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-THEME-

LES CRITERES DE GROUPEMENT ET DEGROUPEMENT DES EQUATIONS D'ETAT (EOS) POUR LA SIMULATION DE RESERVOIR

Soutenue le 22:/ 06 / 2021 devant la commission d'examen

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Hydrocarbon Production Department

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To obtain the Master's Degree

Option: Academic Production

Presented by :

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-THÈME-

EQUATIONS OF STATE (EOS) LUMPING AND DELUMPING CRITERIA FOR RESERVOIR SIMULATION

Discussed on 22: / 06/2021 before the examination committee

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Dedication:

To our grandmother who recently passed away.

To my dear fathers who have always supported me in my life decisions, who have stood by me during my study journey, to the loving mothers who have always stayed up for my nights in the interest of my comfort, whose prayers have always accompanied me at every step, to my dear brothers who were proud of me, to my dear loved ones and friends who took in my hands, and relieve me of my estrangement.

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AMARA Mohamed elmehdi



Abstract:

the use of simulation of reservoir is very important among the objectives of reservoir fluid evaluation, the strong coupling between process and reservoir simulation leads to several numerical approaches of the process in reservoir simulation: equilibrium factors, split factors, pseudo-process or real time coupling of the two simulators, The lumping and delumping models that is used to generate equation of state , the lumping include information from the dynamics process into the grouping of detailed components, because of the huge number of grid blocks in a full field reservoir model, the number of components must be drastically reduced compared to the fluid description needed for the process calculations order to minimize the running time of the simulation process , The use of the these techniques impacts the results of the reservoir fluid behavior comparing with original phase diagram .

Key words: Simulation of reservoir, Equation of state, split factors, grid block.

Résume:

l'utilisation de la simulation de réservoir est très importante parmi les objectifs est l'évaluation du fluide de réservoir, le couplage fort entre processus et simulation de réservoir conduit a plusieurs approches numériques du processus en SR: facteurs d'équilibre, facteurs de division, pseudo-processus ou couplage en temps réel des deux simulateurs. Les modèles de lumping et de delumping qui sont utilisés pour générer l'équation d'état , le schéma de lumping inclut des informations du processus dynamique dans le regroupement de composants détailles , en raison du grand nombre de blocs de grille dans un modèle de réservoir plein champ , le nombre de composants doit être considérablement réduit par rapport a la description du fluide nécessaire pour les calculs de processus a fin de minimiser le temps d'exécution du processus de simulation, l'utilisation de ces techniques a un impact sur les résultats du comportement du fluide du réservoir par rapport au diagramme de phase d'origine.

Les mots clés: Simulation de réservoir, équation d'état, facteurs de division, blocs de grille

ملخص:

دراسة استخدام محاكاة المكمن، من بين أهداف استخدامه تقييم مائع المكمن، و يؤدي الاقتران القوي بين محاكاة العملية و المكمن إلى العديد من المقاربات العددية للعملية من بينها: عوامل التوازن، عوامل الانقسام، عملية زائفة أو اقتران في الوقت الحقيقي لجهازي محاكاة, نماذج التجميع و التقسيم التي تستخدم لإنشاء معادلة الحالة، يشمل مخطط التجميع على معلومات من عملية الديناميكيات في تجميع المكونات التفصيلية ، نظرا للعدد الهائل من الكتل الشبكية في نموذج خزان الحقل الكامل ، يجب تقليل عدد المكونات بشكل كبير مقارنة بوصف السائل المطلوب لحسابات العملية من أجل تقليل وقت تشغيل عملية المحاكاة ، فإن استخدام هذه التقنيات يؤثر على نتائج سلوك مائع الخزان مقارنة بمخطط الطور الأصلى.

الكلمات المفتاحية: محاكاة المكمن، ، عوامل الانقسام، مخطط معادلة الحالة، الكتل الشبكية .

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Abbreviations-Symbols:

Abbreviations:

GUI: Graphical User Interface. **PI:** Productivity Index. **PVT:** Pressure Volume Temperature System. **EOS:** Equation Of State. **BOAST:** Black Oil Applied Simulation Tool. MRTS: Matlab Reservoir Simulation Toolbox. **CEOS:** Cubic Equation Of State. SRK: Soave-Redlich-Kwong Equation Of State. **RK:** Redlich-Kwong Equation Of State. **VDW:** Van Der Waals Equation Of State. **CCE:** Constant-Composition Expansion Tests. **DD:** Differential Liberation Tests. SWT: Swelling Test. CVD: Constant-Volume Depletion Test. PCS: Single Pseudo Components. SCN: Single-Carbon-Number. BTX: Benzene, Toluene And Xylene. RMS: Root Mean Square. MMP: Minimum Miscibility Pressure. MCN: Multi Carbon Number. **CPU:** Central Processing Unit. **NBP:** Normal Boiling Point. GOR: Gas Oil Ratio.

Symbols:

V: volume.
T: temperature.
P: pressure.
P _{total} : total pressure of mixture.
P _i : partial pressure.
n: number of moles.
R: the universal ideal gas constant.
Z: compressibility factor.
a: the increasing attractive forces between molecules at higher pressure.
b: measure of the co-volume of molecules at infinite pressure.
T _c : critical temperature.
P _c : critical pressure.
V _c : critical volume.
ω: acentric factor.
k: a polynomial function of ω , k=f(ω).
ρ: Density.
m: masse.
γ: Specific gravity.
°API: Specific gravity used in oil industry.
ŋ: Cinematic viscosity.
μ: The dynamic viscosity.
Rs : gas solubility.
Bo: Oil formation volume factor .
\mathbf{V}_{t} : volume total.
V sat: standard volume.
V _{rel} : relative volume.
P _b : bubble point pressure.
V I: liquid volume.
Nxx: number of components of a detailed model.
Nx: number of pseudo-components.
N scenarios: number of possible lumping scenarios.
Z i: fraction composition.
M _i : molecular weight.
W n: Weighting factors.

 $X_{\ i}$, Y_{i} are equilibrium phase compositions.

K i: the K-value.

σ: binary interaction parameter.

Ng: number of MCN groups.

 β : introduced as a parameter to quantify the amount of injection gas.

nt: total moles of well-connection stream.

n_{ig}: moles of injection gas in the well-connection stream.

 \mathbf{n}_{o} : moles of reservoir oil in the well-connection stream.

n_g: mole of reservoir gas in the well-connection stream.

GENERAL INTRODUCTION

General Introduction:

In the oil and gas industry, the exploitation process faces challenges and technical problems limit the hydrocarbons recovery operation, to understand the recovery technical limit a study the reservoir fluid behavior in the sub surface environment up to the surface condition is important to evaluate, select and achieve a future recovery options through a current prediction of the reservoir fluid behavior mechanism during its life time.

In 1st chapter, a general information are presented about the simulation of the reservoir describe the fluid behavior at giving conditions, through the combination of reservoir geological model, fluid characterization and the data of reservoir rock – fluid characterize using either black oil phase modeling or compositional one.

The modeling equations used are the cubic equation of state CEOS, represented in the, these equations do model the fluid thermodynamic behavior at giving pressure, temperature and volume conditions, the CEOS defined the relation between system properties.

For a reservoir fluid, 20 to 40 components can be contained in state model for the initial fluid sample divided into light components such as H_2S , CO_2 , and the hydrocarbons C_1 to C_6 , the remained components called heavy fraction, in the reservoir simulation, modeling 40 components is charged and time consuming. In the 2nd chapter, The techniques of minimizing number of the detailed EOS model to smaller pseudo components number only 6-9 components, lumping techniques scheme such as Whitson's, Pederson's schemes are presented along with mixing rules used to determine the pseudo properties maximizing the accuracy of the results.

The Simulations of downstream processes, more detailed fluid data descriptions are required to design and optimize separation processes, delumping of a one pseudo component into several via the inverse process is presented in the 3rd chapter as well, it is applicable through schemes such Ahmed's(1985) and Kat's delumping technique (1983).

In this thesis, at last the impact of using these criteria in simulation on the reservoir fluid properties and phase behavior represented in a case study (3rd chapter) that required the application of many lumping schemes on a sample prepared of the gas condensate of oil field contains 16 components, the Impact can be seen by the comparison of the lumping technique resulted phase diagram approach with the detailed EOS model phase diagram to note the deviation rates of each scheme grouping selection method.

A lumping and delumping method is useful for estimating the properties or behavior of liquid of hydrocarbon phases from data relative to a reference set of hydrocarbon mixtures in a series of thermodynamic states with an acceptable results accuracy.

CHAPTER I: RESERVOIR SIMULATION AND EQUATION OF STATE

CHAPTER I

I-1 Introduction:

The petroleum gisement is a subsurface pool formed of one or more reservoir containing the liquid and/or gaseous hydrocarbons, of sedimentary origin with rare exceptions, limited by impermeable barriers.

Through the exploration of hydrocarbons wells, a lot of information are collected that describe the different aspects of the oil and gas wells in order to create a general idea about the current situation of well (oil and gas in place, porosity, permeability, the fluid (type, characterization and dynamics) and the reservoir rock...) and make the best possible recovery plan of future production for the well with a view of fulfillment the maximum recuperation rate for the longest possible lifetime of well.

The reservoir performance can be presented in two model types:

- ✓ A physical model: presents the total descriptive informations of the reservoir such as the type of fluid (for example heavy black oil), reservoir (carbonate, sand ...), well completion, drainage and type of flowing (natural or gas injection)etc.
- ✓ A mathematical model: which is a set of equations that subject to certain assumptions relate the different numerical information of the reservoir such the API, porosity, the permeability, flow rate, gas injection rate (in assisted well), depth, saturation ...etc; that describes the physical processes active in the reservoir.

The collection of the these two model types allow us to understand farther the behave of the reservoir fluid at the giving conditions through a final results represent the relation fluid-reservoir using a computer program to link the previous data together forming a reservoir simulation, it is grounded on recognized engineering equations, it is started as a basic mathematical models to become more efficient due to the advanced capabilities provided by modern day technology.

I-1-1 Reservoir Simulation :

In general, the simulation is a theoretical (or physical) representation of an operation and an imitation of the system/processes in real life, reservoir simulation is a field developed in petroleum engineering by combing physics, mathematics, reservoir engineering, and computer programming for predicting hydrocarbon fluid-reservoir performance under various operating strategies, in order to estimate the fluid dynamics, which is an important step in the implementation of exploitation progress.

- Reservoir simulation mimics the behavior of a real reservoir system (geology + engineering) through a numerical model based in realistic assumptions.
- Reservoir numerical simulation can be close to reality but it never the reality (should approach reality with time).
- Basically, the simulation model requires that the field under study be described by a grid system, usually referred to as cells or grid blocks, each cell must be assigned reservoir properties to describe the reservoir.
- The computer simulator will allow us to describe a fully heterogeneous reservoir to include varied well performance and to study different recovery mechanisms.⁽¹⁾



Fig. 1: Schematic description of a simulation model

I-1-3 History Of Reservoir Simulation:

- ✓ In 1950–1970 it starts with the black oil fluid (oil, water and gas modeling) model represented in simple geometry in 2-3 dimensions for one or multiple wells, also presents the well conning.
- ✓ 1970–1980, the development includes the Compositional model, also the ability to present the thermal properties of mixture and miscible gas behavior.
- ✓ From the year 1980–1990 particularity of Complex well management is concluded next to fractured reservoirs, special gridding at faults and graphic interface.
- ✓ 1990s –Advanced GUIs, integration with geo-modeling, geomechanics, parallel computer techniques, local grid refinement.⁽²⁾

I-1-4 Reservoir Simulation objectives :

for the main following objectives of study:

- ✓ To build a model of the reservoir and to examine its performance in terms of production and pressure (Tank model).
- \checkmark To predict future performance.
- \checkmark To find ways to increase ultimate recovery or to recover the hydrocarbon more economically. (1)

I-1-5 Simulation Modeling Steps:

A simulation of a system is the operation of modeling its properties in 3D model, involving designing a simulation experiment and performing simulation analysis; the steps of developing a "Simulation Model" are:

- **Step1:** Identify the Problem: Enumerate problems with an existing system. Produce requirements for a proposed system.
- **Step 2**: Formulate the Problem:
 - \checkmark Select the bounds of the system's problem to be studied.
 - \checkmark Define overall objective of the study and a few specific issues to be addressed.
 - ✓ Define performance measures-quantitative criteria on the basis of which different system configurations will be compared and ranked.
 - ✓ Identify, briefly at this stage, the configurations of interest and formulate hypotheses about system performance.
 - \checkmark Decide the time frame of the study, then identify the end-user of the simulation model.
- Step 3: Collect and Process Real System Data: Collect data on system specifications, input variables, as well as the performance of the existing system.
- **Step 4**: Formulate and Develop a Model:
 - \checkmark Develop schematics and network diagrams of the system.
 - \checkmark Translate these conceptual models to simulation software acceptable form.
 - ✓ Verify that the simulation model executes as intended, using the verification techniques including traces, varying input parameters over their acceptable range and checking the output, substituting constants for random variables and manually checking results, and animation.
- **Step 5**: Validate the Model:
 - Compare the model's performance under known conditions with the performance of the real system.

- ✓ Perform statistical inference tests and get the model examined by system experts; assess the confidence that the end user places on the model and address problem if it exists.
- **Step 6**: Document Model for Future Use: Document objectives, assumptions and input variables in detail. Document the experimental design.
- Step 7: Select Appropriate Experimental Design:
 - ✓ Select a performance measure, a few input variables that are likely to influence it, and the levels of each input variable. Generally, in stationary systems, steady-state behavior of the response variable is of interest. Ascertain whether a terminating or a non terminating simulation run is appropriate. Select the run length. Select appropriate starting conditions.
 - \checkmark Select the length of the warm-up period, if required.
 - ✓ Decide the number of independent runs –each run uses a different random number stream and the same starting conditions– by considering output data sample size with the sample size must be large enough (at least 3-5 runs for each configuration) to provide the required confidence in the performance measure estimates. Alternately, use common random numbers to compare alternative configurations by using a separate random number stream for each sampling process in a configuration, the identified output data most likely is to be correlated.
- **Step 8**: Establish Experimental Conditions for Runs:
 - ✓ Address the question of obtaining accurate information and the most information from each run.
 - Determine if the system is stationary (performance measure does not change over time) or non-stationary (performance measure changes over time).
- Step 9: Perform Simulation Runs: Perform runs according to steps 7-8 above.
- Step 10: Interpret and Present Results: Compute numerical estimates (e.g., mean, confidence intervals) of the desired performance measure for each configuration of interest, the test the hypotheses about system performance. Construct graphical displays (e.g., pie charts, histograms) of the output data. Document results and conclusions.

• Step 11: Recommend Further Courses of Action: This may include further experiments to increase the precision and reduce the bias of estimators, to perform sensitivity analyses...etc. Although this is a logical ordering of steps in a simulation study, much iteration at various substages may be required before the objectives of a simulation study are achieved. Not all the steps may be possible and/or required. On the other hand, additional steps may have to be performed.

I-1-6 Methodology Of Reservoir Simulation:

The reservoir simulation is a technology of generalized use in the petroleum industry to evaluate actual and future reservoir performance, a general methodology for reservoir performance is presented in the following points:

- \checkmark The reservoir is divided into the number of blocks (or grid blocks).
- ✓ Basic geological and reservoir data is provided for each block.
- \checkmark Wells are positioned within the arrangement of blocks.
- \checkmark The target rate and well pressure are specified as function of time.
- The appropriate equations derived from the Darcy's law are solved to give the pressure and saturation each block as well as the production and injection for each well.

I-1-7 Elements Of A Reservoir Simulation Study:

In order to have an study for an optimal simulation results, the following elements are required:

- Setting up the study.
- Defining the study's objectives.
- Formulating a model.
- Data preparation.
- Collecting rock and fluid data.
- Reservoir description.
- Collecting well performance and completion data.
- Defining producing conditions.
- History matching.
- Adjusting reservoir parameters to match past performance (usually pressure).
- Predicting performance.
- Running the simulator and analyzing the output.
- Sensitivity analysis of the data.

- Identifying critical parameters.
- Evaluating alternate strategies for development.

Fig 2: Schematic description of simulation elements



I-1-8 Reservoir Simulation Tasks:

The simulation process can be break down to 3 main steps as:

- \checkmark Choice and controls
- Locations of producers and injectors
- Well completion and down hole equipment
- Water or gas injection rates
- The production rate
 - ✓ Reservoir data :
- Reservoir geology
- Drive mechanism, is there any aquifer
 - ✓ Reservoir performance results:
- Well production rates of oil, water and gas
- Field reservoir pressure
- Individual wells pressures and PI.⁽⁴⁾

I-1-9 The Purpose Of Reservoir Simulation Model:

The purpose of the reservoir data modeling in the reservoir simulation presented in finding solutions of the following challenges:

- The field should be developed and produced in order to minimize the economic recovery of hydrocarbon.
- The best enhanced recovery scheme for the reservoir, how and the whenever should it be implemented.
- The ultimate possible economic recovery for the field.
- Presenting the different relations between all types of laboratory data are required and the sensitivity to various data.
- The critical parameters that should be measured in the field application of a recovery scheme.
- To have the best completion scheme for wells in a reservoir.

I-1-10 Compositional Formulation :

The reservoir simulation is used because a real reservoir can only be exploited once which explains the need to understand the fluid subsurface behavior using two main formulations that are common, the black oil model and compositional model.

a- The Black Oil Model:

The Black Oil Model is the most commonly used in reservoir simulation. The methods used in the Black Oil Model are also relatively optimal. In the process of developing a simulation model, a variety of numerical methods, such as Semi-Implicit, Fully-Implicit and Adaptive Implicit methods, have been developed, each of these methods has its own advantages in solution and can be used in certain cases. Although many numerical methods are still used up to now, the basic mathematical approach of Black Oil Model has not been changed yet. In software of some companies, the gas saturation and solution gas oil ratio are considered as the third alternative variable.

This kind of mathematical approaches is the most natural and easy methods to be accepted in order of solving Black Oil Model problems. In three mass-balance equations; some rock and fluid properties, such as relative permeability, capillary pressures, oil formation volume factor, solution gas oil ratio and viscosities are in functions of pressure, saturation and bubble point pressure as measured in laboratory.

CHAPTER I

In this model, oil is treated as a single component with no interaction with the gas or water phases. ⁽⁵⁾

b- Compositional Model:

The compositional reservoir simulation has more equations to solve, per block and time step, which results in an increasing demand on computational power to solve the system compared with the black-oil-simulation. However, with today's increase in getting cheaper availability of computational power, compositional reservoir simulators are the method of choice.

To accurately approximate the production of a near critical fluid with a compositional simulator, e.g. for a condensate gas, a PVT model needs to be matched to experimental data of the reservoir fluid.

The compositional reservoir simulator is calculating the isothermal flow of single components within a hydrocarbon mixture, by determining the movement of a phase via equilibrium calculations. It can account for compositional variations and therefore miscibility calculations,. ⁽⁶⁾



Fig. 3: Schematic description of a reservoir simulation

I-1-11 Derivation Of The Fluid Flow Equation :

The complete mathematical model is a combination of:

- Govering equation.
- Boundary equation.
- Initial condition.

where the basic equations are obtained by combining several physical principals namely:

- Conservation of mass.
- Rate equation.
- Equation of state.

The flow equations for single and multiphase flow are obtained by combining appropriate forms of Darcy's law and the equation of mass conservation, the fluid density is expressed explicitly or implicitly as a function of pressure through an equation of state.

I-2-1 Equation Of State:

In oil and gas industry, the ability to link the previous different parameters of substance which used to describes its behavior, the reservoir fluid in this case by a experimental lab measures on an obtain representative sample from the reservoir in order to determine the system parameters values, the sample become most important feature to understand the flowing mechanisms of under sol phases such oil, by providing reliable volumetric data as a valuable tools that determine the success of phase equilibrium prediction, the corrolations that describes the relationship between substance parameters are called the equation of state EOS.

Equation of state is a thermodynamic expression relates pressure, temperature and volume used to describe the state of the reservoir fluid at certain P, V and T conditions to predict their physical proprieties at given condition, presented in several forms; the EOS are widely used in the oil industry to reduce production coasts and energy consumption by the virtual design of reservoir heat exchanger.

Many equations of state can be used depending on the characteristics of the system under study. Amongst these are the Redlich-Kwong, Peng-Robinson and Soave-Redlich-Kwong equations. Most rely on knowledge of the critical properties of the pure components and the acentric factor,

which is related to the vapor pressure of the substance. Complex mixing rules can apply for multicomponent mixtures. ⁽⁷⁾

I-2-2 Classification Of Equation Of State:

There are different types of EOS which fall into three categories:

A. First class:

These equations are basically cubic equation of state (CEOS). The cubic equations of state such as the Van Der Waals, Redlicha and Kwong, Soave-Redlich-Kwong, and Peng-Robinson, this equations give reasonable results for the thermodynamic behavior of real fluids, used in reservoir simulation.

B. Second class:

These EOS are non-cubic equations in form. They are providing accurate results for both vapor and liquid phases such as Benedict and al equation which is a good example for this class equation.

C. Third class:

These are non analytical EOSs that are highly constrained for some specific fluids. Even though they are constrained, they are capable of expressing real fluid thermodynamic properties precisely.

Among all these EOS, in reservoir simulation the most used equation of state are the Cubic equations, mostly the Soave-Redlich-Kwong (SRK), Redlich-Kwong (RK) then Van Der Waals equations; because it provides an analytical solution than the more complex and complicated other types without time-consuming in iterative calculations in fluid properties performance prediction.⁽⁸⁾

I-2-3 Overview Of Equations Of State:

In 1662, Boyle introduced the concept of pressure to obtain a gas law from J shaped glass tube experiments and qualitatively interpret properties of air. Then the Charles and Gay Lussac's Law published in 1787 that indicates the relationship between the temperature and the volume as follow:

 $V_1.T_2 = V_2.T_1.$ (I-1)

In 1801 the Dalton's law represents the pressure state of a mixture of gases is equal to the total partial pressures sum:

$P_{\text{Total}} = P_1 + P_2 + P_3 + \ldots + P_n = \Sigma^n_{i=1} P_i \ldots (I-2)$

Assuming that the molecules are very far and have no attractive or repulsive forces between them and elastic collisions between these molecules, by the combination of the Charles's and Gay-Lussac's law led to the discovery of the ideal gas law of:

 $\mathbf{PV} = \mathbf{nRT} \dots (I-3)$

Where:

- ✓ P : absolute the pressure [psia];
- ✓ V : the volume [ft^3];
- \checkmark R : the universal gas constant
- \checkmark T : absolute temperature °R and n is the number of moles of gas, lb-mole

Subsequently, the above gas law is applicable only in theoretical cases of non compressible fluid to the so-called ideal gas, it has been found that the ideal gas relation lead to errors up to 500% in application on real states of a substance.

Thus, the ideal gas model appeared to help to understand the thermodynamic properties of the state of substance. Real gases behave differently than ideal gases, the reason for this deviation is that the ideal gas law was derived under the assumption that the volume of molecules is very small and neither molecular attraction nor repulsion exists between them, As a consequence, a correction factor has to be inserted into the ideal gas equation to form the real gas expression.

By elimination of ideal gas assumption, the Van Der Waals invented the first EOS; also Virial and other equations of state quantitatively described the deviation of an actual fluid state from the idealgas state. The extension of the ideal-gas law not only promoted the continuing refinement of the molecular theory, but also, more importantly, provided the basic idea of a method for extending its application to other properties. It is thermodynamics that plays an important role in the study of physical properties of substances.

1. Compressibility factor:

For gases at low pressures, the ideal gas law is a convenient satisfactory tool, the application of the ideal gas law at higher pressures may lead to errors up to 500%, compared to 2-3 % at atmospheric pressure. In order to write an equation of state for a real gas, a correction factor has to be inserted into the ideal gas equation as:

Where 'Z' is the correction or the compressibility factor, it is a measure of the thermodynamic deviation of real gas properties from the ideal gas, is a dimensionless quantity and is defined as the ratio of the actual volume of n-moles of gas at T and p to the ideal volume of the same number of moles at the same T and p:

I-2-4 Cubic Equation Of State :

The cubic equations of state (CEOS) such as Van Der Waals, Redlich-Kwong, Soave, and Peng-Robinson are simple models that have been widely used in oil and gas industry, in order to calculate reservoir fluid properties at arbitrary sets of conditions according to their thermodynamic region of applicability. The functional form of an EOS varies from one that contains few or no substance-dependent parameters to those that are used for reference substances that contain more than 100 substance-dependent parameters.

The cubic equations of states are based on the famous Van Der Waals relation (1873), Van Der Waals attempted to eliminate the assumptions of ideal gas law in the development of an empirical EOS for the real gas:

The term a/V^2 takes into account the increasing attractive forces between molecules at higher pressure, while 'b' is a measure of the co-volume of molecules at infinite pressure. Note that the parameters 'a' and 'b' depend only on the critical pressure and temperature.

Where: **V** is the molar volume, The substance-specific constants **a** and **b** can be calculated from the critical properties T_c , P_c and V_c (noting that V_c is the molar volume at the critical point) as: $\mathbf{a}=3P_cT_c^3$ and $\mathbf{b}=\frac{V_c}{3}$

Long time the original Van Der Waals EOS (VDW-EOS) did not found industrial applications. Redlich and Kwong (1949) discovered that a modified form was convenient for describing the properties of hydrocarbon mixtures. The model, abbreviated here by RK-EOS, is represented by the relation:

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$$P = \frac{RT}{V-b} - \frac{a}{T^{\frac{1}{2}} V (V-b)} \dots \dots (I-7)$$

In fact, RK-EOS introduced an important modification in the formulation of Van Der Waals equation, the temperature dependency of the 'a' parameter, such as:

$$\mathbf{a}$$
 (T)= $\mathbf{a}_{\mathbf{c}}$ (T_c, P_c) \propto (T)(I-8)

The correction factor a (T) of the a parameter is designated often by alpha function. For the RK-EOS, this factor is \propto (T) = 1/ \sqrt{T} .

Much later, Soave (1972) proposed a new modification, known as Soave–Redlich–Kwong EOS (SRK-EOS), in which the model incorporates another important molecular parameter, the acentric factor ' ω '. The result was that the accuracy of VLE computations improved considerably. In the case of SRK-EOS the alpha function is:

$$a^{0.5} = 1 + k(1 - T_r^{0.5})$$

The factor k is a polynomial function of ω , $k=f(\omega)$.

Another equation, proposed by Peng and Robinson (1976) and denoted by PR-EOS, has proved similar accuracy, but more robustness near the critical point. The form is:

The thermodynamic methods based on cubic equations of state are nowadays standard options in commercial simulators. In fact, a cubic EOS distinguishes without ambiguity between monoand two-phase systems. New modifications and mixing rules enlarged the field of applications to all non-electrolytic systems, including supercritical gases, hydrocarbon, polar components and water, small and large molecules, over a large range of pressures and temperatures. ⁽⁹⁾

I-2-5 The Importance Of Using EOS For PVT Modeling :

Petroleum engineers realized the importance of using EOS for PVT modeling in addition to the following: ⁽¹⁰⁾

- Predicting physical properties of the black oil in the laboratories is very expensive
- Difficulty to obtain a representative sample due to reservoir nature or operation issues
- Insufficient sample volume in order to obtain a complete analysis

- Error in lab analyses
- Samples are non representative (not monophasic sample, OBM contamination ...).
- Lab report quality check.
- Esmiting the hydrocarbon reserves.

I-2-6 Fluid Characterization:

To understand and predict the volumetric behavior of oil and gas reservoirs as a function of pressure, knowledge of the physical properties of reservoir fluids must be gained. These fluid properties are usually determined by laboratory experiments performed on samples of actual reservoir fluids. In the absence of experimentally measured properties, it is necessary for the petroleum engineer to determine the properties from empirically derived correlations. The objective of this chapter is to present several of the well-established physical property correlations for the reservoir fluids

1. Density:

Density represents the ratio of the mass of a fluid to its volume, can be rearranged to estimate the density at any pressure and temperature:

$$\rho = \frac{\mathbf{m} \, (\mathbf{kg})}{\mathbf{v} \, (\mathbf{m}^3)} \dots (I-10)$$

2. Specific gravity:

This term represents the ration of the density of a substance to the density of reference material (generally density of reference is the air density which is equal a $1000 \text{ kg}/\text{m}^3$), Both densities are measured or expressed at the same pressure and temperature, is dimensionless unit and can be expressed as :

$$\gamma = \frac{\rho \text{ substance}}{\rho \text{ reference}} \dots \dots \dots \dots \dots \dots \dots \dots (I-11)$$

Although the density and specific gravity are used extensively in the petroleum industry, the API gravity is the preferred gravity scale. This gravity scale is precisely related to the specific gravity by the following expression:

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

3. Viscosity:

The viscosity of a fluid characterizes its ability to flow in a tube, a channel, a container. The viscosity of a fluid is mainly due to the interaction between the molecules constituting the fluid.

- For a ideal fluid, the molecules constituting the fluid slide over each other without friction.
- For a real fluid, viscosity is taken into account and is reflected by the appearance of nonconservative forces

We have two main type of viscosity, dynamic and cinematic viscosity

 The dynamic viscosity noted as μ and represents the shear stress necessary for produce a flow rate gradient of one unit in matter.

$$\vec{\mathbf{F}} = \boldsymbol{\mu} \frac{\partial \mathbf{V}}{\partial \mathbf{y}} \mathbf{S} \vec{\mathbf{i}} \dots (I-12)$$

- \vec{F} : Shear force.
- μ : Dynamic viscosity.

• $\frac{\partial V}{\partial y}$: Strain rate.

• The sign - indicates that this force opposes the direction of movement of the upper layer.

 \checkmark Cinematic viscosity, noted as η , is the ration between the dynamic viscosity and the density :

These gas properties may be obtained from laboratory measurements or by prediction from generalized mathematical expressions.

4. Gas Solubility:

The gas solubility can be calculated rigorously from the experimental measured PVT data at the specified pressure and temperature. The following expression relates the gas solubility R_s to oil density, specific gravity of the oil, gas gravity, and the oil formation volume factor:

$$\mathbf{R}_{s} = \frac{\mathbf{B}_{o}\rho_{o} - 62.4\gamma_{o}}{0.0136\gamma_{g}} \dots \dots \dots \dots \dots \dots (\text{I-14})$$

Where:

- B_o: Oil formation volume factor, bbl/STB.
- P_0 : Oil density, lb/ft^3 .
- γ_0 : Specific gravity of the stock-tank oil.

• γ_g : Specific gravity of the solution gas.

I-2-7 Phase Behavior :

Modeling Process and reservoir simulation are highly dependent on the fluid description, since it is describing, as a mathematical model, the phase behavior of a fluid during different pressure and temperature conditions. Cubic EOSs are mainly used in the petroleum industry to describe the PVT behavior of a mixture.

Oil and gas reservoir fluids are mixtures of a large number of components which when subjected to different environments of P and T may exist in different forms, these forms are termed phases.

Phase behavior is a key aspect in understanding nature and behavior of fluids both in the reservoir and also during the production and transport process.

The phase behaviour of reservoir fluids can be described in a phase diagram which shows the condition of the fluids as a function of pressure and temperature. Plots of pressure versus temperature or pressure versus volume, Show the phases that exist under varying conditions.

I-2-7-1 Pressure – Temperature For Single Component:



Fig. 4: P-T diagram for single component system

- The limit of the vapor pressure line defines the critical point (critical temperature T_c, critical pressureP_c).
- At triple point, the pressure and temperature at which solid, liquid and vapor co-exist under equilibrium conditions.

- At sublimation- pressure line, the pressure and temperature at which solid exists from the area where vapor exists.
- At melting point line, the pressure and temperature at which solid exists from the area where liquid exists.

I-2-7-2 Phase behavior of Reservoir Fluids:



Fig. 5: Diagram phase behavior of reservoir fluids

- Before critical point we have single phase (region liquid).
- After critical point we have single phase too (region gas).
- Under the envelope we found two phases (liquid + gas).

I-2-7-3 Well Influent Behavior From Reservoir To Surface Processing:

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Fig. 6: Well influent behavior from reservoir to surface processing

At the reservoir, the temperature considered as constant between the reservoir and well bore, the fluid displaced under the influent of the pressure difference between the reservoir rock (point01) and well bore (point02); the fluid then reaches the surface moving out of reservoir through the production tubing where a notable drop in pressure and temperature is clear at the well head (point03) compare to well bore conditions, followed by a friction losses when the reservoir fluid reaches the surface treatment network starting with separator (point04). ⁽¹¹⁾

I-2-8 Laboratory analysis of reservoir fluids:

Accurate laboratory studies of PVT and phase-equilibrium behavior of reservoir fluids are necessary for characterizing these fluids and evaluating their volumetric performance at various pressure levels. There are many laboratory analyses that can be made on a reservoir fluid sample, the amount of data desired determines the number of tests performed in the laboratory; in general, there are three types of laboratory tests used to measure hydrocarbon reservoir samples:

1. Primary tests:

These are simple, routine field (on-site) tests involving the measurements of the specific gravity and the gas-oil ratio of the produced hydrocarbon fluids.

2. Routine laboratory tests:

These are several laboratory tests that are routinely conducted to characterize the reservoir hydrocarbon fluid. They include:

- ✓ Compositional analysis of the system.
- ✓ Constant-composition expansion.

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- ✓ Differential liberation.
- ✓ Separator tests.
- ✓ Constant-volume depletion.

3. Special laboratory PVT tests:

These types of tests are performed for very specific applications. If a reservoir is to be depleted under miscible gas injection or a gas cycling scheme, the following tests may be performed:

- ✓ Slim-tube test.
- ✓ Swelling test.

A- Routine laboratory tests

1- compositional analysis of the system:

It is desirable to obtain a fluid sample as early in the life of a field as possible so that the sample will closely approximate the original reservoir fluid. Collection of a fluid sample early in the life of a field reduces the chances of free gas existing in the oil zone of the reservoir.

Most of the parameters measured in a reservoir fluid study can be calculated with some degree of accuracy from the composition. It is the most complete description of reservoir fluid that can be made.

It is recommended that compositional analyses of the reservoir fluid should include a separation of components through C_{10} as a minimum. The more sophisticated research laboratories now the use of equation-of-state that require compositions through C_{30} or higher (see the table that's in the appendix that includes the mole fraction, weight fraction, density, and molecular weight of the individual component).

2- Constant-composition expansion tests (pressure-volume relations, flash liberation, flash vaporisation, or flash expansion):

Constant-composition expansion experiments are performed on condensate gas or crude oil to simulate the pressure-volume relations of these hydrocarbon systems. The test is conducted for the purposes of determining:

- ✓ Saturation pressure (bubble-point or dew-point pressure).
- ✓ Isothermal compressibility coefficients of the single-phase fluid in excess of saturation pressure.
- \checkmark Compressibility factors of the gas phase.

✓ Total hydrocarbon volume as a function of pressure.

The experimental procedure, as shown schematically in Figure 7 involves placing a hydrocarbon fluid sample (oil or gas) in a visual PVT cell at reservoir temperature and at a pressure in excess of the initial reservoir pressure (Figure 7 Section A). The pressure is reduced in steps at constant temperature by removing mercury from the cell, and the change in the total hydrocarbon volume Vt is measured for each pressure increment.

The saturation pressure (bubble-point or dew-point pressure) and the corresponding volume are observed and recorded and used as a reference volume V_{sat} (Figure 7, Section C). The volume of the hydrocarbon system as a function of the cell pressure is reported as the ratio of the reference volume. This volume is termed the relative volume and is expressed mathematically by the following equation: $V_{rel} = \frac{V_t}{V_{sat}}$(I-15)

where :

- V_{rel} : relative volume ($V_{rel} = 1$ at P_{sat})
- V_t : total hydrocarbon volume
- V_{sat}: volume at the saturation pressure

note : no hydrocarbon material is removed from the cell, thus, the composition of the total hydrocarbon mixture in the cell remains fixed at the original composition

$P_1 >>> P_b$	$P_2 > P_b$	$P_3 = P_b$	$P_4 < P_b$	$P_5 < P_4 < P_b$
V _t {Liquid Hg	V _t {Liquid Hg	V _t ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓	V _t Liquid Hg	V _t Gas Liquid Hg
А	В	С	D	Е

Fig. 7: Constant-composition expansion test.

3- Differential liberation (vaporization) test:
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In the differential liberation process, the solution gas that is liberated from an oil sample during a decline in pressure is continuously removed from contact with the oil, and before establishing equilibrium with the liquid phase. This type of liberation is characterized by a varying composition of the total hydrocarbon system. The experimental data obtained from the test include:

- Amount of gas in solution as a function of pressure.
- Properties of the evolved gas including the composition of the liberated gas, the gas compressibility factor, and the gas specific gravity.
- Density of the remaining oil as a function of pressure.

The test is carried out on reservoir oil samples and involves charging a visual PVT cell with a liquid sample at the bubble-point pressure and at reservoir temperature. As shown schematically in Figure 8, the pressure is reduced in steps, usually 10 to 15 pressure levels, and all the liberated gas is removed and its volume is measured at standard conditions. The volume of oil remaining V_l is also measured at each pressure level. It should be noted that the remaining oil is subjected to continual compositional changes as it becomes progressively richer in the heavier components.

It should be pointed out that the differential liberation test represents the behavior of the oil in the reservoir as the pressure declines. We must find a way of bringing this oil to the surface through separators and into the stock tank. This process is a flash or separator process.



Fig. 8: Differential vaporization test.

4- Separator tests:

Separator tests are conducted to determine the changes in the volumetric behavior of the reservoir fluid as the fluid passes through the separator (or separators) and then into the stock tank. The resulting volumetric behavior is influenced to a large extent by the operating conditions.

The primary objective of conducting separator tests, therefore, is to provide the essential laboratory information necessary for determining the optimum surface separation conditions,

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which in turn will maximize the stock-tank oil production. These separator tests are performed only on the original oil at the bubble point.

The above laboratory procedure is repeated at a series of different separator pressures and at a fixed temperature.



Fig. 9: Scheme of separator test

5- Constant-Volume Depletion (CVD) Test :

Constant-volume depletion (CVD) experiments are performed on gas condensates and volatile oils to simulate reservoir depletion performance and compositional variation. The test provides a variety of useful and important information that is used in reservoir.

This experiment is usually needed for retrograde condensate systems. a gas is placed in the cell at reservoir temperature and above the dew point, then the pressure is gradually reduced until liquid des appears on the cell wall. The dew point pressure is recorded, and the system is allowed to regain equilibrium, the pressure is subsequently reduced in steps, where at each step the relative volume of liquid is reported as a function of pressure.

At the end of each step, gas is removed from the cell such that the initial volume of the fluid system is constant throughout the experiment; the composition of the removed gas is measured at each step. ⁽¹²⁾ The laboratory procedure of the test is next:

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Fig. 10: A schematic illustration of the constant-volume depletion test.

CHAPITE II: EOS LUMPING AND DELUMPING

II-1 EOS Lumping:

In the oil reservoirs, the fluid in place exists in 3 different phases and consists of thousands of constituents which are impossible to characterize all in a PVT laboratory, the reservoir fluid reports vary between detailed component information up to carbon numbers of 7 to 30. and in oil industry, the computing time is a major factor in reservoir simulation where the number of components in fluid models is usually held at a minimum, due to simulation time for a compositional reservoir model is already high due to more governing equations to be solved, the iterative nature of flash calculations and the associated additional computing time is limiting the practical capabilities.

A "detailed" EOS model often contains from 20 to 40 components, in order to reduce the time of compositional reservoir simulations, a minimum number of components must be used in the equation of state (EOS) that describe the fluid phase and volumetric behavior, it is important to lump or group single components to PCS in order to decrease the overall number of components in the fluid model to find an optimal pseudoized EOS model that describe all PVT data e relevant to a particular reservoir development.

1-1 Definition:

Lumping (pseudoization) of equations of state by the definition of Pedersen and Al is 'deciding what carbon number fractions to lump (group) into the same pseudocomponents' ⁽¹³⁾.

Pseudoization procedure is founded in the ability of an EOS with fewer components to describe a wide range of phase and volumetric properties, The term lumping [or pseudoization] denotes the reduction of components number used in the calculations of EOS for reservoir fluids, this reduction is accomplished by employing the concept of the pseudocomponents which denotes a group of pure components lumped together and represented by a single component.



Fig. 11: Purpose de lumping process

1-2 Possible Lumping Scenarios:

Usually in a EOS model, a fluid system contains around 20 to 40 components, pure compounds are represented in the first 10 components : H₂S, CO₂, N₂, C₁, C₂, C₃, i-C₄, n-C₄,i-C₅, and n-C₅, where the heavier material components C₆₊ are remaining as a split fractions in single-carbon-number (SCN) [C₆ to C₉] or such as C₁₀₋₁₂, C₁₃₋₁₉, C₂₀₋₂₉, and C₃₀⁺ that represent groups of SCN fractions⁽¹⁴⁾.

The light aromatics or the BTX (Benzene, Toluene, and Xylene isomers) are separate components for process modeling where a lumped EOSx model might contain only 6–9 lumped components.

• Because of the huge number of possible lumping scenarios, it is difficult to select which components to be lumped together.

Assuming an available detailed SCN EOS model (EOSxx) consists of (Nxx) number of components with a satisfying degree of data accuracy, required to be lumped into a pseudo-model (EOSx) with (Nx) number of components. To create a lumped EOSx from a detailed EOSxx it consists to choose where to place (Nx-1) separators in the (Nxx-1) possible separation locations which lead that the number of possible lumping scenarios (N scenarios) can be expressed as follow ⁽¹⁵⁾:

$$N_{scenarios} = \frac{(Nxx-1)!}{(Nx-1)!(Nxx-Nx)!} \dots (2-1)$$

Example: there are 13,884,156 possible lumping scenarios for Nxx = 34 and Nx = 9.



Fig.12: Detailed EOSxx (Nxx Components) Lumped Scheme to an EOSx (Nx Components).

Lumping And Delumping

1-3Proposed Lumping Strategy ⁽¹⁶⁾:

An SPE engineering lumping program made by **SAYYED AHMAD ALAVIAN**, **CURTIS HAYS WHITSON**, and **SISSEL O. MARTINSEN** that can be used to approach component lumping and development of a pseudoized EOSx presented bellow:

- **1.** Start with an accurate, detailed EOS model (EOSxx) preferably a set of fluid compositions described with the EOSxx component slate.
- 2. Define the range of p-T-z relevant to the processes being modeled of relevant fluids.
- **3.** Calculate all PVT properties (densities, viscosities, compositions, phase fractions) with the detailed EOSxx for the entire range of the previous calculated relevant p-T-z.
- 4. Input the already calculated PVT results as "data" into the EOS-based PVT program.
- **5.** Specify the desired number (Nx) of components in the pseudoized EOSx, and any constraints on the lumping strategy: define Nxx and Nx.
- 6. Define the total lumping combinations possible scenarios.
- 7. Use an algorithm for generating the N_{EOSx} scenarios schemes.
- **8.** A reliable method for lumping scheme is used to calculate EOSx average pseudocomponent properties based on a single "averaging" composition Z_i.
- **9.** For each new lumping scheme, use all of the PVT "data" defined in step (3) and calculate a weighted measure of model accuracy, for example : a weighted root mean square (**RMS**) that represents a measure of "accuracy" between the original EOSxx model and the lumped EOSx model by ranking different lumping scenarios.
- **10.** Identify the lumping scheme(s) that give the best model match (lowest **RMS**).
- 11. The process can be repeated using different averaging methods and different averaging composition Z_i in step (8).
- Evaluation of the PVT calculations in detail of the final EOSx model(s) with lowest RMS, comparing with results from the original EOSxx model. Plot and compare data tables.

Liquid Saturation

Fig. 13: Comparison of several lumped EOS schemes with the same number of components (6) with different degrees of accuracy compared to the original EOS model (34 components).



Lumping And Delumping

13. If **MMP** (Minimum Miscibility Pressure) is of particular importance (or other more-complex calculations than could be included in the global search because of CPU limitations), select a subset of the scenarios from the global search (100-500) with lowest RMS values for PVT predictions. Run MMP calculations for these scenarios and compare with MMP from the EOSxx model, to select a best combination of PVT fit (low RMS) and prediction accuracy of the MMP (e.g. +/- 10 psi).

1-4 Component Lumping Strategy:

There are three key points in grouping SCN components to MCN groups:

- The number of MCN groups required, and the distribution of components within each MCN group.
- The estimation of physical properties for each MCN group that is required in phase behavior calculations.
- The retrieval of fluid description in terms of the original components when needed.

The possible number of lumped EOSx models is practical to consider, it is even larger (infinite) if one considers partial lumping of components, where an originating component i can lump partially into several lumped pseudo-components I. To reduce the number of possible lumping schemes we introduce a few constraints on lumping ⁽¹⁷⁾:

- Light, pure component lumping from of non-hydrocarbons with hydrocarbons C₁, N₂, CO₂ and H₂S will not be grouped or they can be only restricted: e.g. N₂ only with C₁.
- 2. Intermediate components will be grouped as C_2 - C_3 and C_4 - C_6 .
- **3.** The number of the pseudo components depends on the complexity Of the mixture and the process being simulated.
- For depletion processes, 3-4 pseudo components are usually enough (black oil model).
- For more compositional sensitive processes (e.g. gas injection), 5 to 6 components re sufficient.
- From 9 to 15 components might be required for the highly sensitive processes such as the slim tube simulation in order to determine the miscibility conditions
- **4.** The accuracy of physical properties values is important for effectively predicts the behavior of hydrocarbon mixtures using EOS.
- 5. The plus fractions are difficult to characterize without an extended composition.

- 6. Hydrocarbons are lumped only by contiguous carbon numbers, for example :
- $C_7 C_{10} = C_7 + C_8 + C_9 + C_{10}$.
- The following lumped pseudocomponents would not be allowed: $C_7C_{10}=C_7+C_{10}$ and $C_8 C_9=C_8+C_9$. For isomers with the same carbon number.
- it is recommend contiguous ordering of the original components by normal boiling point (NBP), as is normally done by PVT laboratories; lumping would then be done using contiguous NBP-ranked components ⁽¹⁸⁾.
- Unconstrained partial lumping(for example 70% of n-C₅ in lumped pseudo-component C_5C_6 and 30% of n-C₅ in lumped pseudo-component C_5C_7). One exception would be a user-specified and fixed amount of original component i is distributed to several lumped components I₁, I₂, etc.
 - **7.** The direct use of plus fraction as one component can results erroneous predictions and calculations of EOS (example : for a gas condensate sample the EOS calculation will sometimes predict a bubble point pressure instead of a dew point pressure at reservoir temperature) ⁽¹⁹⁾.

A. Original Detailed EOSxx Model :

Describing the reservoir fluid system by PVT data that represents the changes in pressure, temperature, and composition expected during reservoir recovery processes, transportation, and surface processing starts with a detailed EOSxx original model that measures the 3 main parameters: pressure (P), temperature (T), and composition (Z). These models which are developed in order to minimize the difference between PVT data and the EOSxx model can be accomplished by tuning procedures for the reservoir fluid one or preferably many samples.

B. Defining Relevant P-T-Z Range ⁽²⁰⁾:

A collection of samples -from 3 to 6- that covering all the reservoir fluid compositions are selected, each sample under the term of the original EOSxx component slate. The PVT calculations are conducting for each sample using the original components model EOSxx in order to adjust the EOS properties of the pseudo- components to fit the PVT experimental data generated with the oil or multicomponent EOS model.

Typical PVT data used for tuning include:

Depletion tests such as constant composition expansion (CCE), differential liberation (DD), or constant volume depletion.

- Multi-stage separator tests are simulated for each reservoir sample, and possibly some of the calculated depletion equilibrium gas and oil mixtures.
- Comprehensive Swelling Test (SWT) for relevant injection gases must be generated with CCE for each oil/injection-gas mixture, sometimes a vaporization test, and in some cases a Minimum Miscibility Pressure (MMP).

Usually the pure components properties are not adjusted; it made only for the most uncertain properties to only such lumped heaviest pseudo-components that have the higher level of uncertainty (critical properties) because they contain many components lumped as a single. EOS tuning is usually accomplished by regressing on the available data using a multivariate to match a specific set of data which may not give reliable predictions for other data.

- **Differential Liberation Test:** The use of DD experiment provides the data about solution gas-oil ratio (Rs), volume factor (Bo, Bg), density at different pressures, gas specific gravity, compressibility factor Z.
- Swelling Test.
- Separator Test: designed to give information about the behavior of the reservoir fluids at surface conditions such as GOR, oil formation volume factor, density and molecular weight.⁽²¹⁾

C. The Averaging Composition:

The composition (Z_i) is chosen heuristically to be used in averaging (it might be for several reservoir fluid compositions) pseudo-component properties in the lumped model EOSx, often it is one of the reservoir fluid compositions with measured PVT.

Theoretically, the averaging composition could be any composition that gives the best overall match between EOSx and EOSxx; one could optimize this composition as part of the overall lumping process. The best averaging composition sometimes is associated with the fluid(s) that exhibit the most-complex phase behavior.

Some trial-and-error is recommended to assess the impact of averaging composition on the final EOSx. so one must decide whether to conserve mass or moles when lumping compositions other than the averaging composition Z_i .

D. MMP Calculations:

For miscible gas injection processes, MMP (minimum miscibility pressure) by the original the lumped model should be similar.

In general, MMP calculation data not used an as part of the lumping strategy to reduce CPU time to compute the MMP (10-20 times longer compare to a large suite of standard PVT tests taking around ~0.15 s CPU). It is included sometimes only in order to help refine the search for an optimal lumping strategy that emphasizes more directly the developed miscibility process. ⁽²²⁾

E. Optimal Lumped EOSx / RMS Criterion:

By ranking the different lumping scenarios, the RMS (Root mean square) is a measure of "accuracy" between the original model EOSxx and the lumped model EOSx. It is the most important aspect of finding a lumped EOSx model that can represents the particular fluid system characteristics. The total model mismatch is given by an RMS with residuals defined as:

$r_n=100(d_x, n-d_{xx}, n) / d_{ref}, n.(2-2)$

Where: d_{xx} : represents the the PVT data calculated EOSxx.

 d_x : is the results calculated from a lumped EOSx.

 d_{ref} : is the reference data value taken as the maximum of all dxx data of a given type in a given simulated lab test (e.g. CCE), the RMS expressed as below : $\delta_{RMS} = \hat{\mathbf{r}} = [\mathbf{A}/\mathbf{B}]^{0.5}$.

The factors A and B respectively represented by:

► $A = \sum_{n=1}^{N \text{ data}} (W_n r_n)^2$ and $B = \sum_{n=1}^{N \text{ data}} (W_n)^2$(2-3)

With: W_n : Weighting factors. ⁽²³⁾

To gauge the accuracy of the lumping process, The RMS value is used. The accuracy measures based on the number and type of simulated data, and their weighting factors making the defining of the RMS perhaps the most challenging step to approach the optimal lumping.

Several lumped EOSx models can be develop for several particular applications with different pseudo-components number for each application, together with the sub-space of (p-T-z) where EOSxx data are generated to define the RMS.

1-5 Lumping Schemes:

The lumping procedures are associated with several problems about reducing the number of the original components without losing the predicting power and accuracy of the equations of state, these problems including the main question:

• How to select the groups of pure components to be represented by one pseudocomponent each?

Several unique techniques have been published that can be used to address the above lumping problem; notably the methods proposed by:

a- Aguilar And McCain Lumping Method:

the extended C_{7+} fraction, into two MCN groups can be grouped (MCN1 & MCN2) using the shown below correlations, MCN2 correct fraction determined in mole percent as the function of the mole percent of C_{7+} in order to get a good match of volumetric data :

 $Z_{MCN2}=0,028686608/(1+335,91986.e^{-0.56345274.Zc}_{7+})$(2-4)

The result of (1) is used to determine the MCN1 fraction as follow :

 $Z_{MNC1} = Zc_{7+} - Z_{MCN2} \dots (2-5)$

b- Pedersen And Al Lumping Method:

This method is based on grouping the components that each group contain approximately the same weight fraction (equal weight criterion) giving all the fluid components of the C_{7+} fractions equal importance.

In order to lump the SCN into groups, Pedersen and Al use the Redlich-Kwong-Soave (RKS) EOS to divide the C_{7+} fraction into three or more groups (by weight) which are approximately have equal size.

The weight Wj can be calculated for each pseudo-component by using the following expression:

 $W_{j} = \sum_{i=1}^{nc} (Z_{i} M W_{i})....(2-6)$

c- Danesh And Al Lumping Method:

In a mixture, the compounds concentration and molecular weight is what proposed by Danesh and Al to base on for this grouping method. The arrangement of original components in the order of theirs normal boiling point temperatures and grouping together in ascending order to form N $_p$ groups so that the values of Σ (Z_i ln M_i) for all the groups become nearly equal, (Quasi-equal-weight criterion). That is:

$$\left[\sum_{i=1}^{l} Z_{i} \cdot \ln M_{i} - (I/N_{p}) \cdot \sum_{i=1}^{n} Z_{i} \ln M_{i}\right] \leq 0 \dots (2-7)$$

And

 $\left[\sum_{i=1}^{l+1} Z_i \ln M_i - (I/N_p) \cdot \sum_{i=1}^n Z_i \ln M_i\right] \ge 0 \dots (2-8)$

- i=1,2,...,n
- I=1,2,...,N_p

Where:

- A mixture with n components, the component i in and 1 or 1+1 is the last component in group I.
- The first component in group I+1 is the next to the last component in group I.
- Z_i : molar composition.
- M_i: molecular weight. ⁽²⁴⁾

d- The Newley And Merrill Lumping Method:

As the starting points for further tuning, this scheme is based on the K-values of the components by minimizing K-values difference between original model EOSxx components and the pseudo-component of EOSx model to ensure similarity of predicted phase behavior and the detailed EOS model to have the best lumping of components.

K-values of pseudocomponents defined by:

$$\mathbf{K}_{\mathrm{m}} = \sum_{i \in \mathrm{m}} \mathbf{Y}_i / \sum_{i \in \mathrm{m}} \mathbf{X}_i \dots \dots (2-9)$$

With:

- K_m: the effective pseudocomponents K-value of a pseudocomponents m.
- X_i and Y_i are equilibrium phase compositions determined at an appropriate feed composition.

The objective function is defined as:

$$\sigma = \sum_{m} \sum_{i \in m} (K_m - K_i) / K_i^2$$
.....(2-10)

With:

• K_i: the K-value of one or group of components as particular pseudo-component.

The lumping procedure steps in order of grouping components of similar K-values into the same pseudocomponents to minimize the objective function are as follow ⁽²⁵⁾:

- 1- flash an appropriate feed composition of the multicomponent EOS (usually at the saturation vapor pressure of the oil or at a composition close to the critical point)
- 2- The components ordered according to their K-values.
- 3- The initial grouping of components based on equal mole fraction by lumping successive components into the same pseudocomponents (modified by moving components between adjacent pseudocomponents, σ is calculated for each realization where the least σ is the best lumping component).

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4- Use the below mixing rule based on K-value weighting to determine the average critical properties of the pseudocomponents model :

$$\beta_{\rm cm} = \sum_{i \in m} (\beta_i \, Z_i \, K_i^{-1/2}) / \sum_{i \in m} (Z_i \, K_i^{-1/2}) \dots (2-11)$$

Where:

 β_{cm} = T $_{cm},$ V $_{cm},$ P $_{cm}$ or $\omega_{cm}.$

Z i: overall component composition.

Based on the EOSxx components molecular weights, the pseudocomponents molecular weights are given by: $\mathbf{M}_{i} = \sum_{i \in \mathbf{m}} (\mathbf{M}_{i} \mathbf{Z}_{i}) / \sum_{i \in \mathbf{m}} \mathbf{Z}_{i} \dots \dots (2-12)$

Considering m and n represent two distinct pseudocomponents, binary interaction parameters are determined by:

$$\delta_{mn} = \left[\sum_{i \in m} \sum_{j \in n} (Z_i \ Z_j \ \delta_{ij} \ K_i^{-1/2} \ K_j^{-1/2})\right] / \left[\sum_{i \in m} \sum_{j \in n} (Z_i \ Z_j \ K_i^{-1/2} \ K_j^{-1/2})\right] \dots \dots (2-13)$$

e- Whitson's Lumping Scheme ⁽²⁶⁾:

Whitson (1980) proposed a regrouping scheme whereby the compositional distribution of the C_{7+} fraction is reduced to only a few multiple-carbon-number (MCN) groups. Whitson suggested that the number of MCN groups necessary to describe the plus fraction is given by the following empirical rule:

$$N_g = Int [1+3, 3 \log (N-n)]....(2-14)$$

Where:

- Ng = number of MCN groups
- Int = integer
- N = number of carbon atoms of the last component in the hydrocarbon system
- n = number of carbon atoms of the first component in the plus fraction, i.e., n = 7 for C7+.

The integer function requires that the real expression evaluated inside the brackets be rounded to the nearest integer. Whitson pointed out that for black-oil systems, one could reduce the calculated value of Ng.

The molecular weights separating each MCN group are calculated from the following expression: $M_i = Mc_7 (M_{N+}/Mc_7)^{I/Ng}....(2-15)$

Where :

- ✓ $(M)_{N+}$ = molecular weight of the last reported component in the extended analysis of the hydrocarbon system.
- ✓ M_{C7} = molecular weight of C_7
- ✓ $I = 1, 2, ..., N_g$

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Components with molecular weight falling within the boundaries of M_{I-1} to M_I are included in the Ith MCN group.

Example of Whitson scheme:

Given the following compositional analysis of the C_{7+} fraction in a condensate system, determine the appropriate number of pseudo-components forming in the C_{7+} .

Table-1 condensate system compositional analysis of the C_{7+} fraction:

Components	Zi	Components	Zi
C ₇	0.00347	C ₁₂	0.00095
C ₈	0.00268	C ₁₃	0.00073
C ₉	0.00207	C ₁₄	0.000566
C ₁₀	0.001596	C ₁₅	0.000437
C ₁₁	0.00123	C ₁₆₊	0.001671

Solution :

• molecular weight Determination for each component in the system:

Table-2 component's molecular weight determination:

Components	Zi	Mi	Components	Zi	Mi
C7	0.00347	96	C ₁₂	0.00095	161
C8	0.00268	107	C ₁₃	0.00073	175
C9	0.00207	121	C ₁₄	0.000566	190
C10	0.001596	134	C ₁₅	0.000437	206
C11	0.00123	147	C ₁₆₊	0.001671	259

• Calculate the number of pseudo-components :

 N_g = Int [1+3,3 log (N-n)] => N_g =Int[1+3,3log(16-7)] = 4

• Determine the molecular weights separating the hydrocarbon groups :

Using the expression (2-15):

 $M_i = M_{C7} (M_{N+}/M_{C7})^{I/Ng}$

 $M_1 = 96(259/96)^{1/4} = 123.$

 $M_2 = 96(259/96)^{2/4} = 157.$

 $M_3 = 96(259/96)^{3/4} = 202.$

 $M_4 = 96(259/96)^{4/4} = 259.$

Analysis:

- First pseudo-component includes all components with molecular weight ranged between 96 to123; it includes C₇, C₈, and C₉.
- Second pseudo-component contains all components with a molecular weight higher than 123 to 158. This group includes C₁₀ and C₁₁.
- Third pseudo-component includes components molecular weight higher than 158 to 202. Therefore, this group includes C₁₂, C₁₃, and C₁₄.
- Fourth pseudo-component is the pseudo-component includes all the remaining components C_{15} and C_{16+} .

1-6 The Lumped Components Proprieties:

The reservoir fluids contains large concentration of high molecular weight components including the plus fraction such as C_{7+} . It is convenient that to characterize the pseudo-component that needs its pseudo-physical and pseudo-critical properties, different approaches have been developed to characterize the petroleum plus fractions to improve prediction of the pseudo-components properties by equations of state (EOSs), the different properties for the pseudo-components can be giving using the mixing rules should be used for determining the EOS constants (p_c , T_c , and ω) for the new lumped pseudo-components, the choice of a correct mixing rule is as important as the lumping scheme; because there are numerous ways to mix the properties of the individual components. Some of these mixing rules are given next.

✤ Hong's Mixing Rules:

By Hong (1982), it is based on the weight fraction average wi ,Hong concluded that it is the best mixing parameter in characterizing the C_{7+} fractions, the Hong mixing rules are expressed as follow:

- Pseudo-critical pressure : P $_{cL}=\Sigma^{L} W_{i} P_{ci} \dots (2-16)$
- Pseudo-critical temperature : $T_{cL}=\Sigma^L W_i T_{ci}$ (2-17)
- Pseudo-critical volume : V $_{cL}=\Sigma^{L}W_{i}V_{ci}$ (2-18)
- Pseudo-acentric factor : $\omega_L = \Sigma^L W_i \omega_i \dots (2-19)$
- Pseudo-molecular weight : $M_L = \Sigma^L W_i M_i \dots (2-20)$
- Binary interaction coefficient: K $_{kL}=1-\Sigma_i {}^L \Sigma_j {}^L W_i W_j (1-K_{ij})$(2-21) Where :
- the average weight fraction $W_i = Z_I M_I / \Sigma^L (Z_I M_I)$(2-22)
- K _{kL}: binary interaction coefficient between the k'th component and the lumped fraction.

Remark: L in the below correlation denotes the lumped fraction.

♦ Lee's Mixing Rules:

Lee et al. (1979), in their proposed regrouping model, employed Kay's mixing rules as the characterizing approach for determining the properties of the lumped fractions. i in the lumped fraction as:

$$\Phi_{\mathbf{I}} = \mathbf{Z}_{\mathbf{I}} / \Sigma^{\mathbf{L}} \mathbf{Z}_{\mathbf{i}} \dots \dots \dots \dots (2-23)$$

the following rules are proposed:

- Pseudo-molecular weight: $M_L = \Sigma^L \Phi_i M_i$ (2-24)
- $\gamma_L = M_L / \Sigma^L [\Phi_i M_i / \gamma_i]$ (2-25).
- Pseudo-critical volume : $V_{cL} = \Sigma^{L} [\Phi_{i} M_{i} V_{ci} / M_{i}] \dots (2-26)$.
- Pseudo-critical pressure: $P_{cL} = \Sigma^{L} [\Phi_{i} P_{ci}] \dots (2-27)$.
- Pseudo-critical temperature: $T_{cL} = \Sigma^{L} [\Phi_{i} T_{ci}] \dots (2-28)$.
- Pseudo-acentric factor: $\omega_L = \Sigma^L [\Phi_i \omega_{ci}] \dots (2-29)$.

Using a mixing rule in order to calculate the pseudo properties of reduced component models may effect in the phase behavior predictions by resulting a significant change in accuracy of the predicting results.

The reduced model is desirable that it be created with as little adjustment to the properties that calculates EOS properties required only a little adjustment of the original components properties to match the phase behavior of the reservoir fluids. ⁽²⁷⁾

II-2 Delumping:

2-1 Introduction:

Inverse lumping (or delumping) for the purpose of retrieving the detailed fluid description from lumped components with reasonable accuracy was first investigated by Schlijper et al. (1988); in their approach, they used the equilibrium K values of the lumped components to approximate the K values of the original components. Split parameters were defined to link the lumped components to the original components based on the feed composition, the split parameters were estimated from a range of feed compositions that reflects the changes can take place during a displacement process. They used this approach to calculate the phase properties of the lumped model in a depletion process.

2-2 Delumping Process:

The operations allowing to predict the reservoir simulation results that Would be obtained using finely detailed modeling (Where the fluids are represented by a greater number of components), by using of different mathematical formulations.

The essential idea implemented for delumping compositional simulations is to calculate the equilibrium coefficients of the fluids in the detailed compositional representation from variables and/or parameters involved in the phase properties calculation from the moment that the parameters useful for calculation of the phase properties in the lumped

representation have been estimated so as to reproduce the parameters of the phases in the state equation of the detailed compositional description.

In general, delumping is a term for translating compositions of lumped systems into compositions of detailed systems

2-3 Analysis:

The analysis should consist of screening the used fluid models and their subsurface simulation result validity, comparison of central processing unit (CPU) times (since calculation time is a limiting factor when it comes to reservoir simulation), as well as interpretation of the whole process, from setting up the simulations to post processing the calculated results.

In 1988, Schlijper and Drohm formed the delumping or inverse lumping, as one of the first delumping methods; they proposed a method by which results from a flash calculation of the lumped system (lumped equilibrium K-values) are obtained to approximate detailed fluid compositions by the use of EOS - and split - parameters (determined by feed composition and expected change in composition) through Gibbs energy minimization.

In 1990, Danesh et al proposed a different delumping method by modifying the Wilson equation to correlate the detailed-component K-values with the acentric factor and reduced temperature at a constant pressure and temperature, to retrieve the detailed K- values, they used the linear trend of the lumped K-values, given by:

Ln
$$K_i = c_0 + c_1(1 + \omega_i)(1 - \frac{T_{ci}}{T})$$
(2-30)

 c_1 and c_2 are constants, determined by fitting the trend to the lumped data. ⁽²⁸⁾

In 1996, Leibovici et al proposed a similar approach but they correlated K-values with EOS parameters $\theta_{i,j}$ of the components:

Ln $\phi_i^{l,v} = c_0 + \sum_{j=1}^n c_j \theta_{i,j}$ (2-31) with n is number of EOS parameter.

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2-4 Black-Oil Delumping:

Black-oil delumping method based primarily on the compositional information generated in the depletion process that is used initially to provide data for the black-oil simulation in a typical workflow.

With advances in computing speed, it is becoming more typical to use a fully compositional fluid description in hydrocarbon reservoir simulation, however, the faster computers become the stronger the simulation engineer's tendency to build more challenging (and thus more CPU intensive) models. Compositional simulation in today's multi-million-cell models is still practically unfeasible.

In 2000, Whitson and Brule introduced that the black-oil delumping method by presenting a procedure to calculate gas and oil compositions at reservoir conditions from surface phase properties (compositions and densities) combined with the black-oil properties.

In 2002, Hoda extended this concept to develop the first black-oil delumping method, called BOz delumping, based on a set of split factor tables generated from a depletion PVT experiment.

To recognize the presence of the reservoir phases, Hoda utilized the comparison between the producing gas-oil ratio (Rp) and the black-oil properties (solution gas-oil ratio (Rs) and oil-gas ratio (rs)). Table 3 summarizes the presence of the reservoir oil (RO),

reservoir gas (RG), and injection gas (IG) for depletion and injection gas recovery processes on the black-oil delumping implementation.

Condition	Simulation Case		
Condition	Depletion	Gas Injection	
$R_p < R_s$	RO	RO	
$R_s \leq R_p \leq 1/r_s$	RO+RG	RO+RG	
$R_p > 1/r_s$	RG	RG+IG	

Table-3 Reservoir phases identification on the Hoda BOz delumping implementation:

In 2005, Hoda proposed another black-oil delumping method which is also based on a depletion PVT experiment, their delumping method requires the surface phase properties (mass amount and density) from reservoir simulation and a look up table generated from a depletion PVT experiment to obtain composition and mole amount of the reservoir phase.

In 2010, Vignati et al modified the Ghorayeb and Holmes black-oil delumping scheme to recognize the nature of the free gas (liberated gas from reservoir oil, gas cap and injection gas), they proposed a procedure to re-estimate the composition of reservoir gas entering a completion by utilizing the tracer tracking feature available in most commercial reservoir simulators.

• The Split factors:

The split factors define the conversion parameter from a surface phase rate of the reservoir simulation output to the mole amount of the reservoir phase. The split factors are set up as a lookup table using pressure as the variable. Each reservoir phase has one set of conversion table as well as the injection gas (if exists in the simulation).

The split factor is calculated from the molar volume and composition of the equilibrium phase of simulated depletion PVT experiments using a detailed-EOS model.

2-5 Compositional Delumping:

Our proposed black-oil delumping method was developed based on the similarity between the reservoir simulation and depletion PVT experiment on a pressure and phase composition, using of the same approach to develop a new method of delumping a lumpedcomponent into the corresponding detailed-components based on the unique correlation of the phase composition and pressure of the lumped EOS reservoir simulation and the

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detailed EOS depletion experiment. The split factor used to split the lumped-component (l) into the contributing detailed-components (d). The split factors (S) used to convert lumped EOS fluid containing N_l components to a detailed EOS containing N_d components can be described by:

For: $d=1, 2 ... N_i$

Where:

 S_{id} : split factor used to convert the lumped-component d to the detailed-component l.

• q: quantity.

To generate the split factor, we conducted a depletion PVT experiment (the CCE is recommended) on reservoir fluid at the reservoir temperature using a detailed EOS model. From each pressure point, the equilibrium liquid (EQL) and equilibrium vapor (EQV) compositions collected and then calculated the split factors of both phases. The pressure range of the depletion PVT experiment should cover the expected pressure range of the reservoir simulation, the phase depletion split factor represents the delumping split factor of reservoir simulation well-connection phase streams as given by (D S \cong p) where D S = the phase-specific split factor generated from the depletion PVT experiment and p = saturation pressure of the depletion PVT experiment. The C₇₊ mole fraction is used as the control variable to distinguish the liquid and vapor phase, the complete split factor table consists of sets of the split factor as a function of pressure and composition (C₇₊ mole fraction).

The compositional delumping procedure for depletion recovery process includes flashing the well-connection production streams at well-connection pressure and temperature and then applying the split factor tables phase-wise to get the detailed compositional profile, it is done for every time step of the reservoir simulation. The two phase streams are finally combined to get the mixture well-connection stream. For gas injection processes, the amount of injection gas is estimated from stream information and, accordingly, removed from the stream before applying the phase-specific pressuredependent split factors. The compositional delumping procedures are summarized in Fig.15.

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Fig. 15: Compositional delumping procedures

To split the injection gas stream from the connection-well stream, the β introduced as a parameter to quantify the amount of injection gas in the well-connection production stream:

$$n_o + n_g + n_{ig} = n_t \dots(2-34)$$

Where:

- **n**_t is total moles of well-connection stream.
- **n**_{ig} is moles of injection gas in the well-connection stream.
- **n**_ois moles of reservoir oil in the well-connection stream.
- $\mathbf{n_g}$ is a mole of reservoir gas in the well-connection stream. ⁽²⁹⁾

CHAPITE III: THE IMPCT OF LUMPING AND DELUMPING ON FLUID CHARACTERIZATION

III-1 Case Study ⁽³⁰⁾:

The proper use of the characterization of a hydrocarbon mixture heavy fraction in the equation of state in order to determinate the pseudo components properties leads to satisfactory prediction of the PVT behavior, in order to reduce the cost and time consumed the lumping process is the best solution, however,

Several problems are associated with "regrouping or lumping" process of the original components, such as the risqué of losing the predicting power of the equation of state, the selection of group representation as one component, the impact of lumping techniques on fluid characterization.

In order to define this impact, a case study by the application of several lumping schemes on a sample of reservoir fluid prepared from the gas condensate oil field, comparing the results of each technique impact and examined on the phase diagram to find the accurate lumping method for accurate fluid characterization.

In the laboratory, reservoir fluid compositions are determined by using gas chromatography. Also, the properties of heavy oil fraction were measured with the existing standards methods in the laboratory the results are in the table below:

Component	Zi	Component	Zi
C ₁	0.413506	C ₈	0.00268
C ₂	0.0403	C ₉	0.00207
C ₃	0.2153	C ₁₀	0.00159
i-C ₄	0.0539	C ₁₁	0.00123
n-C ₄	0.0543	C ₁₂	0.00095
i-C ₅	0.0515	C ₁₃	0.00073
n-C ₅	0.0519	C ₁₄	0.000566
C_6	0.1039	C ₁₅	0.000437
C ₇	0.00347	C ₁₆₊	0.001671

Table-4 Composition of reservoir fluid:

Remark:

- ✓ The molecular weight and the specific gravity of C_{16+} is equal to 259 and 0.908 respectively.
- ✓ The mixing rule used in this case in lee mixing rule in the 3rd chapter in order to determinate th pseudo components properties.
- ✓ The lumping schemes used in this study are Whitson's, Pederson's and Danesh's lumping techniques.

1- Whitson lumping scheme:

Whitson suggested that the number of MCN groups is necessary to describe the plus fraction is given by the empirical rule N_g :

N_g= Int [1+3.3 log (N-n)]

The light components of the fluid are not lumped, the determining the appropriate number of pseudo-components forming only in the C7+ by using the Whitson's Lumping Scheme in the following steps:

a- the molecular weight of each component of the reservoir fluid system:

Using the expression: $M_i = Mc_7 (M_{N+} / Mc_7)^{I/Ng}$, the molecular weight of each componets is calaculated where n is number of carbon atomes in each component :

$\mathbf{Mn} = \mathbf{nM}_{\mathrm{C}} + (2\mathbf{n}+2) \mathbf{M}_{\mathrm{H}}$

- M_C: molecular weight of carbon atom 12 g/mol.
- M_H: molecular weight of hydrogen atom 1 g/mol.

TableW-1: Molecular weight of the components of fluid system:

component	Zi	M W _i
C ₇	0.00347	96
C ₈	0.00268	107
C ₉	0.00207	121
C ₁₀	0.00159	134
C ₁₁	0.00123	147
C ₁₂	0.00095	161
C ₁₃	0.00073	175
C ₁₄	0.000566	190
C ₁₅	0.000437	206
C ₁₆₊	0.001671	259

b- By the using of the empirical rule N_g , the calculation of the number pseudo components is as follow:

N=16, **n**=7

 $N_g = Int [1+3.3 \log (16-7)] = 4$

The number of pseudo components for lumped model is 4.

- $\mbox{c-Using the previous result to determine the molecular weight of the 4 pseudo} \\ \mbox{components with the correlation :} \qquad \mbox{M}_i = Mc_7 \left(\ M_{N^+} / \ Mc_7 \right)^{i/Ng}$
- ✓ $M_1 = 96 (259/96)^{1/4} = 123.0359$
- The first pseudo component includes the components of molecular weight from 96 to 123; it includes C₇, C₈ and C₉.
 - ✓ $\mathbf{M}_1 = 96 \ (259/96)^{2/4} = 157.6757$
- The 2^{nd} pseudo component includes the components of molecular weight from 123 to 158; it includes C_{10} and C_{11} .

✓ $M_1 = 96 (259/96)^{3/4} = 202.0937$

• The 3^{rd} pseudo component includes the components of molecular weight from 158 to 202; it includes C_{12} , C_{13} and C_{14} .

✓ $\mathbf{M}_1 = 96 (259/96)^{4/4} = 259$

- The 4th pseudo component includes the remaining components.
 - d- The use of the expression below is in order to determine the molecular fraction of the pseudo components Zp_i, the expression: $Zp_i = \sum_{i=1}^n Z_i$.

The results of molecular fraction of the pseudo components Zp_i in the table W-2:

Pseudo Components	Components	Zi	Zpi	
	C ₇	0.00347		
1	C ₈	0.00268	0.00822	
	C ₉	0.00207		
3	C ₁₀	0.00159	0.002826	
2	C ₁₁	0.00123		
	C ₁₂	0.00095		
3	C ₁₃	0.00073	0.002246	
	C ₁₄	0.000566		
4	C ₁₅	0.000437	0.002108	
	C ₁₆₊	0.001671	0.002108	

e- Determine of pseudo components properties:

The mixing rules can be employed to characterize the pseudo-component in terms of its pseudo physical and pseudo-critical properties starting from the giving properties of the original components, the mixing rule is as important as the lumping scheme.

In this Example Using Lee's mixing rules to determine the physical and critical properties of the four pseudo-components:

	Common		Mi	Гі	V ci	P ci	T ci	ωi
Group I	compon	Zi	from	from	from	from	from	from
	ent		appendix	appendix	appendix	appendix	appendix	appendix
	C ₇	0.00347	96	0.727	0.06289	453	985	0.280
1	C ₈	0.00268	107	0.748	0.06264	419	1036	0.312
	C ₉	0.00207	121	0.768	0.06258	383	1058	0.348
2	C ₁₀	0.001596	134	0.782	0.06273	351	1128	0.385
2	C ₁₁	0.00123	147	0.793	0.06258	383	1058	0.348
	C ₁₂	0.00095	161	0.804	0.06306	302	1203	0.454
3	C ₁₃	0.00073	175	0.815	0.06311	286	1236	0.484
	C ₁₄	0.000566	190	0.825	0.06316	270	1270	0.516
4	C ₁₅	0.000437	206	0.826	0.06325	255	1304	0.550
4	C ₁₆₊	0.001671	259	0.908	0.0638*	215*	1467	0.68*

TableW-3: Thermodynamics property of components:

To use this rule, normalized mole fraction of the component i in the lumped fraction Φ_i must be defined, where: $\Phi_i = Z_i / \Sigma^L Z_i$

the results in the next table:

Table W-4: Φ_i of pseudo components:

Component	Zi	Φi
C ₇	0.00347	0.423171
C ₈	0.00268	0.326829
C ₉	0.00207	0.252439
C ₁₀	0.00159	0.57
C ₁₁	0.123	0.439286
C ₁₂	0.00095	0.431818
C ₁₃	0.00073	0.331818
C ₁₄	0.000566	0.257273
C ₁₅	0.000437	0.208095
C ₁₆₊	0.001671	0.795714

The properties of the pseudo components by Whitson lumping scheme calculated by lee's mixing rule.

Table W-5: Thermodynamics property of each group by Whitson's lumping scheme:

Pseudo components	1	2	3	4
Zi	0.00822	0.002826	0.002246	0.002108
Mi	105.9	139.7	172.9	248
γ_{i}	0.746	0.787	0.814	0.892
Vi	0.0627	0.0628	0.0631	0.0637
Pi	424	339.7	288	223.3
T _i	1020	1144.5	1230.6	1433
00 i	0.3076	0.4000	0.4794	0.6531

The impact of Whitson scheme can be determined by comparing the scheme with the phase diagram:



Fig. 16: Impact of Whitson's lumping scheme on phase diagram

The phase diagram shows that the Whitson lumping scheme can predict the phase diagram of this gas condensate systems fluid with good approximation, the Whitson's lumping scheme accuracy then can be attributed to function of the number of MCN groups

and iterative method to find the molecular weight of each group, so the determination of the number of groups is the excellent characteristics of this approach.

2- Pedersen Lumping Scheme:

The components lumping process suggested by Pedersen et al based on that each group containing approximately the same weight fraction giving all hydrocarbon segments of the C_{7+} fractions equal importance. The fraction is divided into three or more groups by weight so they are equal size approximately.

To determine each the weight of pseudo component W_i the following expression can be used to: $W_i = \sum_{i=1}^{nc} (Z_i, M W_i)$

a- Determine the values (Z i. M. W i) for each components:

Table P-1: Molecular weight of components:

Component	Zi	M W _i	Z _i . M. W _i
C ₇	0.00347	96	0,33312
C ₈	0.00268	107	0,28676
C ₉	0.00207	121	0,25047
C ₁₀	0.00159	134	0,21306
C ₁₁	0.00123	147	0,18081
C ₁₂	0.00095	161	0,15295
C ₁₃	0.00073	175	0,12775
C ₁₄	0.000566	190	0,10754
C ₁₅	0.000437	206	0,090022
C ₁₆₊	0.001671	259	0,432789

 $W t = \sum_{i=1}^{nc} (Z_i \cdot M W_i) = 2,175271$

By choosing the number of pseudo components 3 components, the molecular weight of the each group will be: $W_i = 1/3 \left[\sum_{i=1}^{nc} (Z_i, M, W_i) \right] = 2.175271/3 = 0.7254$

According to this value of W i groups are:

- 1st group includes C₇ and C₈.
- 2nd group includes C₉ to C₁₂.
- 3rd group includes the remaining components.

On determine the factor Z_i of each one of the 3 pseudo components by using the correlation $\mathbf{Z}.\mathbf{p}_i = \sum_{i=1}^{n} \mathbf{Z}_i$, then with the application of lee's mixing rule on determine the lumped fraction Φ_i as well, the results in the next table:

Pseudo Components	Components	Zi	Zpi	$\Phi_{ m i}$
1	C ₇	0.00347	0.00615	0,56422764
1	C ₈	0.00268	0,00015	0,43577236
	C ₉	0.00207		0,35445205
2	C ₁₀	0.00159	0,00584	0,27226027
2	C ₁₁	0.00123		0,21061644
	C ₁₂	0.00095		0,16267123
3	C ₁₃	0.00073		0,21445358
	C ₁₄	0.000566	0.002404	0,16627497
	C ₁₅	0.000437	0,003404	0,12837838
	C ₁₆₊	0.001671		0,49089307

Table P-2: values of Z_i and Φ i of the pseudo components:

The results of the calculation of the pseudo components properties using the Lee's mixing rules as follow:

Pseudo components	1	2	3
Zi	0.00615	0.00584	0.003404
Mi	100.7935	136.5223	222.7089
\Box_i	0.736566	0.784092	0.868659
Vi	0.062774	0.062787	0.063528
Pi	438.1837	348.8955	244.5065
T _i	1007.2	1123.4	1363.8
ω _i	0.293945	0.390271	0.594009

 Table P-3: Molecular percent of each group:

By applying the Pedersen lumping scheme to lump the hydrocarbon from C7 to C16+ into 3 pseudo components (3 groups are selected).



Fig. 17: Impact of Pedersen lumping scheme on phase diagram

The results of in the phase diagram of the system are under the impact of Pedersen lumping scheme, therefore, this figure shows that the Pedersen lumping scheme can predict the phase diagram of this gas condensate systems fluid.

It is clear from the diagram the simple relationship that exists between the concentration of components and molecular weight in the Pedersen lumping scheme. The Choice of the number of pseudo components is based on the limitations, total number of initial components and experiences, for these reasons the accuracy of this method would not be high.

3- Danesh and Al scheme:

Danesh and Al (1992) proposed a lumping method based on the concentration and molecular weight of compounds in a mixture. This grouping method arranged the original components in order of their normal boiling point temperatures and grouped together in ascending order to form N_P groups so that the values of Σ (Z I ln M_i) for all the groups become nearly equal, (Quasi-equal-weight criterion). That is:

 $\begin{bmatrix} \sum_{i=1}^{l} Z_{i} \cdot \ln M_{i} - (I/N_{p}) \cdot \sum_{i=1}^{n} Z_{i} \ln M_{i} \end{bmatrix} \leq 0 \dots (a)$ $\begin{bmatrix} \sum_{i=1}^{l+1} Z_{i} \cdot \ln M_{i} - (I/N_{p}) \cdot \sum_{i=1}^{n} Z_{i} \ln M_{i} \end{bmatrix} \geq 0 \dots (b)$

With

$$i=1, 2... n and I=1, 2... N_{p}$$

Component	Zi	Ln(M W i)	$Z_i *Ln(M W i)$
C ₇	0.00347	4.5643	0.015838
C ₈	0.00268	4.6728	0.012523
C ₉	0.00207	4.7958	0.009927
C ₁₀	0.00159	4.8978	0.007788
C ₁₁	0.00123	4.9904	0.006138
C ₁₂	0.00095	5.0814	0.004827
C ₁₃	0.00073	5.1648	0.00377
C ₁₄	0.000566	5.247	0.00297
C ₁₅	0.000437	5.3279	0.002328
C ₁₆₊	0.001671	5.5568	0.009285

 Table D-1:
 the molecular weight of components:

Based on the A and B rules the components are divided into 4 main groups, the lee mixing rules is used also to determine the fraction Φ_i as follow:

Group	component	Zi	Φ_{i}
1	C ₇	0.00347	1
2	C ₈	0.00268	0.564211
	C ₉	0.00207	0.435789
3	C ₁₀	0.00159	0.421751
	C ₁₁	0.00123	0.32626
	C ₁₂	0.00095	0.251989
4	C ₁₃	0.00073	0.214454
	C ₁₄	0.000566	0.166275
	C ₁₅	0.000437	0.128378
	C ₁₆₊	0.001671	0.490893

Table D-2 pseudo components and the Φ i of components:

The pseudo components' properties are calculated using lee's mixing rules, the results in next **Table D-3**:

Pseudo components	1	2	3	4
Zi	0.00347	0.00475	0.00377	0.003404
Mi	96	113.1011	145.0451	222.7089
\Box_{i}	0.06289	0.062612	0.062882	0.063528
V_i	0.06289	0.062612	0.062882	0.063528
Pi	453	403.3116	330.1698	244.5065
T _i	985	1045.587	1159.297	1363.779
00 i	0.28	0.327688	0.41348	0.594009

In this method, choosing the number of groups was done similar to the Pedersen lumping scheme. In Danesh et al lumping scheme some limitation is defined for choosing the molecular weight of groups, so it would be more accurate than the Pedersen lumping scheme.



Fig. 18: Impact of Danesh et al. lumping scheme on phase diagram

Results:

From the previous lumping scheme application on a reservoir fluid components, and by comparing the phase diagram for reservoir fluid with the results from lumping phase

diagrams of some lumping schemes such as Whitson's Lumping Scheme, Pedersen lumping scheme and Danesh lumping scheme, it is clear that:

- The use of Whitson's scheme reduces loss of the predicting this scheme phase diagrams is most the match of the original phase diagram.
- Pederson's and Danesh's scheme proximity led to the same results.
- The effect of all schemes is on the curve of the dew point in severely rates.
- The effect starts from the critical point that reduces the accuracy of the results.

Simulation running Time:

A simulation case in which the number of the original components were 20 components and a project of lumping the component to 13 was done; the results the both EOS does provides the same results of oil recovery percentage, in other words the reducing of the original mixture component number provides a same results with the reducing of simulation process running time to more then than half. The results in the diagram below:



Fig. 19: Oil Recovery results difference between detailed and lumped model

- The running of the history matching of the two cases provides same performances and reduces running time from 5h37m16sto....4h35m05s.

- The running of the prediction of the two cases provides same performances and reduces running time from 5h48m48sto....3h47m10s.

GENERAL CONCLUSION

General Conclusion:

The common use of the simulation process in hydrocarbons industry in order to over the recovery limits to achieve the maximum production rate at the lowest cost is based on the combination of the petro-physical and geological models of the reservoir-rock properties in single model represents system behavior in a 3D model in function of time.

These properties determined based on the others available, the ability to link the substance parameters describing its behavior presented in several equation are used such as VDW, RK and SRK called cubic EOS represents a thermodynamic expression relates pressure, temperature and volume to describe the state of the reservoir fluid at giving PVT conditions.

In a mixture, there might be up to 40 components, to examine each component and simulate its behavior it is a long time consuming process, so the lumping techniques are used to reduce the number of components to a smaller manageable number of pseudo-components in order to minimize the running time of the simulation process.

The number of the pseudo-components depends on the sensitivity and complexity of the operation desired to be simulated, this process can be described in 3 main steps: determine the number of MCN groups required, the estimation of physical properties for each MCN and the retrieval of fluid description, the lumping process is controlled by tuning rules set the possibilities of components lumping, the resulting pseudo-components properties can be determine using mixing rules.

In the opposite case to split the lumped model into more components, delumping or the inverse process of the lumping can be used to determine the original mixture components and properties using black oil model or the compositional model.

The use of the these techniques impacts the results of the reservoir fluid behavior comparing with original phase diagram, the impact can be observed starting at the critical point effecting the dew point curve, the variation is clear in the case of phase change from mono gas phase to dual phase (liquid & gas), this impact is due to the accuracy of the results of the used schemes and mixing rules, but the results remain acceptable to represent the system behavior.

The lumping and delumping process is an approved method for reducing and modifying the properties of the components of a petroleum mixture, with a high accuracy results that represents the original fluid mixture behavior only through the behave of a few components which have a close range of properties that can be modeled as one components.

Recommendation:

- Depending on the results of the case study, the lumping process is a good method to reduce the costs of reservoir fluid analyzing operation and so the time consumed in simulation by reducing the number of fluid components according to specific schemes such s Whitson's, Pederson's and Danesh's lumping techniques considering that Whitson's scheme is the best lumping scheme with high accuracy and low effect on the results comparing with original model results and the other lumping schemes.
- The use of the lumping scheme does effects the accuracy of the data as well the results of the study case. The effect of these schemes starts at the critical point as deviation of the dew point curve into the inside of the phase diagram in different rates depending on the pseudo component selection. The lumping techniques remain a good procedure in the reservoir simulation operation that gives results with acceptable accuracy.
- In the other side, the processing time of the simulation operation is reduced nearly to a half time difference such as between the original model EOS ₂₀ and the lumped one EOS ₁₃.

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APPENDIX

Compound	Formula	Molecular weight	Critical pressure (psla)	Critical temperature (°F)	Critical volume (ft³/lb)	Liquid specific gravity (water = 1)	Gas specific (air = 1)	Acentric factor
Methane	CH4	16.042	667.0	-116.66	0.0985	(0.3)	0.55400	0.0115
Ethane	C ₂ H ₆	30.069	706.6	89.92	0.0775	0.35643	1.03830	0.0994
Propane	C_3H_8	44.096	615.5	205.92	0.0728	0.50738	1.52270	0.1529
Isobutane	C4H10	58.122	527.9	274.41	0.0715	0.56295	2.00710	0.1865
n-Butane	C_4H_{10}	58.122	550.9	305.55	0.0703	0.58408	2.00710	0.2003
Isopentane	C5H12	72.149	490.4	369	0.0685	0.62460	2.49140	0.2284
n-Pentane	$C_{5}H_{12}$	72.149	488.8	385.8	0.0676	0.63113	2.49140	0.2515
n-Hexane	C6H14	86.175	436.9	453.3	0.0688	0.66404	2.97580	0.2993
n-Heptane	C7H16	100.202	396.8	512.9	0.0682	0.68819	3.46020	0.3483
n-Octane	C_8H_{18}	114.229	360.7	564.2	0.0673	0.70698	3.94450	0.3977
n-Nonane	C9H20	128.255	330.7	610.8	0.693	0.72186	4.42890	0.4421
n-Decane	C10H22	142,282	304.6	652.2	0.0703	0.73406	4.91330	0.4875
Carbon monoxide	CO	28.01	506.7	-220.63	0.0527	0.79265	0.96720	0.0510
Carbon dioxide	CO2	44.01	1070.0	87.76	0.0343	0.82203	1.51970	0.2239
Hydrogen sulfide	H ₂ S	34.082	1306.5	212,81	0.0462	0.80269	1.17690	0.1010
Air	-	28.9586	551.9	-220.97	0.0458	0.87603	1.00000	-
Hydrogen	H ₂	2.0159	190.7	-399.9	0.5319	0.07087	0.06961	-0.2140
Oxygen	02	31.9988	731.4	-181.43	0.0367	1.14230	1.10500	0.0222
Nitrogen	N ₂	28.0135	492.5	-232.53	0.0511	0.80687	0.96740	0.0372
Water	H ₂ O	18.0153	3200.1	705.1	0.04975	1.00000	0.62210	0.3443

	table 1	:	physical	properties	of each	components
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Water	H ₂ O	18.0153	3200.1	705.1	0.04975		1.00000	0.62210	0.3443
			- 1					. 1	
	tab	ole 1 : p	hysical prop	perties of	each com	ponent	S		
Group	T _b (°R)	γ	K	м	T _c (°R)	P _c (psia)	ω	V _c (ft³/lb)	Group
C ₆	607	0.690	12.27	84	923	483	0.250	0.06395	C ₆
C ₇	658	0.727	11.96	96	985	453	0.280	0.06289	C7
C ₈	702	0.749	11.87	107	1,036	419	0.312	0.06264	C_8
C ₉	748	0.768	11.82	121	1,085	383	0.348	0.06258	C ₉
C ₁₀	791	0.782	11.83	134	1,128	351	0.385	0.06273	C ₁₀
C11	829	0.793	11.85	147	1,166	325	0.419	0.06291	C ₁₁
C12	867	0.804	11.86	161	1,203	302	0.454	0.06306	C ₁₂
C13	901	0.815	11.85	175	1,236	286	0.484	0.06311	C ₁₃
C14	936	0.826	11.84	190	1,270	270	0.516	0.06316	C14
C15	971	0.836	11.84	206	1,304	255	0.550	0.06325	C15
C16	1,002	0.843	11.87	222	1,332	241	0.582	0.06342	C16
C17	1,032	0.851	11.87	237	1,360	230	0.613	0.06350	C ₁₇
C18	1,055	0.856	11.89	251	1,380	222	0.638	0.06362	C ₁₈
C19	1,077	0.861	11.91	263	1,400	214	0.662	0.06372	C19
C20	1,101	0.866	11.92	275	1,421	207	0.690	0.06384	C ₂₀
C21	1,124	0.871	11.94	291	1,442	200	0.717	0.06394	C21
C22	1,146	0.876	11.95	300	1,461	193	0.743	0.06402	C22
C23	1,167	0.881	11.95	312	1,480	188	0.768	0.06408	C23
C24	1,187	0.885	11.96	324	1,497	182	0.793	0.06417	C24

C	1 207	0 000	11.00	227	1 5 1 5	177	0.810	0.06421	C
25	1,207	0.000	11.99	557	1,515	177	0.819	0.00451	C25
C ₂₆	1,226	0.892	12.00	349	1,531	173	0.844	0.06438	C ₂₆
C27	1,244	0.896	12.00	360	1,547	169	0.868	0.06443	C27
C28	1,262	0.899	12.02	372	1,562	165	0.894	0.06454	C28
C29	1,277	0.902	12.03	382	1,574	161	0.915	0.06459	C29
C ₃₀	1,294	0.905	12.04	394	1,589	158	0.941	0.06468	C30
C31	1,310	0.909	12.04	404	1,603	143	0.897	0.06469	C31
C32	1,326	0.912	12.05	415	1,616	138	0.909	0.06475	C32
C33	1,341	0.915	12.05	426	1,629	134	0.921	0.06480	C33
C34	1,355	0.917	12.07	437	1,640	130	0.932	0.06489	C34
C35	1,368	0.920	12.07	445	1,651	127	0.942	0.06490	C35
C ₃₆	1,382	0.922	12.08	456	1,662	124	0.954	0.06499	C36
C37	1,394	0.925	12.08	464	1,673	121	0.964	0.06499	C37
C38	1,407	0.927	12.09	475	1,683	118	0.975	0.06506	C38
C39	1,419	0.929	12.10	484	1,693	115	0.985	0.06511	C39
C_{40}	1,432	0.931	12.11	495	1,703	112	0.997	0.06517	C ₄₀
C ₄₁	1,442	0.933	12.11	502	1,712	110	1.006	0.06520	C41
C ₄₂	1,453	0.934	12.13	512	1,720	108	1.016	0.06529	C42
C43	1,464	0.936	12.13	521	1,729	105	1.026	0.06532	C43
C44	1,477	0.938	12.14	531	1,739	103	1.038	0.06538	C44
C45	1,487	0.940	12.14	539	1,747	101	1.048	0.06540	C45

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table 2 : generalized physical properties



Fig 1 : Standing and Katz compressibility factors chart. (Courtesy of GPSA and GPA Engineering Data Book, EO Edition, 1987.)

Hydrocarbon Analysis of Reservoir Fluid Sample

Composition of Reservoir Fluid Sample (by Flash, Extended-Capillary Chromatography)

Component Name	Mol %	Wt %	Liquid Density (gm/cc)	MW					
Hydrogen Sulfide	0.00	0.00	0.8006	34.08					
Carbon Dioxide	0.25	0.11	0.8172	44.01					
Nitrogen	0.88	0.25	0.8086	28.013					
Methane	23.94	3.82	0.2997	16.043					
Ethane	11.67	3.49	0.3562	30.07					
Propane	9.36	4.11	0.5070	44.097	To	tal Samul	e Properti	65	
iso-Butane	1.39	0.81	0.5629	58.123	10	ai Sampi	e i roperu		
n-Butane	4.61	2.66	0.5840	58.123	Molecular Weight			10	0.55
iso-Pentane	1.50	1.07	0.6244	72.15	Equivalent Liquid I	Density, gr	n/scc		7204
n-Pentane	2.48	1.78	0.6311	72.15	1	,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,			
Hexanes	3.26	2.73	0.6850	84					
Heptanes	5.83	5.57	0.7220	96					
Octanes	5.52	5.88	0.7450	107					
Nonanes	3.74	4.50	0.7640	121					
Decanes	3.38	4.50	0.7780	134					
Undecanes	2.57	3.76	0.7890	147					
Dodecanes	2.02	3.23	0.8000	161					
Tridecanes	2.02	3.52	0.8110	175					
Tetradecanes	1.65	3.12	0.8220	190					
Pentadecanes	1.48	3.03	0.8320	206					
Hexadecanes	1.16	2.57	0.8390	222					
Heptadecanes	1.06	2.50	0.8470	237					
Octadecanes	0.93	2.31	0.8520	251					
Nonadecanes	0.88	2.31	0.8570	263					
Eicosanes	0.77	2.11	0.8620	275					
Heneicosanes	0.68	1.96	0.8670	291					
Docosanes	0.60	1.83	0.8720	305					
Tricosanes	0.55	1.74	0.8770	318	Disc Exactions	Mal %	14/4 9/	Density	MANAZ
Tetracosanes	0.48	1.57	0.8810	331	FIUS FRUCIONS	MOI /6	VVI /0	Density	max
Pentacosanes	0.47	1.60	0.8850	345	Heptanes plus	40.66	79.17	0.8494	196
Hexacosanes	0.41	1.46	0.8890	359	Undecanes plus	22.19	58.72	0.8907	266
Heptacosanes	0.36	1.33	0.8930	374	Pentadecanes plus	13.93	45.09	0.9204	326
Octacosanes	0.37	1.41	0.8960	388	Eicosanes plus	8.42	32.37	0.9540	387
Nonacosanes	0.34	1.34	0.8990	402	Pentacosanes plus	5.34	23.16	0.9916	437
Triacontanes plus	3.39	16.02	1.0440	474	Triacontanes plus	3.39	16.02	1.0440	474
Totals	100.00	100.00			F				

Table 3: shows a chromatographic "fingerprint" compositional analysis of the Big Butte crude oil system.

Pressure psig	Relative Volume	
5000	0.9460	
4500	0.9530	
4000	0.9607	
3500	0.9691	
3000	0.9785	
2500	0.9890	
2300	0.9938	
2200	0.9962	
2100	0.9987	
2051	1.0000	
2047	1.0010	
2041	1.0025	
2024	1.0069	
2002	1.0127	
1933	1.0320	
1843	1.0602	
1742	1.0966	
1612	1.1524	
1467	1.2299	
1297	1.3431	
1102	1.5325	
862	1.8992	
653	2.4711	
482	3.4050	

Pressure-Volume Relations of Reservoir Fluid at 260°F (Constant-Composition Expansion)

Differential Vaporization at 260°F

Pressure psig	Solution Gas/Oil Ratio (1)	Relative Oil Volume (2)	Relative Total Volume (3)	Oil Density gm/cc	Deviation Factor Z	Gas Formation Volume Factor (4)	Incremental Gas Gravity
2051	1004	1.808	1.808	0.5989			
1900	930	1.764	1.887	0.6063	0.880	0.00937	0.843
1700	838	1.708	2.017	0.6165	0.884	0.01052	0.840
1500	757	1.660	2.185	0.6253	0.887	0.01194	0.844
1300	678	1.612	2.413	0.6348	0.892	0.01384	0.857
1100	601	1.566	2.743	0.6440	0.899	0.01644	0.876
900	529	1.521	3.229	0.6536	0.906	0.02019	0.901
700	456	1.476	4.029	0.6635	0.917	0.02616	0.948
500	379	1.424	5.537	0.6755	0.933	0.03695	0.018
300	291	1.362	9.214	0.6896	0.955	0.06183	1.188
170	223	1.309	16.246	0.7020	0.974	0.10738	1.373
0	0	1.110		0.7298			2.230
	at 60°F =	1.000					

Gravity of Residual Oil = 43.1°API at 60°F

(1) Cubic feet of gas at 14.73 psia and 60°F per barrel of residual oil at 60°F.

(2) Barrels of oil at indicated pressure and temperature per barrel of residual oil at 60°F.

(3) Barrels of oil plus liberated gas at indicated pressure and temperature per barrel of residual oil at 60°F.

(4) Cubic feet of gas at indicated pressure and temperature per cubic foot at 14.73 psia and 60°F.

Separator	Tests	of	Reservoir	Fluid	Sam	ple
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Separator Pressure PSI Gauge	Separator Temperature °F	Gas/Oil Ratio (1)	Gas/Oil Ratio (2)	Stock Tank Gravity °API @ 60°F	Formation Volume Factor (3)	Separator Volume Factor (4)	Specific Gravity of Flashed Gas
200 to 0	71	431	490			1.138	0.739*
	71	222	223	48.2	1.549	1.006	1.367
100 to 0	72	522	566			1.083	0.801*
	72	126	127	48.6	1.529	1.006	1.402
50 to 0	71	607	632			1.041	0.869*
	71	54	54	48.6	1.532	1.006	1.398
25 to 0	70	669	682			1.020	0.923*
	70	25	25	48.4	1.558	1.006	1.340

*Collected and analyzed in the laboratory

(1) Gas/oil ratio in cubic feet of gas @ 60°F and 14.75 psi absolute per barrel of oil @ indicated pressure and temperature.

(2) Gas/oil ratio in cubic feet of gas @ 60°F and 14.73 psi absolute per barrel of stock-tank oil @ 60°F.

(3) Formation volume factor in barrels of saturated oil @ 2051 psi gauge and 260°F per barrel of stock-tank oil @ 60°F.

(4) Separator volume factor in barrels of oil @ indicated pressure and temperature per barrel of stock-tank oil @ 60°F.