	0.05
63	35.16	13.60	-0.61	31.68	-0.10	24.18	-0.31
64	29.51	95.89	2.25	31.18	0.06	29.33	-0.01
65	25.92	70.55	1.72	30.76	0.19	23.42	-0.10
66	26.68	91.51	2.43	26.65	-0.00	26.40	-0.01
67	29.65	99.17	2.34	30.28	0.02	73.69	1.49
68	31.34	70.09	1.24	46.89	0.50	32.89	0.05
69	29.80	67.42	1.26	45.64	0.53	30.62	0.03
70	27.00	50.10	0.86	49.59	0.84	25.41	-0.06

Avg. Pred./Actual Ratio =	2.17	1.09	1.15
# of MMP's =	26	26	26
Average Deviation =	138.2%	12.0%	26.4%
Standard Deviation =	169.1%	24.0%	43.9%

Table C-8: cont'd

		NOUAR & FLOCK LEAN GAS (1988)		NOUAR & FLOCK LEAN GAS (1988) ADJUSTED	
	MMP	-predicted MMP		-predicted MMP/0.78	
SYSTEM #	(MPa)	(MPa)	DEV.	(MPa)	DEV.
45	38.00	36.67	-0.03	47.01	0.24
46	41.50	38.63	-0.07	49.53	0.19
47	44.00	41.58	-0.06	53.31	0.21
48	45.50	42.46	-0.07	54.44	0.20
49	32.00	31.75	-0.01	40.71	0.27
50	31.50	23.01	-0.27	29.50	-0.06
51	25.00	19.36	-0.23	24.82	-0.01
52	37.00	24.71	-0.33	31.68	-0.14
53	46.50	25.91	-0.44	33.22	-0.29
54	64.81	32.58	-0.50	41.77	-0.36
55	61.02	32.53	-0.47	41.71	-0.32
56	58.61	32.78	-0.44	42.03	-0.28
57	62.05	32.43	-0.48	41.58	-0.33
58	46.20	31.13	-0.33	39.91	-0.14
59	44.13	31.73	-0.28	40.68	-0.08
60	47.23	30.89	-0.35	39.60	-0.16
[illegible]	34.34	28.45	-0.17	36.47	0.06
62	33.44	29.72	-0.11	38.10	0.14
63	35.16	27.96	-0.20	35.85	0.02
64	29.51	28.90	-0.02	37.05	0.26
65	25.92	26.20	0.01	33.59	0.30
66	26.68	26.29	-0.01	33.71	0.26
67	29.65	28.42	-0.04	36.44	0.23
68	31.34	21.62	-0.31	27.72	-0.12
69	29.80	21.72	-0.27	27.85	-0.07
70	27.00	20.01	-0.26	25.65	-0.05

Avg. Pred./Actual Ratio = 0.78 1.00
# of MMP's = 26 26
Average Deviation = 22.0% 18.2%
Standard Deviation = 27.9% 21.4%

Table C-9: Oil M.Wt. Influence on Nouar, Flock & Dranchuk (1990b) Correlation

	OIL COMPOSITION				NOUAR ET AL. (1990b)		
SYSTEM #	C1 (mol%)	C2-C6 (mol%)	M.Wt. (kg/kmol)	MMP (MPa)	-predicted MMP (MPa)	DEV.	*DEV.
67	13.80	45.50	105.48	29.65	73.69	1.49	
47	36.53	19.89	117.94	44.00	88.23	1.01	
48	36.53	19.89	117.94	45.50	77.76	0.71	
56	9.37	11.96	119.79	58.61	87.34	0.49	
59	22.69	12.30	102.33	44.13	63.80	0.45	
54	0.00	11.71	132.07	64.81	91.78	0.42	
63	38.62	12.72	81.45	35.16	24.18	-0.31	-0.31
52	40.00	26.60	65.01	37.00	25.97	-0.30	-0.30
50	49.90	27.20	52.52	31.50	23.09	-0.27	-0.27
55	9.37	11.96	119.79	61.02	76.63	0.26	
61	38.62	12.72	81.45	34.34	27.20	-0.21	-0.21
58	22.69	12.30	102.33	46.20	54.49	0.18	
57	9.37	11.96	119.79	62.05	72.46	0.17	
53	32.90	25.20	75.89	46.50	38.83	-0.16	-0.16
65	34.85	39.00	75.14	25.92	23.42	-0.10	-0.10
60	22.69	13.30	102.33	47.23	50.88	0.08	
51	49.90	27.20	52.52	25.00	23.08	-0.08	-0.08
68	30.00	35.00	69.95	31.34	32.89	0.05	0.05
62	38.62	12.72	81.45	33.44	34.98	0.05	0.05
46	55.14	21.35	73.58	41.50	40.09	-0.03	-0.03
70	24.04	51.12	61.70	27.00	25.41	-0.06	-0.06
69	30.00	35.00	69.95	29.80	30.62	0.03	0.03
49	43.51	32.28	77.27	32.00	32.46	0.01	0.01
66	42.70	36.00	64.98	26.68	26.40	-0.01	-0.01
64	55.64	26.59	48.53	29.51	29.33	-0.01	-0.01
45	55.14	21.35	73.58	38.00	38.04	0.00	0.00

Avg. Pred./Actual Ratio	=	1.15	0.91
# of MMP's	=	26	16
Average Deviation	=	26.4%	10.3%
Standard Deviation	=	43.9%	15.3%

* neglecting oils with M.Wt.'s > 100 kg/kmol

Table C-10: Nitrogen Correlation MMP Predictions for
Impure N2 Injection Streams

	MMP	-correlation deviations						
SYSTEM #	(MPa)	GLASO'85	F&A	HL&C	E&M	N&F	GLASO'88	NF&D
71	40.09	-24.86%	-42.40%	-38.98%	-6.91%	83.81%	-46.98%	-43.23%
72	41.47	-23.94%	-42.37%	-38.99%	-8.25%	64.09%	-43.67%	-41.45%
73	41.47	-27.36%	-44.32%	-41.02%	-7.33%	77.69%	-48.74%	-45.12%
74	41.47	-23.94%	-42.37%	-38.99%	-5.47%	64.09%	-43.67%	-41.45%
75	34.58	-12.89%	-33.23%	-29.26%	6.94%	113.10%	-38.53%	-34.18%
76	35.61	-11.42%	-32.88%	-28.95%	6.77%	91.10%	-34.41%	-31.82%
77	40.44	-25.51%	-42.90%	-39.51%	5.66%	82.22%	-47.44%	-43.72%
78	40.78	-22.65%	-41.39%	-37.96%	6.65%	66.87%	-42.72%	-40.46%
79	36.65	-17.81%	-37.00%	-33.26%	3.71%	101.06%	-42.00%	-37.90%
80	38.54	-18.16%	-37.99%	-34.35%	1.45%	76.57%	-39.39%	-37.00%
81	25.72	14.63%	-2.99%	0.63%	37.13%	255.79%	3.61%	2.64%
Avg. Pred./Actual Ratio =		0.82	0.64	0.67	1.04	1.98	0.61	0.64
# of MMP's =		11	11	11	11	11	11	11
Average Deviation =		20.29%	36.35%	32.90%	8.75%	97.86%	39.20%	36.27%
Standard Deviation =		21.99%	39.89%	36.37%	13.28%	116.24%	42.98%	39.85%

WHERE: GLASO'85 = GLASO (1985) NITROGEN CORRELATION
F&A = FIROOZABADI & AZIZ (1986) CORRELATION
HL&C = HUDGINS, LLAVE & CHUNG CORRELATION
E&M = EAKIN & MITCH (1988) CORRELATION
N&F = NOUAR & FLOCK (1988) N2 CORRELATION
GLASO'88 = GLASO (1988) CORRELATION
NF&D = NOUAR, FLOCK & DRANCHUK (1990b) CORRELATION

Table C-11: Hydrocarbon Correlation MMP Predictions for
Eakin & Mitch Light Oil Data

	MMP	-correlation deviations				
SYSTEM #	(MPa)	F&A	N&F	E&M	GLASO	KUO
82	27.51	-16.07%	-14.07%	1.89%	-33.44%	14.18%
83	30.14	-20.70%	-21.50%	-1.19%	-22.22%	35.93%
84	24.75	-6.71%	-4.48%	5.41%	-30.59%	-1.05%
85	26.58	-10.08%	-10.99%	4.74%	-16.99%	20.20%
86	22.17	4.15%	6.63%	5.41%	-27.08%	-23.73%
87	23.89	0.04%	-0.96%	5.15%	-12.83%	-7.66%
88	25.79	-10.47%	-8.34%	2.17%	-33.35%	-2.68%
89	27.25	-12.29%	-13.17%	3.19%	-18.98%	20.18%
90	22.68	1.81%	4.23%	5.64%	-28.62%	-22.13%
91	24.79	-3.59%	-4.56%	3.91%	-15.88%	-7.06%
92	25.44	-9.24%	-7.08%	6.68%	-27.28%	4.01%
93	29.44	-18.8[illegible]	-19.63%	-2.75%	-19.56%	17.22%
94	25.46	-9.31%	-7.15%	3.42%	-26.64%	-23.33%
95	27.81	-14.06%	-14.92%	-1.44%	-14.08%	-8.45%
96	22.17	4.15%	6.63%	1.89%	-36.61%	-36.63%
97	23.97	-0.29%	-1.29%	1.79%	-25.31%	-23.57%
98	22.68	1.81%	4.23%	-5.64%	-45.50%	-49.51%
99	24.66	-3.08%	-4.06%	-5.96%	-37.19%	-39.42%
100	20.62	11.98%	14.65%	-4.36%	-48.51%	-60.43%
101	21.48	11.27%	10.15%	0.00%	-39.92%	-50.47%
102	21.65	6.65%	9.19%	-0.18%	-42.89%	-46.33%
103	23.46	1.88%	0.85%	-0.17%	-33.94%	-35.42%
104	20.00	15.45%	18.20%	0.95%	-46.86%	-57.95%
105	22.51	6.18%	5.11%	-2.27%	-42.61%	-51.29%
106	23.20	-0.47%	1.90%	-1.85%	-43.85%	-48.28%
107	24.24	-1.40%	-2.39%	0.41%	-32.62%	-35.44%
108	23.41	-1.37%	0.98%	-0.56%	-49.71%	-61.43%
109	24.61	-2.89%	-3.86%	-0.61%	-41.38%	-52.13%
110	28.51	-19.01%	-17.08%	13.43%		
111	32.13	-25.61%	-26.36%	5.45%		
112	27.51	-16.07%	-14.07%	1.09%	-43.79%	-46.31%
113	30.61	-21.92%	-22.70%	-1.93%	-35.42%	-37.08%
Avg. Pred./Actual Ratio =		0.95	0.96	1.01	0.68	0.76
# of MMP's =		32	32	32	30	30
Average Deviation =		9.0%	9.4%	3.2%	32.5%	31.3%
Standard Deviation =		11.7%	11.9%	4.2%	34.8%	36.9%

WHERE:
F&A = FIROOZABADI AND AZIZ (1986) CORRELATION
N&F = NOUAR AND FLOCK (1988) LEAN GAS CORRELATION
E&M = EAKIN AND MITCH (1988) CORRELATION
GLASO = GLASO (1985) HYDROCARBON CORRELATION
KUO = KUO (1985) CORRELATION

Table C-12: Hydrocarbon Correlation MMP Predictions for Eakin & Mitch Medium Oil Data

SYSTEM #	MMP (MPa)	-correlation deviations F&A	N&F	E&M	GLASO	KUO	BENHAM
114	34.37	15.27%	40.65%	-7.36%	-4.09%	-37.77%	-43.26%
115	35.87	14.05%	35.60%	-2.54%	24.73%	-23.47%	-23.61%
116	32.79	20.49%	47.36%	-1.10%	97.62%	36.51%	
117	35.87	14.05%	35.60%	-2.76%	146.20%	62.75%	
118	30.44	29.80%	58.74%	-5.55%	66.19%	14.65%	
119	32.16	27.21%	51.24%	-3.23%	115.15%	41.54%	
120	27.23	45.10%	77.45%	-12.27%	26.85%	-11.53%	
121	28.72	42.44%	69.36%	-9.05%	66.15%	9.42%	
122	31.34	26.07%	54.18%	-6.76%	61.58%	14.13%	
123	33.12	23.52%	46.86%	-4.47%	109.13%	40.87%	
124	26.48	49.21%	82.48%	-6.19%	30.81%	-4.97%	
125	28.03	45.95%	73.53%	-3.00%	70.73%	17.10%	
126	30.44	29.80%	58.74%	1.35%	86.89%	23.84%	
127	33.37	22.60%	45.76%	-1.47%	133.80%	47.36%	
128	26.92	46.77%	79.49%	9.06%	69.22%	3.30%	
129	30.23	35.33%	60.90%	1.82%	109.32%	19.99%	
130	21.13	86.99%	128.68%	6.48%	29.65%	-5.28%	-20.02%
131	24.06	70.03%	102.16%	2.99%	58.70%	8.51%	13.47%
132	20.62	91.61%	134.34%	-0.39%	11.21%	-20.86%	-28.71%
133	23.37	75.05%	108.13%	-2.74%	37.99%	-8.92%	-13.14%
134	17.51	125.64%	175.96%	2.17%	-1.02%	-33.63%	-32.04%
135	19.69	107.77%	147.03%	1.27%	26.06%	-23.01%	-20.77%
136	20.02	97.35%	141.36%	4.15%	14.66%	-17.33%	-26.57%
137	23.03	77.64%	111.20%	0.22%	40.17%	-6.26%	-10.55%
138	17.00	132.41%	184.24%	9.24%	2.28%	-29.53%	-28.82%
139	22.57	81.26%	115.51%	-8.20%	10.33%	-30.78%	-30.88%
140	23.41	68.77%	106.41%	-3.12%	11.22%	-27.00%	-35.50%
141	25.41	61.00%	91.42%	-2.95%	44.40%	-12.26%	-15.39%
142	24.13	63.74%	100.25%	-3.23%	-2.47%	-46.71%	-46.13%
143	25.75	58.87%	88.89%	-3.61%	31.24%	-34.83%	-32.82%
144	26.21	54.29%	85.12%	-7.90%	32.45%	-8.33%	-6.91%
Avg. Pred./Actual Ratio =		1.56	1.88	0.98	1.50	0.99	0.76
# of MMP's =		31	31	31	31	31	17
Average Deviation =		56.1%	88.3%	4.4%	50.7%	23.3%	25.2%
Standard Deviation =		65.7%	98.3%	5.4%	66.0%	28.0%	28.3%

WHERE:
F&A = FIROOZABADI AND AZIZ (1986) CORRELATION
N&F = NOUAR & FLOCK (1988) LEAN GAS CORRELATION
E&M = EAKIN & MITCH (1988) CORRELATION
GLASO = GLASO (1985) HYDROCARBON CORRELATION
KUO = KUO (1985) CORRELATION

Table C-13: Hydrocarbon Correlation MMP Predictions for
Eakin & Mitch Non-Hydrocarbon Gases/Light Oil Mixtures

	MMP	-correlation deviations			
SYSTEM #	(MPa)	F&A	N&F	E&M	GLASO
145	21.34	8.20%	10.78%	-2.72%	-52.34%
146	25.30	-5.53%	-6.48%	-5.89%	-58.34%
147	16.65	38.68%	41.98%	19.10%	-39.12%
148	21.31	12.15%	11.03%	6.57%	-50.65%
149	16.91	36.55%	39.80%	9.52%	-40.35%
150	18.86	26.72%	25.45%	12.14%	-44.44%
151	19.06	21.14%	24.03%	4.88%	-46.82%
152	22.75	5.05%	4.00%	0.62%	-53.78%
153	18.03	28.06%	31.11%	4.77%	-44.07%
154	21.68	10.24%	9.13%	-0.46%	-51.67%
155	22.37	3.22%	5.68%	-6.88%	-55.39%
156	24.03	-0.54%	-1.54%	-2.25%	-56.71%
157	21.13	9.28%	11.88%	0.95%	-54.14%
158	23.37	2.27%	1.24%	0.17%	-56.38%
159	18.57	24.34%	27.30%	81.69%	-55.57%
160	18.89	26.52%	25.25%	66.01%	-51.50%
Avg. Pred./Actual Ratio	=	1.15	1.16	1.12	0.49
# of MMP's	=	16	16	16	16
Average Deviation	=	16.2%	17.3%	14.0%	50.7%
Standard Deviation	=	20.9%	22.3%	28.1%	52.7%

WHERE: F&A = FIROOZABADI & AZIZ (1986) CORRELATION
N&F = NOUAR & FLOCK (1988) LEAN GAS CORRELATION
E&M = EAKIN & MITCH (1988) CORRELATION
GLASO = GLASO (1985) HYDROCARBON CORRELATION

Table C-14: Hydrocarbon Correlation MMP Predictions for
Eakin & Mitch Non-Hydrocarbon Gases/Medium Oil Mixtures

SYSTEM #	MMP (MPa)	-correlation deviations F&A	N&F	E&M	GLASO
161	21.99	79.67%	119.74%	-3.91%	
162	25.55	60.12%	90.37%	1.45%	
163	17.86	121.22%	170.55%	7.73%	
164	23.72	72.47%	105.06%	-0.97%	
165	17.42	126.81%	177.38%	-3.79%	
166	20.24	102.12%	140.32%	0.35%	
167	19.34	104.29%	149.84%	0.93%	
168	24.06	70.03%	102.16%	-0.91%	
169	16.31	142.24%	196.26%	6.44%	
170	21.89	86.89%	122.20%	-3.79%	
171	22.74	73.75%	112.49%	-7.43%	
172	25.79	58.63%	88.60%	-2.29%	
173	21.20	86.37%	127.92%	1.48%	
174	23.82	71.75%	104.20%	3.99%	
175	6.83	478.48%	607.47%	472.67%	27.22%
176	10.65	284.13%	356.71%	233.90%	48.77%
Avg. Pred./Actual Ratio =		2.26	2.73	1.44	1.38
# of MMP's =		16	16	16	2
Average Deviation =		126.2%	173.2%	47.0%	38.0%
Standard Deviation =		169.5%	222.7%	136.2%	55.9%

WHERE: F&A = FIROOZABADI & AZIZ (1986) CORRELATION
N&F = NOUAR & FLOCK (1988) LEAN GAS CORRELATION
E&M = EAKIN & MITCH (1988) CORRELATION
GLASO = GLASO (1985) HYDROCARBON CORRELATION

Appendix D

MMP Correlation Sample Calculations

Sample calculations for all but two of the evaluated lean-gas, rich-gas, or nitrogen MMP correlations are presented in this section. The Benham et al. (1960), Glasø hydrocarbon (1985), Kuo (1985), and Eakin and Mitch (1988) correlation sample calculations were performed using system 3, a rich CGD gas/oil mixture. The Blackwell (Stalkup, 1983), Firoozabadi and Aziz (1986), and Nouar and Flock hydrocarbon (1988) correlations were used to calculate the MMP of system 27, a lean VGD gas/oil mixture. The two Glasø nitrogen correlations (1985 and 1988), and the Hudgins et al. (1988) correlations were used to predict the MMP of system 45, a nitrogen VGD gas/oil mixture.

The two correlations for which sample calculations have not been presented are the Nouar and Flock nitrogen (1988) correlation, and the Nouar, Flock, and Dranchuk (1990b) correlation. The calculation procedure for the Nouar and Flock N_2 correlation is identical to the Nouar and Flock hydrocarbon correlation, for which a sample calculation is presented in this section. The only difference between the two correlations are the required Nouar and Flock tabulated input parameters, which are different for N_2 or lean injection gases. The Nouar, Flock and Dranchuk nitrogen correlation is in the form of a computer program, so no calculation presentation is possible. The required input parameters are, however, the same as those required for the Nouar and Flock hydrocarbon correlation.

Refer to Table B-2 for a complete listing of the input parameters required by each correlation studied. The majority of the MMP correlations require molecular weight calculations for selected pseudocomponent groups, and a couple require the pseudocritical pressure or temperature of the gas or oil to be calculated. These calculations were made on a mole fraction basis, using molecular weight and pseudocritical data for pure component fractions published by the API (1970).

Oil compositional data generally was published in the literature up to a certain hydrocarbon (usually C_6), and the molecular weight of the heavy-ends-plus fraction (usually C_{7+}) was also provided. Gas compositional data was presented in the same fashion, but the molecular weight of the heavy fraction was never provided. For the purpose of calculating molecular weights and pseudocritical pressure and temperature values for the injection gases, the values associated with the heaviest listed hydrocarbon were assumed to apply. This assumption is felt to result in minimal error since the vast majority of heaviest-end components published for the gases represented only a few mol% (or less) of the gas mixture.

The Blackwell correlation required the pseudocritical temperature of the reservoir oil to be calculated. The critical temperature of the heavy fraction was estimated using the work of Whitson (1983). The molecular weight of the heavy fraction was related to the closest Whitson single-carbon-number (SCN) grouping on the basis of molecular weight. The critical temperature of that SCN component was assumed to represent the critical temperature of the heavy fraction.

The Glasø (1988) nitrogen correlation requires that the oil API gravity be known, in order to determine which of two equations should be used to calculate the MMP (refer to A.2.5). One equation is for oils having API gravities greater than 45°, and the other for API gravities less than 45°. Unfortunately, oil API gravity values were seldom published with the experimental MMP data listed in Table B-1. To estimate the API gravity of an oil, the Whitson (1983) SCN properties were used. The specific gravity of Whitson's SCN component having a molecular weight identical to the molecular weight of the C_{7+} fraction of the reservoir oil was determined. This specific gravity of the C_{7+} fraction was then used to calculate the API gravity (Craft and Hawkins, 1959). This method of calculating the oil API gravity assumes that the stock-tank-oil is composed entirely of C_{7+} fractions, so the resulting API gravity values will be slightly high. However, for 16 MMP calculations presented by Glasø (for which API values were not presented), the API calculations using the Whitson SCN values were correct (i.e. either greater or less than 45° API) in each case.

```
- sample calculation for system # 3
INPUT DATA CONTAINING RESERVOIR OIL & INJECTED GAS COMPOSITIONS
            xi          yi       M.Wt.  xi*M.Wt. yi*M.Wt.
COMP.       (OIL)       (GAS)   (kg/kmol)(kg/kmol)(kg/kmol)
-----------------------------------------------------------
H2S         0.0169      0.0000   34.080   0.5760   0.0000          TEMP.(C)
CO2         0.0367      0.0000   44.010   1.6152   0.0000          MMPexp.(K
N2          0.0045      0.0000   28.020   0.1261   0.0000          MWC7+
C1          0.2696      0.6800   16.043   4.3252  10.9092          MWC10+
C2          0.0621      0.0000   30.070   1.8673   0.0000
C3          0.0487      0.0000   44.097   2.1475   0.0000
i-C4        0.0110      0.0000   58.124   0.6394   0.0000
n-C4        0.0316      0.3200   58.124   1.8367  18.5997
i-C5        0.0175      0.0000   72.151   1.2626   0.0000
n-C5        0.0213      0.0000   72.151   1.5368   0.0000
C6          0.0350      0.0000   86.178   3.0162   0.0000
C7          0.0377      0.0000  100.205   3.7777   0.0000
C8          0.0374      0.0000  114.232   4.2723   0.0000
C9          0.0331      0.0000  128.259   4.2454   0.0000
C10+        0.3369      0.0000  283.000  95.3427   0.0000
-----------------------------------------------------------
TOTALS      1.0000      1.0000

-the graphical Benham et al. correlation (Stalkup, 1983) requires the follo

          yC2-C4 = mol% C2-C4 in the injection gas (including CO2 & H2S)
          T      = reservoir temperature, degrees F
          MWC2+  = M.Wt. of C2-C4 fraction in the injection gas (including C
          MWC5+  = M.Wt. of C5+ fraction in the oil
-input:
          yC2-C4 =       32.00 %
          T      =      188.00 F
          MWC5+  =      218.64 kg/kmol
          MWC2+  =       58.12 kg/kmol

-results (extrapolated from graphical correlation):
          -at 150 degrees F, MMP = 2250 psi
          -at 200 degrees F, MMP = 2850 psi

          -interpolating to 188 degrees F, MMP = 2706 psi

          MMP    =       18657 KPa       (18.66 MPa)
          DEV.   =        8.24 %
```

Glaso (1985) Hydrocarbon Gas Correlation

- sample calculation for system # 3

INPUT DATA CONTAINING RESERVOIR OIL & INJECTED GAS COMPOSITIONS

COMP.	MOL% IN OIL	MOL% IN GAS	yi (GAS)	M.Wt. (kg/kmol)	yi*M.Wt. (kg/kmol)
H2S	1.69	0.00	0.0000	34.080	0.0000
CO2	3.67	0.00	0.0000	44.010	0.0000
N2	0.45	0.00	0.0000	28.020	0.0000
C1	26.96	68.00	0.6800	16.043	10.9092
C2	6.21	0.00	0.0000	30.070	0.0000
C3	4.87	0.00	0.0000	44.097	0.0000
i-C4	1.10	0.00	0.0000	58.124	0.0000
n-C4	3.16	32.00	0.3200	58.124	18.5997
i-C5	1.75	0.00	0.0000	72.151	0.0000
n-C5	2.13	0.00	0.0000	72.151	0.0000
C6	3.50	0.00	0.0000	86.178	0.0000
C7	3.77	0.00			
C8	3.74	0.00			
C9	3.31	0.00			
C10+	33.69	0.00			
TOTALS	100.00	100.00			

TEMP.(C) : 86.70
MMPexp.(KPa) : 17237
MWC7+ : 242
MWC10+ : 283

-the Glaso Hydrocarbon Gas Correlation (converted to SI units) is as follows:

(MMP)x=34 = 43636.9-175.196y-(322.296-1.276y)z
+(7.770*10^(-12)y^5.258e^(319.8zy^(-1.703))(1.8T+32)
(MMP)x=44 = 37941.8-132.641y-(557.876-1.882y)z
+(11.721*10^(-9)y^3.730e^(13.567zy^(-1.058))(1.8T+32)
(MMP)x=54 = 51276.3-177.216y-(506.868-1.475y)z
+(33.922*10^(-14)y^5.520e^(21.706zy^(-1.109))(1.8T+32)

-where:

MMP = KPa
x = M.Wt. of C2-C6 fraction in the injection gas (including CO2 & H2S)
y = corrected MWC7+ in stock tank oil
= [2.622/(SGC7+)^(-0.846)]^6.588
z = C1 in gas, mol% (including N2)
T = reservoir temperature, C

-note: The value used for z in the correlation is dependent on the amount of intermediates in the reservoir oil and the injection gas. If the amount of intermediates in the gas (C2-C6, CO2, H2S) exceeds the amount of intermediates in the oil, z is taken as the amount of C1 in the injection gas. However, if the amount of intermediates in the oil exceeds the amount of intermediates in the gas, z is taken as the amount of C1 in the oil.

-the injection gas intermediate fraction (32.00%) is larger than the reservoir oil intermediate fraction (28.08%), so z is taken as the amount of C1 (&N2) in the injection gas.

-input:

x = 58.12 kg/kmol
z = 68.00 %
T = 86.70 C
SGC7+ = not given
MWC7+ = 242.00 kg/kmol

-since the SGC7+ data was not available, the MWC7+ value cannot be corrected. However, as suggested by Glaso (1985), y should be taken as the given MWC7+ value.

y = 242

-results for each of the three MMP equations, using:

x=34: MMP = 33593 KPa
x=44: MMP = 26362 KPa
x=54: MMP = 24477 KPa

-extrapolating to x = 58.12 kg/kmol:

MMP = 23658 KPa (23.66 MPa)
DEV = 37.25%

Kuo (1988) Correlation

```
- sample calculation for system # 3
INPUT DATA CONTAINING RESERVOIR OIL & INJECTED GAS COMPOSITIONS
            xi        yi       M.Wt.  xi*M.Wt. yi*M.Wt.
COMP.     (OIL)     (GAS)   (kg/kmol)(kg/kmol)(kg/kmol)
-----------------------------------------------------
H2S       0.0169    0.0000   34.080   0.5760   0.0000        TEMP.(C)       :   86.70
CO2       0.0367    0.0000   44.010   1.6152   0.0000        MMPexp.(KPa)   :   17237
N2        0.0045    0.0000   28.020   0.1261   0.0000        MWC7+          :     242
C1        0.2696    0.6800   16.043   4.3252  10.9092        MWC10+         :     283
C2        0.0621    0.0000   30.070   1.8673   0.0000
C3        0.0487    0.0000   44.097   2.1475   0.0000
i-C4      0.0110    0.0000   58.124   0.6394   0.0000
n-C4      0.0316    0.3200   58.124   1.8367  18.5997
i-C5      0.0175    0.0000   72.151   1.2626   0.0000
n-C5      0.0213    0.0000   72.151   1.5368   0.0000
C6        0.0350    0.0000   86.178   3.0162   0.0000
C7        0.0377    0.0000  100.205   3.7777   0.0000
C8        0.0374    0.0000  114.232   4.2723   0.0000
C9        0.0331    0.0000  128.259   4.2454   0.0000
C10+      0.3369    0.0000  283.000  95.3427   0.0000
-----------------------------------------------------
TOTALS    1.0000    1.0000

-the Kuo Correlation (converted to SI units) is as follows:

C*LOG(MMP/6.894757) = LOG(yC1)-(A+B*(1.8T+32))*LOG(1.8T+32)
                      -D*LOG(MWC5+)-(E+F*MWC2+)*LOG(MWC2+)
-where:
        MMP    =  KPa
        yC1    =  mol% C1 in the injection gas (including N2)
        MWC2+  =  M.Wt. of C2-C4 fraction in the injection gas (including CO2 & H2S)
        T      =  reservoir temperature, C
        MWC5+  =  M.Wt. of C5+ fraction in the oil
-and:
            A =  0.19899861      C = 0.583478      E = 0.578210
            B = -0.00055769      D = -0.62406      F = 0.000589
-input:
        yC1    =        68.00 %
        T      =        86.70 C
        MWC5+  =       218.64 kg/kmol
        MWC2+  =        58.12 kg/kmol
-results:
        C*LOG(MMP/6.894757)= 1.997978

        MMP   =         18314 KPa      (18.31 MPa)
        DEV.  =          6.25 %
```

- sample calculation for system # 3

INPUT DATA CONTAINING RESERVOIR OIL & INJECTED GAS COMPOSITIONS

COMP.	MOL% IN OIL	yi (GAS)	Pc (KPa)	Tc (K)	yi*Pc (KPa)	yi*Tc (K)
H2S	0.0169	0.0000	9004.6	373.50	0.000	0.000
CO2	0.0367	0.0000	7377.4	304.20	0.000	0.000
N2	0.0045	0.0000	3399.1	126.30	0.000	0.000
C1	0.2696	0.6800	4604.0	190.58	3130.720	129.594
C2	0.0621	0.0000	4880.0	305.42	0.000	0.000
C3	0.0487	0.0000	4250.0	369.82	0.000	0.000
i-C4	0.0110	0.0000	3648.0	408.14	0.000	0.000
n-C4	0.0316	0.3200	3797.0	425.18	1215.040	136.058
i-C5	0.0175	0.0000	3381.0	460.43	0.000	0.000
n-C5	0.0213	0.0000	3369.0	469.65	0.000	0.000
C6	0.0350	0.0000	3012.0	507.45	0.000	0.000
C7	0.0377	0.0000	2736.0	540.25	0.000	0.000
C8	0.0374	0.0000				
C9	0.0331	0.0000				
C10+	0.3369	0.0000				
TOTALS	1.0000	1.0000			4345.760	265.652

TEMP.(C)	:	86.70
MMPexp.(KPa)	:	17237
MWC7+	:	242
MWC10+	:	283

-the Eakin & Mitch Correlation (converted to SI units) is as follows:

ln(MMP/Pc)=(0.1697-0.06912/Tr)yC1(MWC7+)^0.5
+[2.3865-0.005955(MWC7+)/Tr]yC2+
+(0.1776-0.01023/Tr)yN2(MWC7+)^0.5
+[0.01221(MWC7+)-(0.0005899(MWC7+)^1.5)/Tr]yCO2
+[101.429/(MWC7+)+0.003750(MWC7+)/Tr]yH2S

-where:

MMP = KPa
Pc = injection gas pseudocritical pressure, KPa
Tr = injection gas pseudoreduced temperature (=T/Tc)
T = reservoir temperature, K
Tc = injection gas pseudocritical temperature, K
MWC7+ = M.Wt. of C7+ heavy fraction in reservoir fluid, kg/kmol
yC1 = mole fraction of C1 in the injection gas
yC2+ = mole fraction of C2+ in the injection gas
yN2 = mole fraction of N2 in the injection gas
yCO2 = mole fraction of CO2 in the injection gas
yH2S = mole fraction of H2S in the injection gas

-input: Pc = 4346 KPa Tr = 1.3546 yC2+ = 0.3200
Tc = 265.65 K MWC7+ = 242 yN2 = 0.0000
T = 359.85 K yC1 = 0.6800 yCO2 = 0.0000
-results: yH2S = 0.0000

MMP=Pc*e^x, where x=RHS of E&M original equation
x = 1.67861
MMP = 23285 KPa (23.29 MPa)
DEV. = 35.09%

Blackwell (Stalkup, 1983) Correlation

```
- sample calculation for system # 27
INPUT DATA CONTAINING RESERVOIR OIL & INJECTED GAS COMPOSITIONS
           xi        yi     M.Wt.     xi*MW       Tc       xi*Tc
COMP.     (OIL)     (GAS)  (kg/kmol)(kg/kmol)     (K)       (K)
----------------------------------------------------------------
H2S       0.0000    0.0000   34.080    0.0000   373.50     0.000      TEMP.(C)          :   171.11
CO2       0.0360    0.0000   44.010    1.5844   304.20    10.951      SAT.PRESS.(KPa)   :    32750
N2        0.0025    0.0000   28.020    0.0701   126.30     0.316      MMPexp.(KPa)      :    33095
C1        0.5686    1.0000   16.043    9.1220   190.58   108.364      MWC7+             :    183.6
C2        0.0937    0.0000   30.070    2.8176   305.42    28.618      MWC10+            :      217
C3        0.0548    0.0000   44.097    2.4165   369.82    20.266      Tc-C10+(K)        :      740
i-C4      0.0146    0.0000   58.124    0.8486   408.14     5.959      Tc est. method    : WHITSON
n-C4      0.0261    0.0000   58.124    1.5170   425.18    11.097
i-C5      0.0120    0.0000   72.151    0.8658   460.43     5.525
n-C5      0.0139    0.0000   72.151    1.0029   469.65     6.528
C6        0.0126    0.0000   86.178    1.0858   507.45     6.394
C7        0.0126    0.0000  100.205    1.2626   540.25     6.807
C8        0.0206    0.0000  114.232    2.3532   568.83    11.718
C9        0.0213    0.0000  128.259    2.7319   594.64    12.666
C10+      0.1114    0.0000  217.000   24.1738   740.00    82.436
----------------------------------------------------------------
 TOTALS   1.0007    1.0000             51.852             317.645

-the Blackwell Correlation (converted to SI units) is as follows:

         MMP    = Ps(x+4.09068)/(2.252354x)
          & x   = Wi*W1*Tr^(1/3)/W7+

-where:  MMP    = KPa
         Ps     = oil saturation pressure at reservoir temperature, KPa
         W1     = kg C1 per kg-mole oil (including N2)
         Wi     = kg C2-C6 per kg-mole oil (including CO2 & H2S)
         W7+    = kg C7+ per kg-mole oil
         Tr     = pseudoreduced temperature of reservoir fluid
                = T/Tc
         Tc     = pseudocritical temperature of reservoir fluid, K
         T      = reservoir temperature, K
-input:
         Ps    =    32750.0 KPa      Wi    =   12.1386
         Tc    =     317.64 K        W1    =    9.1921
         T     =     444.26 K        W7+   =   30.5215
         Tr    =     1.3986                  ---------
                                               51.8522
-results:
         x     =   4.088313
         MMP   =      29089 KPa      (29.09 MPa)
         DEV.  =     -12.10 %
```

Firoozabadi & Aziz (1986) Correlation

```
- sample calculation for system # 27
INPUT DATA CONTAINING RESERVOIR OIL & INJECTED GAS COMPOSITIONS
           MOL%     MOL%
COMP.     IN OIL   IN GAS
--------------------------
H2S         0.00     0.00          TEMP.(C)        :   171.11
CO2         3.60     0.00          MMPexp.(KPa)    :    33095
N2          0.25     0.00          MWC7+           :    183.6
C1         56.86   100.00          MWC10+          :      217
C2          9.37     0.00
C3          5.48     0.00
i-C4        1.46     0.00
n-C4        2.61     0.00
i-C5        1.20     0.00
n-C5        1.39     0.00
C6          1.26     0.00
C7          1.26     0.00
C8          2.06     0.00
C9          2.13     0.00
C10+       11.14     0.00
--------------------------
 TOTALS   100.07   100.00

-the Firoozabadi & Aziz Correlation (converted to SI units) is as follows:

        MMP    = (9433-188*10^3*X+1430*10^3*X^2)*6.894757
         & X   = (%C2-C5)/[(MWC7+)*(1.8*T+32)^0.25]
-where:
        MMP    = KPa
        %C2-C5 = mol% C2-C5 in reservoir oil
                 (including CO2 & H2S)
        MWC7+  = molecular weight of C7+ heavy fraction in the oil
        T      = reservoir temperature, C

-input:
        %C2-C5 =    25.11 %
        MWC7+       183.6
        T      =   171.11 C

-results:
        X      = 0.031849
        MMP    =    33756 KPa      (33.76 MPa)
        DEV.   =     2.00 %
```

Nouar & Flock (1988) Lean Gas Correlation

- sample calculation for system # 27

INPUT DATA CONTAINING RESERVOIR OIL & INJECTED GAS COMPOSITIONS

COMP.	xi (OIL)	yi (GAS)	M.Wt. (kg/kmol)	xi*MW (kg/kmol)
H2S	0.0000	0.0000	34.080	0.0000
CO2	0.0360	0.0000	44.010	1.5844
N2	0.0025	0.0000	28.020	0.0701
C1	0.5686	1.0000	16.043	9.1220
C2	0.0937	0.0000	30.070	2.8176
C3	0.0548	0.0000	44.097	2.4165
i-C4	0.0146	0.0000	58.124	0.8486
n-C4	0.0261	0.0000	58.124	1.5170
i-C5	0.0120	0.0000	72.151	0.8658
n-C5	0.0139	0.0000	72.151	1.0029
C6	0.0126	0.0000	86.178	1.0858
C7	0.0126	0.0000	100.205	1.2626
C8	0.0206	0.0000	114.232	2.3532
C9	0.0213	0.0000	128.259	2.7319
C10+	0.1114	0.0000	217.000	24.1738
TOTALS	1.0007	1.0000		51.8522

TEMP.(C) : 171.11
MMPexp.(KPa) : 33095
MWC7+ : 183.6
MWC10+ : 217

-the first step required is to separate the reservoir oil into light, intermediate, and heavy pseudocomponents, as indicated below. The molecular weight of each pseudocomponent is then calculated.

PSEUDOCOMPONENT GROUPINGS:

*light fraction - C1,N2:
Xl = 0.5711
AMW = 16.095

*int. fraction (C2-C6,CO2,H2S):
Xi = 0.2637
AMW = 46.032

*heavy fraction (C7+):
Xh = 0.1659
AMW = 183.600

-Nouar & Flock calculated the miscibility conditions of several ideal ternary systems. The next step is to find four of these ternary systems which circumscribe the actual reservoir oil on the basis of the molecular weights of the intermediate and heavy pseudocomponents.

TERNARY		MWI	MWH
#1	C1-C3-C12	44	170
#2	C1-C3-C15	44	212
#3	C1-C4-C12	58	170
#4	C1-C4-C15	58	212

-for each of these ternary systems, the following 4 equations are solved:

C0 = -Xi-(1-a1*xic+a2*xic^2)(Xl-1+xic+b1*xic)
C1 = 1+b1(1-a1*xic+a2*xic^2)-(a1-2*a2*xic)(Xl-1+xic+b1*xic)
C2 = b1(a1-2*a2*xic)-a2(Xl-1+xic+b1*xic)
C3 = a2*b1

-the calculated values of C0, C1, C2 & C3 are then substituted into the following equation to determine the value of XIC for each ideal ternary at the critical point. XIC represents the mole fraction of the oil intermediate component at the critical point.

0 = C0+C1*XIC+C2*XIC^2+C3*XIC^3

-where: a1, a2, b1, & xic are correlation parameters specific to a particular ternary at a specific temperature (see Nouar & Flock, 1988, Table 2).

-and: Xi = mole fraction of intermediates (C2-C6, CO2 & H2S) in the reservoir oil
Xl = mole fraction of light-ends (C1 & N2) in the reservoir oil

-The Nouar & Flock tabulated data falls between 30 & 90 degrees C, in 15 degree C increments. The MMP of each ternary at 75 and 90 degrees C must then be calculated, and these results used to extrapolate the MMP to 171.11 degrees C.

-for each ternary at each temperature, the correlation coefficients are:

AT T = 75 C

TERNARY	MWI	MWH	xic	b1	a1	a2
#1	44	170	0.7087	-0.893	1.051	-0.456
#2	44	212	0.7087	-0.916	1.057	-0.429
#3	58	170	0.3617	-0.787	2.328	-1.078
#4	58	212	0.3617	-0.833	2.369	-0.895

AT T = 90 C

TERNARY	MWI	MWH	xic	b1	a1	a2
#1	44	170	0.8943	-0.912	0.699	-0.431
#2	44	212	0.8943	-0.932	0.681	-0.440
#3	58	170	0.4257	-0.812	1.770	-1.385
#4	58	212	0.4257	-0.854	1.719	-1.340

-C0 through C3 values, and then XIC values, are calculated for each ternary:

AT T = 75 C

TERNARY	C0	C1	C2	C3	XIC
#1	-0.25448	1.575944	-1.67671	0.407208	0.203267
#2	-0.25061	1.582563	-1.68365	0.392964	0.1[illegible]227
#3	-0.25774	2.080188	-2.82516	0.848386	0.155021
#4	-0.25410	2.089853	-2.84250	0.745535	0.151607

AT T = 90 C

TERNARY	C0	C1	C2	C3	XIC
#1	-0.25313	1.487230	-1.49147	0.393072	0.213241
#2	-0.24931	1.503922	-1.53011	0.41008	0.206918
#3	-0.25784	1.997789	-2.83732	1.12462	0.165346
#4	-0.25439	2.027173	-2.93377	1.14436	0.160391

-Nouar & Flock graphically correlated XIC values with MMP's as a function of temperature, and the MWI and MWH values for the reservoir oil (Figures 3 through 22 of Nouar & Flock, 1988). Reading the MMP from the appropriate Figure for each ternary:

AT T =			75 C		90 C	
TERNARY	MWI	MWH	XIC	MMP(MPa)	XIC	MMP(MPa)
#1	44	170	0.203	25.9	0.213	26.1
#2	44	212	0.198	30.6	0.207	30.8
#3	58	170	0.155	26.7	0.165	26.8
#4	58	212	0.152	31.1	0.160	31.4

-interp./extrap. between ternaries 1&2 and 3&4 to MWH:

AT T =			75 C	90 C
			MMP	MMP
TERNARY	MWI	MWH	(MPa)	(MPa)
#5	44	183.6	27.42	27.62
#6	58	183.6	28.12	28.29

-interp./extrap. between ternaries 5&6 to MWI:

			75	90
TERNARY	MWH	MWI	MMP(MPa)	MMP(MPa)
#7	183.6	46.032	27.52	27.72

-extrapolating the results to T = 171.11 C:

MMP = 28.77 MPa

DEV. = -13.06%

Glaso (1985) Nitrogen Gas Correlation

```
- sample calculation for system # 45
INPUT DATA CONTAINING RESERVOIR OIL & INJECTED GAS COMPOSITIONS
          MOL%     MOL%
COMP.     IN OIL   IN GAS
--------------------------
H2S         0.00     0.00          TEMP.(C)         :   60.00
CO2         0.49     0.00          MMPexp.(KPa)     :   38000
N2          0.47   100.00          MWC7+            :     232
C1         54.67     0.00
C2          8.75     0.00
C3          4.87     0.00
i-C4        0.71     0.00
n-C4        2.26     0.00
i-C5        0.75     0.00
n-C5        1.29     0.00
C6          2.23     0.00
C7+        23.52     0.00
--------------------------
 TOTALS   100.01   100.00

-the Glaso N2 correlation (converted to SI units) is as follows:

-for Fr > 28%:
MMP(MWC7+>160) = 43878.2-83.358*MWC7+
                +(7.77*10^(-12)MWC7+^5.258*e^[23025MWC7+^(-1.703)]-143.41)(1.8T+32)
MMP(MWC7+<160) = 53055.2-83.358*MWC7+
                +(7.77*10^(-12)MWC7+^5.258*e^[23025MWC7+^(-1.703)]-274.2)(1.8T+32)
-where:
        MMP   = KPa
        MWC7+ = M.Wt. of C7+ heavy fraction in reservoir oil
        T     = reservoir temperature, C
        Fr    = mol% C2-C6 in reservoir fluid (including CO2 & H2S)

-for Fr < 28%:
MMP(Fr<28) = 64562-83.358*MWC7+
            +(7.77*10^(-12)MWC7+^5.258*e^[23025MWC7+^(-1.703)]-143.41)*(1.8T+32)-684.65Fr

-input:
        MWC7+   =    232
        T       =     60 C
        Fr      =  21.35 %

-results:
        MMP(MWC7+>160) =     30219 KPa
        MMP(MWC7+<160) =     21085 KPa
        MMP(Fr<28)     =     36285 KPa

-since Fr < 28%, the final value applies:
        MMP  =      36285 KPa      (36.62 MPa)
        DEV. =      -4.51%
```

Glaso (1988) Correlation

- sample calculation for system # 45

INPUT DATA CONTAINING RESERVOIR OIL & INJECTED GAS COMPOSITIONS

COMP.	MOL% IN OIL	MOL% IN GAS
H2S	0.00	0.00
CO2	0.49	0.00
N2	0.47	100.00
C1	54.67	0.00
C2	8.75	0.00
C3	4.87	0.00
i-C4	0.71	0.00
n-C4	2.26	0.00
i-C5	0.75	0.00
n-C5	1.29	0.00
C6	2.23	0.00
C7+	23.52	0.00
TOTALS	100.01	100.00

TEMP.(C) : 60.00
MMPexp.(KPa) : 38000
MWC7+ : 232

-the Glaso correlation (converted to SI units) is as follows:

$$MMP(API<45) = (725.0-3.85x-9.22y+0.63z)*100$$
$$MMP(API>45) = (878.8-9.17x-1.71y-1.25z)*100$$

-where:

MMP=KPa
x = mol% C1 in the reservoir oil (including N2)
y = mol% intermediates (C2-C6) in reservoir oil (including CO2 & H2S)
z = reservoir temperature, C

-input:

x = 55.14 %
y = 21.35 %
z = 60.00 C

-results:

MMP(API<45) = 35366 KPa (35.37 MPa)
MMP(API>45) = 26166 KPa (26.17 MPa)

-the oil API gravity was not given, but can be estimated using the MWC7+ value. Using the work of Whitson (1980), specific gravity (SG) values were estimated for the particular MWC7+. The oil API gravity was then calculated using:

$$API = (141.5/S.G.) - 131.5$$ (Craft & Hawkins, 1959)

-the estimated SG = 0.848, so the calculated API gravity is 35.4, and:

MMP(API<45) = 35366 KPa (35.37 MPa)
DEV. = -6.93%

- sample calculation for system # 45

INPUT DATA CONTAINING RESERVOIR OIL & INJECTED GAS COMPOSITIONS

COMP.	MOL% IN OIL	MOL% IN GAS
H2S	0.00	0.00
CO2	0.49	0.00
N2	0.47	100.00
C1	54.67	0.00
C2	8.75	0.00
C3	4.87	0.00
i-C4	0.71	0.00
n-C4	2.26	0.00
i-C5	0.75	0.00
n-C5	1.29	0.00
C6	2.23	0.00
C7+	23.52	0.00
TOTALS	100.01	100.00

TEMP.(C) : 60.00
MMPexp.(KPa) : 38000
MWC7+ : 232

-the Hudgins, Llave & Chung N2 Correlation (converted to SI units) is as follows:

MMP = [5568e^(-R1)+3641e^(-R2)]*6.894757
&
R1 = [792.06(C2-C5)]/[(MWC7+)*(1.8*T+32)^0.25]
R2 = [2.158*10^(6)*(C1^5.632)]/[(MWC7+)*(1.8T+32)^0.25]

-where:

MMP = KPa
T = reservoir temperature, C
C1 = mole fraction of C1 in the reservoir oil (including N2)
C2-C5 = mole fraction of C2-C5 in the reservoir oil (including CO2 & H2S)
MWC7+ = molecular weight of C7+ heavy components in the reservoir oil

-input:

T = 60.00 C
C1 = 0.5514
C2-C5 = 0.1912
MWC7+ = 232

-results:

R1 = 0.189769
R2 = 94.61766
MMP = 31754 KPa (31.75 MPa)
DEV. = -16.44%