Evaluation of the Best Equation of State for Enhanced Oil Recovery Use in Ultra-high Pressure Hydraulic Calculation

A Dissertation
Presented to
The Faculty of the Department of Civil and Environmental Engineering
University of Houston

In Partial Fulfillment
Of the Requirements for the Degree
Doctor of Philosophy
In Civil Engineering

By
Chen Chuan J Kuo (aka J. C. Kuo)
May 2015

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Abstract

Enhanced oil recovery (EOR), is an essential part of oil and gas production nowadays. Gases used include carbon dioxide (CO_2), natural gas, or nitrogen (N_2). The discharge pressure of the platform injection compressor could be as high as 12,000 psi. The proper selection of the size of the gas injection system and platform becomes critically important and is found to be heavily affected by the simulated results from process involving the equation of state (EOS). The EOS of a system has been proven to be very reliable in predicting the properties of most hydrocarbon based fluids. An engineering design starts with EOS selection, process simulation, heat and material balance calculation, equipment sizing and finally detailed engineering. This study focuses on the investigation of the most probable and applicable equations of state (EsOS) such as GERG-EOS, BWRS-EOS, LKP-EOS and PR-EOS in the high pressure compression simulation industry.

Aspen HYSYS is a commercial process modeling tool for conceptual design, optimization, and performance monitoring for oil & gas production, gas processing, petroleum refining, and air separation industries. Because the critical thermodynamic properties including enthalpy, entropy, vapor pressure and density are shown to be related to the compressibility factor, this study adopted Aspen HYSYS as the simulation tool to evaluate all four EsOS. The predicted compressibility factors (Z) from the different EsOS were compared to experimental data obtained from a wide variety of sources. The results suggest that for the case of pure CO_2 and pure N_2, all EsOS tested within the low

pressure range up to 1000 psia can produce accurate results. For high pressure conditions up to 12,000 psia, the GERG can provide the most accurate predictions. Considering the hydrocarbon/CO_2 mixture and hydrocarbon/N_2 mixture, for low pressure system it is found the results from GERG, LKP and PR EsOS fit better with the experimental data than those from BWRS. However for high pressure system, it appears that GERG, BWRS and LKP can provide good prediction. Furthermore, for high temperature case, the LKP proves to give the most accurate results. It is recommended to use LKP for offshore EOR gas injection operations.

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List of Symbols and EOS Parameters

Ideal gas law

P: Absolute pressure

V: Volume

n: Number of moles

R: Universal gas constant, R=10.731 (ft3 *psi)/ (^{o}R *lb-mol)

T: Temperature (in ^{o}R, Degree Rankin)

Van der Waals, Soave-Redlich-Kwong and Peng-Robinson

$a \ or \ b$: Substance-specific constants. It can be calculated from the critical properties including T_c and P_c.

T_c : Critical temperature

P_c : Critical Pressure

*ω: A*centric factor for the species.

T_r : Reduced temperature; $=T/T_c$

P_r : Reduced Pressure; $=P/P_c$

X_i : Mole fraction

k_{ij} : Binary interaction coefficient

m_i: Dimensionless parameter and can be calculated by acentric factor.

a, b , m_i, α_i, A, and B: PR-EOS parameters.

Benedict-Webb-Rubin-Starling

γ : Parameter and can be calculated by $\gamma = \frac{1}{\rho_c^2}$

ρ : Molar density.

ρ_c : Critical molar density

Ao, Bo, Co, Do, Eo, $a, b\ , c, d$:BWRS EOS parameters.

Lee Kesler Plocker

$V_r = \ \frac{P_c\, V}{RT_c}$ is the reduced volume

$b_1, b_2, b_3, b_4, c_1, c_2, c_3, d_1, d_2, \beta\ \gamma$ and ω :LKP EOS twelve parameters.

GERG (2008)

a *:* Molar Helmoltz free energy; A parameter of the Peng-Robinson EOS.

A : Parameter of total Helmholtz free energy

b : Parameter of the Peng-Robinson EOS (molar co-volume) Coefficient

B : Second virtual coefficient

α : Reduced molar Helmholtz free energy

X: Molar composition (vector of mole fractions)

τ : Inversely reduced temperature *(* $\tau = \frac{T}{T_r}$).

N = The number of components in the mixture,

Subscripts

c : At the critical point such as critical temperature or pressure.

Exp : Exponential term

i : Serial number

j : Serial number

r : Reducing property

Component Abbreviations and Chemical Formulas

Ar: Argon

C_1: CH_4 : Methane

C_2: C_2H_6 : Ethane

C_3: C_3H_8 : Propane

CO : Carbon monoxide

CO_2 : Carbon dioxide

H_2 : Hydrogen

H_2O : Water

H_2S: Hydrogen Sulfide

He : Helium

i-C_4 : Isobutane (2-Methylpropane) or i-C_4H_{10}

i-C_5 : Isopentane (2-Methylbutane) or i-C_5H_{12}

N_2: Nitrogen

n-C_4 : n-Butane or n-C_4H_{10}

n-C_5 : n-Pentane or n-C_5H_{12}

n-C_6 : n-Hexane or n-C_6H_{14}

n-C_7: n-C_7H_{16} or n-Heptane

n-C_8: n-C_8H_{18} or n-Octane

NOx : Oxides of nitrogen or Nitrogen oxide

O_2: Oxygen

SOx: Sulfur Oxides

List of Acronyms

AET: Advanced Extraction Technology. NRU technology provider.

AGRU: Acid Gas Removal Unit. Usually remove the CO_2 and H_2S.

ASPEN: Enterprise optimization software and services include integrated supply chain management solutions. For the design, operation, management of manufacturing facilities. WWW.apenstech.com

ASU: Air Separation Unit (co-produces oxygen & nitrogen from air)

Bbl : Barrel of liquid

BFD: Block Flow Diagram

BTU / SCF: BTU / Standard Cubic Feet (measure of heating value)

BTU: British Thermal Unit

CAPEX: Capital Expenditure

CCS: Carbon Capture & Sequestration

CMS: Carbon Molecular Sieve

Compressibility factor : Z factor as PV=ZRT

DEG: Di-ethylene Glycol

Degree API or ^{O} API or API gravity: Degrees API (measure of crude density, inverse scale). Degree API= (141.5/Specific Gravity)-131.5

EG: Ethylene Glycol

EOR: Enhanced oil Recovery (also called Improved Secondary Oil Recovery)

EOS: Equation of State

EsOS: Equations of State.

GHG: Green House Gas. It is a gas in an atmosphere that absorbs and emits radiation within the thermal infrared range.

GOR: Gas Oil Ratio (SCF/Bbl)

GTI: Gas Technology Institute in USA

HHV: Higher Heating Value

HMB: Heat and Material Balance

IGGU: Inert Gas Generation Unit

JT: Joule Thomson Effect. Gas expands from high pressure to low pressure and usually results to lower temperature.

LNG: Liquefied Natural Gas

LPG: Liquefied Petroleum Gas (usually refers to propane & butane)

MMSCFD: Million Standard Cubic Feet per Day

MRU: Mercury Removal Unit.

MTPA: Million Tonne per Annum for LNG base load plant

MTR: Membrane Technology Research. NRU technology provider

NGL : Natural Gas Liquids

NRU: Nitrogen Removal Unit

OPEX: Operating Expense

PSA: Pressure Swing Absorption (process for gas purification)

PSI or psi: Pounds per Square Inch

PSIG or psig: Pounds per Square Inch Gauge

PVT: pressure, P, volume, V, and temperature, T relation

PρT : pressure, P, Density, ρ , and temperature, T relation

RVP: Reid Vapor Pressure

SCF: Standard Cubic Feet per Day

SOR: Secondary Oil Recovery

Specific Gravity: Density of crude/ water density at 60 ^{o}F

TEG: Tri-Ethylene Glycol

The ten most popular EsOS used by the oil and gas industry are GERG-EOS, Benedict-Webb-Rubin-Starling (BWRS-EOS), Lee-Kessler Plocker (LKP-EOS), Peng-Robinson (PR-EOS), Kabadi-Danner (KD-EOS), Peng-Robinson-Stryjek-Vera (PRSV-EOS), Soave-Redlich-Kwong (SRK-EOS), Aspen RefProps (NIST-EOS), Generalized Cubic (GC-EOS), and Zudkevitch Joffee (ZJ-EOS).

USA: United States of America

USD: USA dollar

VLE: Vapor-Liquid Equilibrium states.

VRS: Hydrocarbon (Vapor Recovery System)

Chapter 1. Introduction

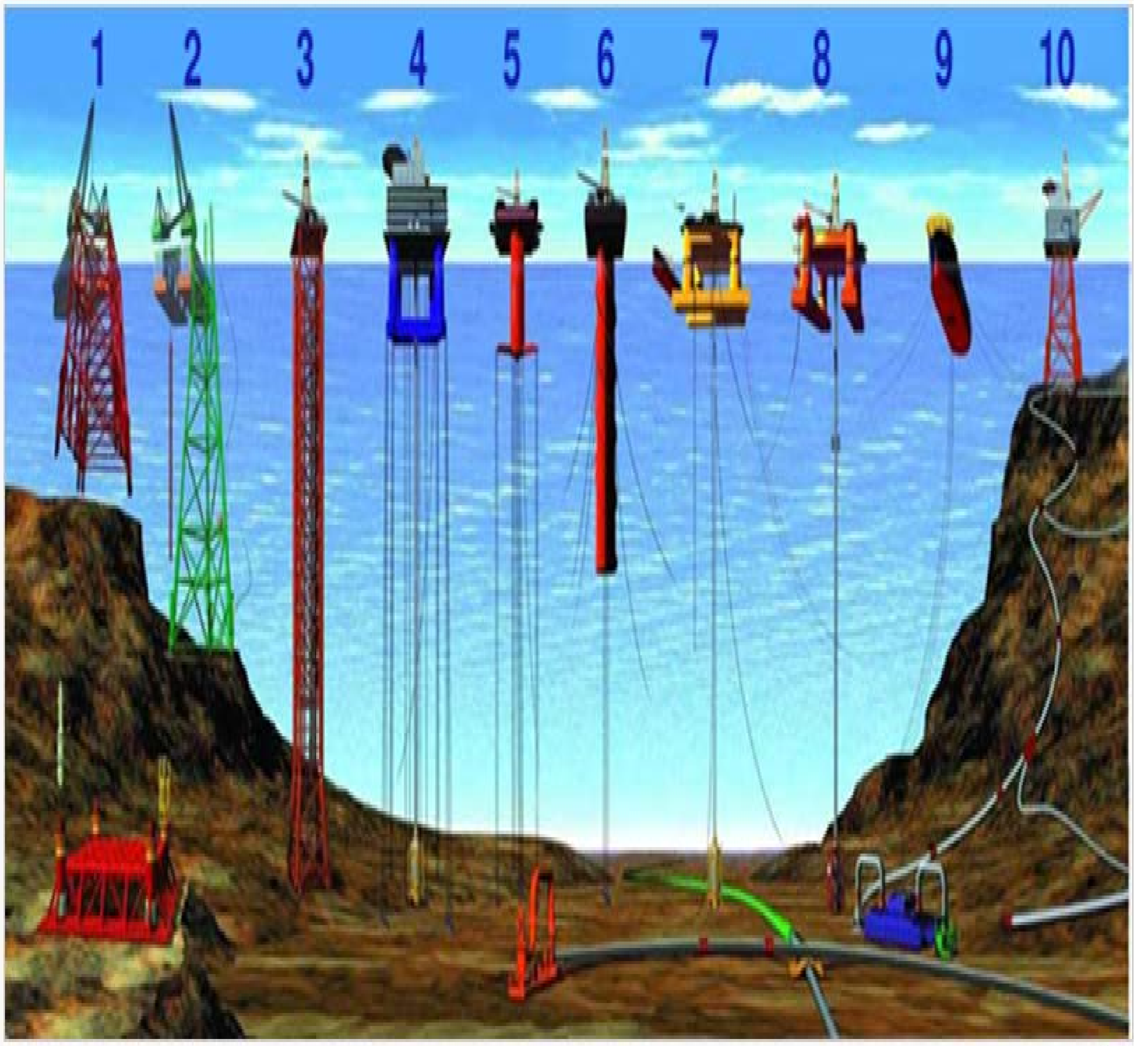
1.1 Problem Statement

Producing oil and gas from deep-water reservoirs creates numerous engineering, technical, and project cost challenges. Many oil companies have been exploring in deep water (>1,200 feet (>366 meters)) for over 25 years. Today many operations are deeper than 7,000 feet (2,134 m) of water (Larino, 2014, British Petroleum website). The oil and gas reservoir itself can be an additional 35,000 feet below sea level underneath layers of hard rock, thick salt and tightly-packed sands. Massive production platforms with specially designed systems and pipelines are required. Platform costs can be in the multiple billion dollar range depending on water depth and environmental conditions (British Petroleum, 2014). Enhanced oil recovery (EOR), also known as improved oil recovery or tertiary recovery (as separated from primary and secondary recovery), is an essential part of production. By using EOR, 30 to 60 % or more of the reservoir's original oil can be extracted compared with 20 to 40 % using the primary and secondary recovery method (Wikipedia (b),2014).

The Equation of State (EOS) of a system is the relationship between the thermodynamic variables like pressure, P, volume, V, and temperature, T (PVT). (Reid et al.,1987). EOS has been proven to be very reliable in predicting the properties of most hydrocarbon based fluids over a wide range of operating conditions. The accurate knowledge of the thermodynamic properties of natural gases and other mixtures of natural gas components is of indispensable importance for the basic engineering consideration and performance of technical processes. This requires thermodynamic property calculations for a wide range of mixture compositions and operating conditions in the homogeneous gas, liquid, and supercritical regions, and also for Vapor-Liquid Equilibrium (VLE) states. These data can advantageously be calculated from EOS. An engineering design starts with EOS selection, process simulations, heat and material balance (HMB) preparation, equipment sizing, and finally detailed engineering analysis. Currently, there are not any Equations of State (EsOS) for natural gases that are appropriate for all of the exemplified applications and that satisfy the demands concerning the accuracy in the description of thermodynamic properties over the entire fluid region. An appropriate EOS that can adequately model the PVT and VLE calculations at ultra-high pressure nearly 10,000 psi is required to do the simulation. The ten most popular EsOS used by the oil and gas industry are GERG-EOS, Benedict-Webb-Rubin-Starling (BWRS-EOS), Lee-Kessler Plocker (LKP-EOS), Peng-Robinson (PR-EOS), Kabadi-Danner (KD-EOS), Peng-Robinson-Stryjek-Vera (PRSV-EOS), Soave-Redlich-Kwong (SRK-EOS), Aspen RefProps (NIST-EOS), Generalized Cubic (GC-EOS), and Zudkevitch Joffee (ZJ-EOS). (ASPEN HYSYS, 2011).

Historically, the development of GERG-EOS was intended to provide high accuracy for typical natural gas components (Wagner, 2014). While it is considered to be very accurate, it has not been widely implemented in most commercial process simulators. In fact, only HYSYS by Aspen Technology has this EOS for usage. Furthermore, the PR-EOS has generally been the most widely used for oil, gas, and petrochemical industries. Many engineering contractors working in process design have used PR extensively. Compressor manufacturers, such as General Electric (GE) and Dresser-Rand (D-R), have also tested the accuracy of EOS for high pressure compression applications and compared the accuracy of Relich-Kwong (RK-EOS), Lee-Kessler Plocker (LKP-EOS) and Peng-Robinson (PR-EOS) in predicting compressor performance (Colby, 1987; Sandberg 2005).

Oil will last only another 100 to 150 years depending on world consumption. Furthermore, most of the oil production has already been applied with the primary or secondary recovery methods for production. In many areas the more challenging EOR procedure is followed to improve the production of oil. Assuming that a platform under consideration in Figure 1.1, 1.2 and 1.3 is located at a water depth of 7,000 feet , the oil and gas reservoir itself adds an additional 24,000 feet below sea level. The developed block flow diagram (BFD) for testing EsOS in offshore oil production and an EOR gas injection process scheme is presented in Figure 1.4. Depending on the circumstances such as water depth and environmental conditions, the platform may be fixed to the ocean floor, may consist of an artificial island, or may float. There are ten different kinds of types as shown. Detail study is required to determine the most economical type of platform to be used for project. Many deep water platforms could cost over multi-billion USD.



1, 2) conventional fixed platforms; 3) compliant tower; 4, 5) vertically moored tension leg and mini-tension leg platform; 6) spar; 7,8) semi-submersibles; 9) floating production, storage, and offloading facility; 10) sub-sea completion and tie-back to host facility.[4]

Figure 1.1 Different Platforms for Offshore Oil Production and EOR (National Oceanic and Atmospheric Administration, 2010)

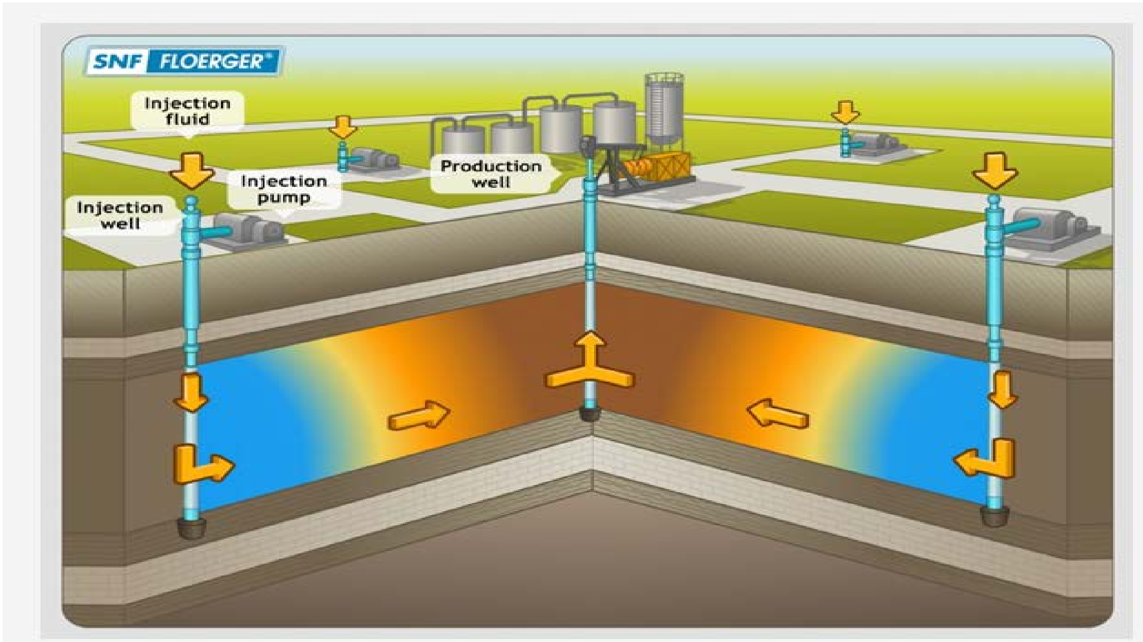


Figure 1.2 EOR (2b1st company website http://www.2b1stconsulting.com/about-us/, 2014)

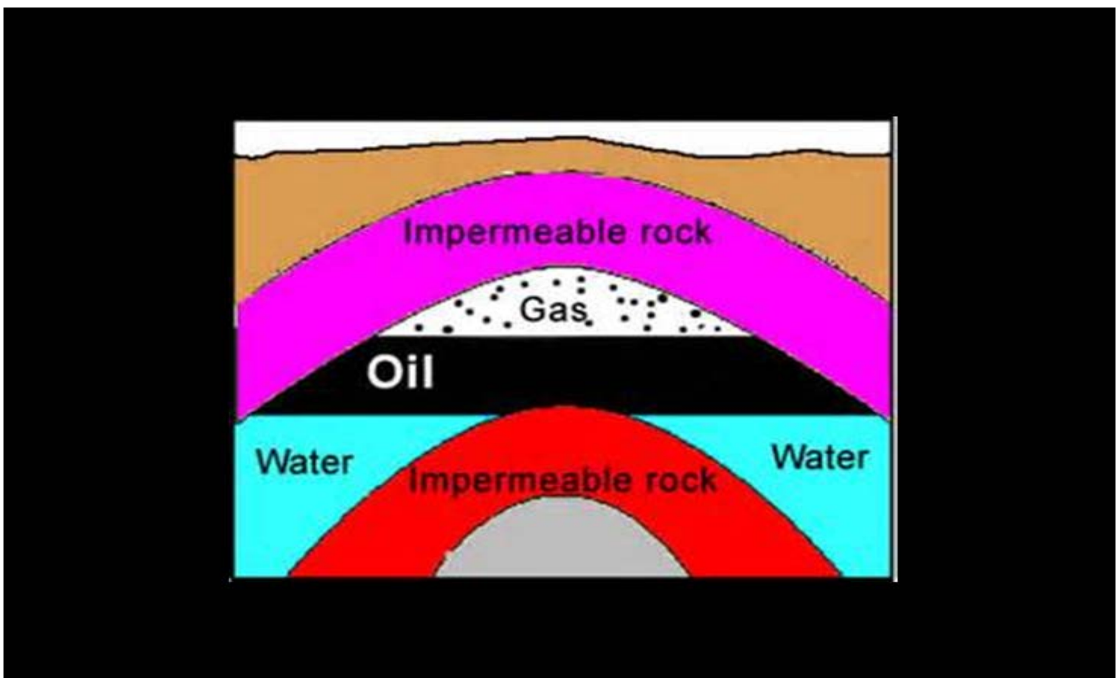


Figure 1.3 Typical Reservoirs (Math/Science Nucleus, 2014)

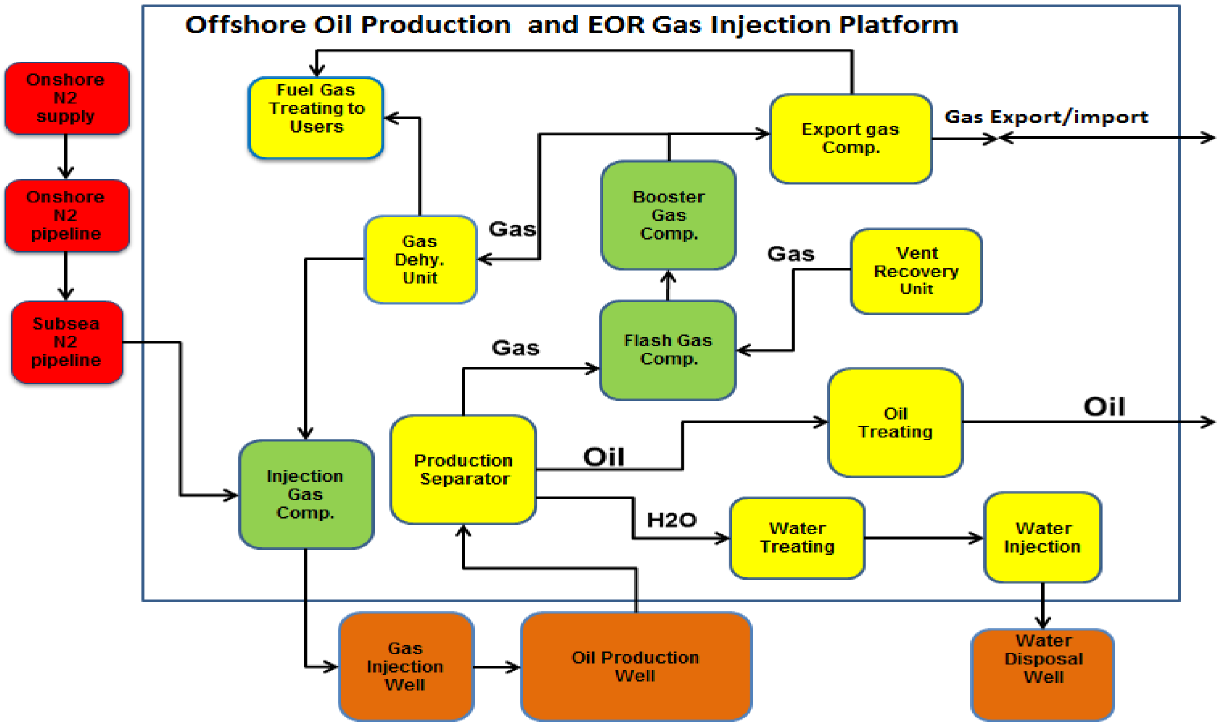


Figure 1.4 BFD for offshore oil production and EOR gas injection platform

As shown in Figure 1.4, the onshore N_2 supply going to offshore platform through the onshore pipeline first and then the offshore subsea pipeline. The Injection Gas Compressors (IGC) will compress the makeup N_2 and the recycle gas to ultrahigh pressure and inject to the gas injection well. High pressure N_2 will mix with the oil inside the reservoir and then going to the platform production separator. This is a three phase separator to separate the oil, water and gas. Water is then carried to the water treating facilities to remove the hydrocarbon before transporting to the water injection pump to inject to the water disposal well. Oil however is delivered to the oil treating unit to remove the water before going for sale. The gas is sent to the Flash Gas Compressors (FGC) which compresses the gas from the vent recovery unit to Booster Gas Compressors

(BGC). The discharge of the flash gas compressors (FGC) will be further compressed by the BGC. Gas from BGC discharge can be used as the fuel gas after removing the water by the gas dehydration unit. Any excess gas can be sold by going through Export Gas Compressors. In the later stage of the platform production, as the hydrocarbon gas production is reduced, some imported gases are used as fuel gases. All fuel gas supplies are required to go to the fuel gas treating unit before serving as fuel gases. The dehydrated gas can be combined with the N_2 supplies and further compressed through the IGC as injected gas for EOR purpose.

Because of the density and molecular weight differences between CO_2, natural gas, and N_2, the estimated compressor discharge pressure required to inject the corresponding gas into the reservoir is around 9,000, 14,000 and 12,000 psia respectively. For EOS comparison, for example, if N_2 is used, the platform injection compressor discharge pressure required is 12,000 psia.

The size of injection equipment system including the separators, compressors, and air coolers can be heavily impacted by the simulated results from different EsOS. Furthermore, the deep-water platform is very expensive (in multiple billion dollar range). Larger gas injection equipment means a larger platform is required. The cost difference of the overall project based on different EsOS may be in the range of 5% to 10% depending on the water depth, environmental conditions, and the injection gas flow rate. Because the engineering analysis must provide process simulations for both surface production and gas injection facilities, it is therefore necessary to compare the different EsOS with actual experimental data to examine the performance of various EsOS model. After the system evaluation and study, the most appropriate EOS can ultimately be selected for use in simulation and equipment design.

The following questions or data sources must be answered or obtained to determine “the best EOS for use in ultra-high pressure compression hydraulic calculation.”

1) There are nearly 30 different EsOS available for different systems. What are the types of EsOS? Which one is the best for ultra-high pressure process simulation, equipment design and engineering details design?
2) Can a technically sound process simulator be selected to test the EsOS? There are 40+ process simulators available; which is the most appropriate one to use?
3) There are many laboratory test data available for low pressure up to 1000 psia. However, there are not many test data available for ultra-high pressure (>12,000 psia). Gathering the limited data under the condition of ultrahigh pressure become necessary to valid the EOS models (Aleksandrov, 2011).
4) How high is the hydraulic pressure required for gas injection discharge including the 7000-ft water depth and 24,000-ft reservoir thickness? The cost impact is very high by using various EsOS. What are the corresponding hydraulic profiles under different pressures for gas injection?
5) What factor can be used to evaluate the performance of EsOS tested?

6) Under an ultra-high pressure condition, the investigation on types and number of sets of compressors is especially needed.

Some current production techniques for maintaining crude oil recovery from a reservoir utilize the injection of nitrogen as enhanced oil recovery (EOR) method. Gradually, the equilibrium nitrogen dissolved in the crude oil will come to the surface as associated gas when the nitrogen breaks through. Therefore nitrogen removal on feed gas having high N_2 content is also an important subject to be investigated.

For any gas or LNG plant, higher levels of nitrogen within the feed gas mean lower profitable volumes or additional capital investment. (Obrien,2004) Nitrogen Removal Unit (NRU) can be expensive to build and difficult to operate. The challenges facing the gas industry are highlighted by the Gas Technology Institute (GTI, USA) in their estimates that 11% of current daily gas production and 16% of all known gas reserves in the USA contain some nitrogen. Recent gas reservoir discoveries around the world were also found to contain significant levels of nitrogen up to the 15% range. Gas companies typically set the maximum concentration limits on nitrogen content in the pipeline between 4.0 to 7.0 percent depending on the local product specifications. Therefore, in general, the nitrogen levels that are greater than 7.0 percent must undergo removal. (Pahade ,1985) (Pahade et al.,1991).

The assessment of the design criteria, such as (1) feed gas nitrogen concentrations, (2) NRU inlet pressure, (3) NRU capacity, (4) product specifications, (5) approaches for the final disposition of the recovered hydrocarbon stream: (e.g., as fuel gas, re-injection or recycle back to feed gas), (6) environmental NO_x emissions impact, and (7) allowable methane concentration in the nitrogen vent, to be considered for the selection of an optimum NRU technology is also addressed in this study. The available technologies including both commercially demonstrated NRU technologies as well as the future developments are introduced by way of process flow diagrams, descriptions, technology highlights, pre-treatment requirements, strength and weakness and technology licensor/vendor lists.

1.2 Literature Review

Producing oil and gas from deep-water reservoirs is necessary for future energy industries. Massive production platforms with specially designed systems and pipelines are required and its costs can be in the multiple billion dollar range depending on water depth and environmental conditions. (British Petroleum , 2014.

1.2.1 Enhanced oil recovery (EOR)

Worldwide there are an estimated 50 billion barrels of oil recoverable by EOR methods from offshore oil reservoirs. Up until now, gas injection for EOR has proven successful onshore, but had only had limited applications offshore. CO_2, N_2 and/or natural gas injection are considered to be the gas of choice for offshore EOR because of its availability, successful experience, and lower cost (Watts, 2014). EOR is an essential part of production for future energy requirements. By using EOR, 30 to 60 % or more of the reservoir's original oil can be extracted compared to 20 to 40 % using the primary and secondary recovery method. (Electric Power Research Institute,1999)

Also known as Tertiary Oil Recovery, Improved Oil Recovery, and Advanced Secondary Recovery, EOR is generally applied after the primary and secondary Recovery Techniques have been employed. While the demarcation between Primary, Secondary and Tertiary Recoveries has some overlaps, EOR is generally considered for application in mature or depleted fields as a means of enhancing and prolonging liquids production. Flaring of produced gas is not considered viable in almost all geographic locations. Therefore the motivations for EOR may be one of those listed below:

- A depleted field that must be abandoned unless the liquid production can be boosted by EOR.
- Development of a new field for production of liquids may not be economic without EOR.
- A distance to market which renders a pipeline for selling associated gas uneconomic.
- The Gas to Oil Ratio (GOR) may be too low to justify pipelining of the surplus associated gas (after meeting internal fuel needs).
- The incremental liquids production may be more valuable than monetizing the gas.
- The cost of cleaning up a high level of impurities (CO_2, N_2, and H_2S) in the gas may make monetization of the gas uneconomic.

- As an outlet for CO_2 if CO_2 sequestration is to be pursued.
- Synergy with waste streams from a Gas to Liquid (GTL) plant. Hydrogen plant, or even boiler stacks, which can provide a relatively low-cost gas medium for EOR.
- Any combinations of the above.

Sometimes, for instance, in the reservoir formation, the predicted primary production rate is so low that EOR needs to be included in the base development plan and is generally initiated soon after the start of production. Indeed, with the larger reservoirs (the “elephants”) having been mostly already discovered, the new reservoirs that will be explored and developed in the future will be smaller ones, and the increase in production and recovery of the oil-in-place due to EOR may be a vital aspect of the justification for the large capital investment necessary for field development.

EOR enhances oil production by the injection of an external medium – gas, chemicals, polymers, surfactants, or other chemicals. This study addresses the EOS issues related to the injection gas such as CO_2, N_2 and natural gas. The gas flood may operate in miscible or immiscible mode. Gas may also be used for pressure-maintenance in a reservoir to enhance recovery or prolong production of liquids.

Miscible flood involves injecting gas into the reservoir so that it dissolves in the oil. The dissolved gas causes several changes in the reservoir performance. It lowers the density and viscosity of the oil phase, and accordingly reduces the hydrostatic head from the reservoir to the wellhead. It also reduces the frictional pressure drop for the oil flowing from the outer reservoir areas to the wellbore, thereby increasing oil production. Two miscibility-generating mechanisms have been identified: enriching mechanism (when using rich gas) and a vaporizing mechanism (which uses lean gas). Volume swell due to the dissolved gas and immiscible gas displacement are additional mechanisms that could be contributing to the overall gas EOR phenomenon. The injected gas results in an increase in the Gas to Oil Ratio (GOR), therefore, have to be continually injected into the reservoir for sustained production gains.

Offshore EOR requires several large and significant enhancements. These include the supply or manufacturing of large volumes of gas, compression to high pressures for injection, and purification of the associated gas to meet sales specification and to possibly recover some gas for reinjection. Considering the space and weight limitations by code on an existing platform, it will generally not allow the addition of much new equipment as this will require either extensive modifications of the existing structure or the addition of a new platform or structure.

Gas-based EOR has been employed in many locations worldwide. Carbon Dioxide (CO_2) is the most widely used gas for EOR. Other gases used in EOR production include Nitrogen (N_2), acid gas (a mixture of CO_2 & Hydrogen Sulphide), associated gas, and natural gas, including Sour Gas. Steam is used extensively in California. In the rest of the world, steam is the primary media in Venezuela, Indonesia, Trinidad and Brazil, with CO_2 and hydrocarbons being minor contributors to EOR production. CO_2 is the most widely used gas in the

USA for EOR, mostly in Texas, Wyoming, and Mississippi. Hydrocarbon gas has been used in Alaska, and nitrogen, chemicals, polymers and surfactants are minor contributors to EOR production. In Canada, steam dominates EOR production due to the colder climate and the large reserves of heavy oil in Western Canada. Hydrocarbons and CO_2 are the other dominant media used in Canada. EOR projects in the planning stages focus on CO_2 and steam.

Taber, Martin & Seright (Society of Petroleum Engineer (SPE),1996) have discussed the EOR screening criteria in details. They stated that EOR is most suited to reservoirs having sandstone or carbonate formations with high permeability streaks and a minimum of fractures. Generally, nitrogen works better with lighter oils (> 35 American Petroleum Institute (API) gravity), in deeper reservoirs (10,000 to 18,500 feet depth), and with higher oil saturation of the pore volume (>40%). Carbon dioxide is more effective with heavier oils (>22 API gravity), in intermediate depth reservoirs (2,500 to 4,000 feet depth), and lower oil saturation (>20%). Hydrocarbon miscible flood is effective with heavier oils (>23 API gravity), in shallower reservoirs (4,000 to 16,000 feet depth), and moderate oil saturation (>30%). Regardless of which gas is used for EOR, there will be a tendency for the gas to strip out some additional light ends from the reservoir, and recovery of these light ends for sales (as opposed to re-injecting them) will require changes to the topsides.

1.2.2 Carbon Dioxide (CO_2):

CO_2 may be naturally occurring or produced from a system man-made. Naturally occurring CO_2 is obtained from underground reservoirs and is available in the US Gulf Coast area. Man-made CO_2 is probably most economically recovered from refinery waste vents, for example, from the Steam Methane Reforming-based Hydrogen plant vent. It must be noted only the older hydrogen plants – those having a "wet" system on the back-end for hydrogen purification - vent a pure CO_2 stream. The newer plants use a Pressure Swing Adsorption (PSA) system for hydrogen purification, and the CO_2 produced in these plants is contained in the PSA off-gas - a low-BTU fuel gas, which is typically fired in the reformer furnace. The CO_2 vent stream will need cooling and significant compression.

A high quality CO_2 stream can also be readily recovered from a gasification plant – whether it is for producing synthesis gas or power. Other large sources of man-made CO_2, for instance, boiler stacks, contain a mixture of N_2 (87%), CO_2 (10%), water (saturated) and Oxygen (3%). In addition to cooling, the stack vent gases will need to be purified; because while N_2 and CO_2 both assist EOR, they do not work in conjunction unless the reservoir depth and pressure are high enough to render nitrogen miscible. A number of older EOR projects used flue gas initially but experienced significant problems (corrosion) and have since switched to nitrogen. Flue gas is not being used for EOR according to available literature.

Use of man-made CO_2 also helps reduce Green House Gas (GHG) emissions and reduces the corporate GHG footprint. As CO_2 is supplied from onshore sources, the distance from shore will be a key factor. It should be noted that the sequestration aspect of CO_2 injection will be effective for a few years only until the gas saturated with CO_2 breaks through. Then the removal of CO_2 becomes necessary (for meeting inert gas specifications in the sale gas), resulting in recycling recovered CO_2 back into the reservoir. If longer-term sequestration is sought, the CO_2 injection is suggested to be moved to other reservoirs at some point since only a small amount of the injected CO_2 may remain in a producing reservoir.

For offshore EOR, the CO_2 has one major safety concern. Because it is heavier than air, CO_2 will not raise and disperse. In the case of CO_2 release due to the emergency shut down or leakage, the dispersed but still high concentrated CO_2 could form a cloud which could hurt or kill the operating personnel on the platform. This is especially true in a very high pressure system which contains a lot of CO_2 in small volume.

1.2.3 Nitrogen (N_2):

Nitrogen may be supplied from the onshore sources such as purchased from existing Inert Gas Generation Units (IGGU) which provide nitrogen for inserting facilities via pipeline. When N_2 is injected, the injected gas will eventually break through (sufficient quantity of the injected gas will be seen in the associated or co-produced gas), which will affect the composition of the associated gas to a significant extent that gas cleanup will be necessary. The topsides therefore require to be modified in order to render the product gas suitable for sales. Some form of purification such as Nitrogen Removal Unit (NRU) can be employed. The additional benefit of producing a recycle gas for injection lowers the purchased gas requirements, thereby saving operating cost. This applies in case of N_2, and natural gas injection.

1.2.4 Natural Gas:

Natural gas may be supplied from the onshore sources or extracted from internally produced associated gas, while H_2S, acid gas, and sour gas will be generally co-produced. Because the molecular weight of the natural gas is the lightest, the injection compressor discharge pressure is the highest at nearly 14,000 psi.

1.3 Assessment of Nitrogen Removal Technologies on Feed Gas

Dismissed as a useless by-product of crude oil production until the second half of the 20th century, natural gas now accounts for about 23 percent of the world's energy consumption. An environmentally friendly and efficient energy source, natural gas is the cleanest-burning conventional fuel, producing lower levels of greenhouse gas emissions than heavier hydrocarbon fuels such as coal and oil. Historically, natural gas also has been one of the most economical energy sources. Natural gas fuels electric power generators, heats buildings, and is used as a raw material in many consumer products, such as those made of traditional plastics. The natural gas demand is growing. The International Energy Agency predicts that the demand for natural gas will grow by approximately 44 percent through 2035. Recent gas reservoir discoveries around the world were found to contain significant levels of nitrogen up to the 15% range. Also, as mentioned above, some current production techniques for maintaining crude oil recovery from a reservoir utilize the injection of nitrogen as enhanced oil recovery (EOR) method. Gradually, the equilibrium nitrogen dissolved in the crude oil will come to the surface as associated gas when the nitrogen breaks through. The challenges facing the gas industry are highlighted by the Gas Technology Institute (GTI, USA) in their estimates that 11% of current daily gas production and 16% of all known gas reserves in the USA contain some nitrogen.

Nitrogen Removal Unit (NRU) is a required facility to separate the nitrogen and hydrocarbon. (Finn, 2007) For any gas or LNG plant, higher levels of nitrogen within the feed gas mean lower profitable volumes or additional capital investment. NRU can be expensive to build and difficult to operate. Gas companies typically set maximum concentration limits on nitrogen content in the pipeline between 4.0 to 7.0 percent depending on the local product specifications. Therefore, in general, nitrogen levels of greater than 7.0 percent must undergo removal. Nitrogen removal processes for natural gas using cryogenic processing, membrane, adsorption, and liquid solvents are currently available, but all of these methods most likely require high recompression of the methane product, which penalizes their economics. Many other companies are trying to find a more economical way to remove the nitrogen from the natural gas.

For example, on a 5.0 Million Tonne per Annum (MTPA) LNG plant where 1.0 % more nitrogen in the feed gas will result in anywhere from 0.6 to

1.0 percent lower LNG production. The projected loss in revenues could approach 200 million in US dollars over an assumed 20 year plant life cycle, based on an assigned value of 208 USD / Tonne (assumes a value pricing difference of 4.0 USD per Million BTU between feed gas and LNG).

All currently available technologies (Hahn, et al., 2007), considering both commercially demonstrated NRU technologies as well as those in the developments to be evaluated by way of process flow diagrams, descriptions, technology highlights, pre-treatment requirements, strength and weakness and technology licensor/vendor include

- Cryogenic Distillation,
- Membranes (Membrane Technology and Research (MTR),
- Molecular Gate System,
- Solvent Absorption,
- Nitrogen Sponge,
- Pressure Swing Adsorption (PSA),Carbon Molecular Sieve (CMS),
- Lean Oil Absorption,
- Chelating Chemical.

1.3.1 Different NRU Technologies

1.3.1.1 Cryogenic Distillation

The Cryogenic Distillation technology is the most commonly used on a commercial scale (Millward et al., 2004). Multiple contractors can provide the Engineering, Procurement and Construction (EPC) such as APCI, Bechtel/IPSI, Linde, KBR, BCCK, Costain and some other EPC companies worldwide (Costain

Energy &Process, 2005). Many distillation technologies have long been used to separate nitrogen from natural gas. It achieves 99+% hydrocarbons (majority is Methane) recovery within a wide range of nitrogen feed content and is typically used for high feed gas rate applications.

A NRU block flow diagram example is shown in Figure 1.5 (Elliot, et al., 2008). The technology typically consists of five major steps: inlet receiving/compression, pre-treatments, J-T or expander chilling, cryogenic fractionation, and recompression (Low et al., 2000) (Swallow, 1983). Commonly used schemes include single column (Figure 1.6) (Elliot, et al., 2008)., double columns (Figure 1.7) (Jones et al., 1999) and triple columns (aka pre-separator with two columns or pre-fractionator with two columns) (Figure 1.8) (Hahn et al., 2007) (Costain Energy & Process., 2005). One of the primary contributors to NRU facility cost is the required compression for the inlet gas and the sales gas. (Henley et al., 1981) This is the most expensive technology to build but with the most flexibility in term of the design parameters such as feed gas composition, inlet pressure, vent hydrocarbon concentration. Due to the greenhouse effect, continuous venting hydrocarbon causes a lot of concerns. In some old NRU, the N2 vent has 3.0% of hydrocarbon. However in the new NRU, the vent could be limited to 1.0% or even 0.1%. (Gas Processors Suppliers Association, 2011) Furthermore additional thermal oxidizer or incinerator is required to destruct the hydrocarbon in order to minimize the Green House Gas (GHG) effect. This makes this technology even more expensive.

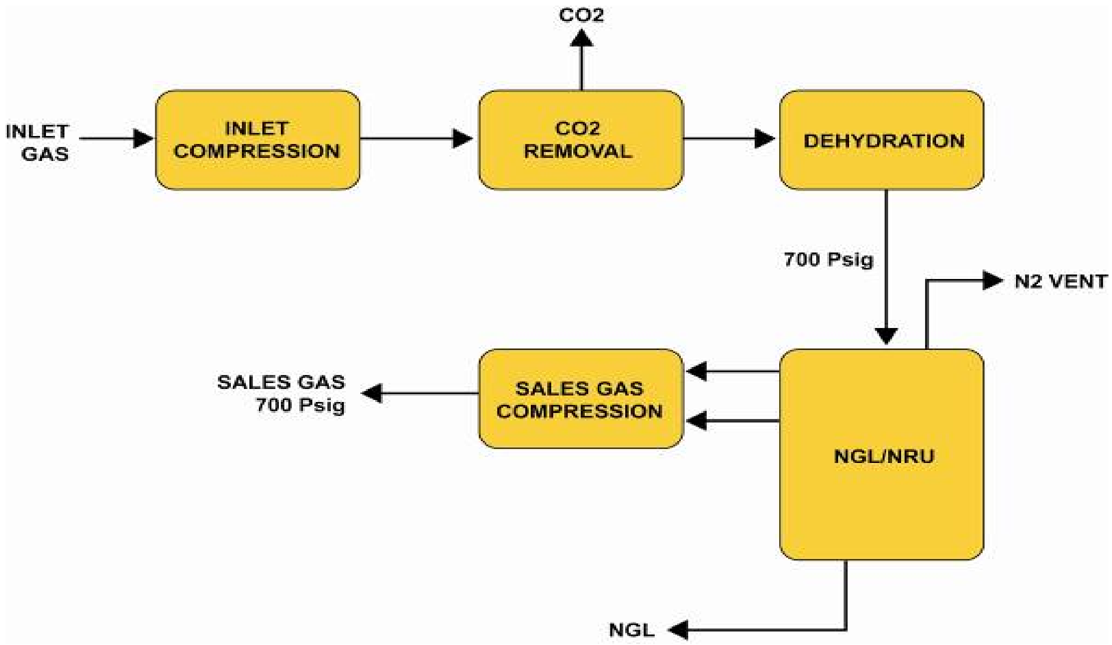


Figure 1.5 NRU Block Flow Diagram (Elliot et al.,2008)

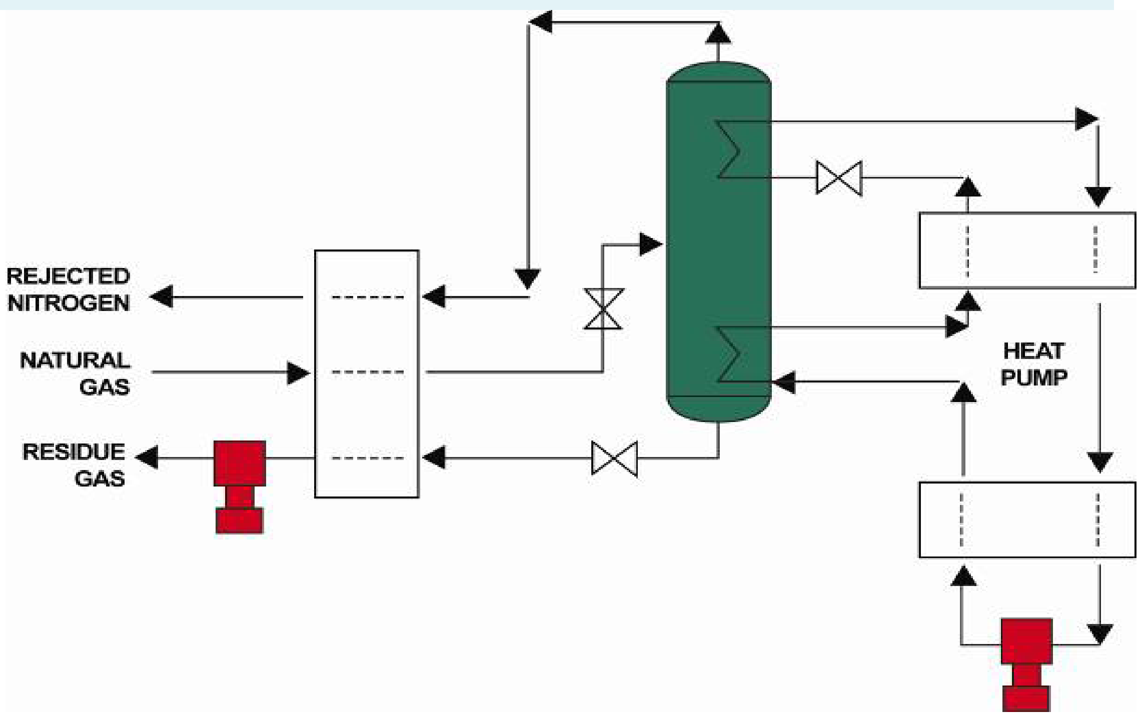


Figure 1.6 Single Column Cryogenic Distillation (Elliot et al.,2008)

1.3.1.1.1 Inlet Receiving/Compression

Depending on the source of feed gas to the NRU, the nitrogen removal system will require some types of inlet receiving equipment. Many projects require equipment such as a slug catcher, a vapor/liquid separator and/or a compression system to raise the inlet pressure.

1.3.1.1.2 Pre-treatments

The feed to the nitrogen rejection unit is pre-treated to remove components that could freeze in downstream cryogenic equipment. The CO_2 is typically removed to 50–100 Part Per Million by Volume (PPMV) levels using amine treating. Acid gas such as H_2S is also removed to less than 4 PPMV to meet sales gas specification. After amine treating in the acid gas removal unit (AGRU), the sweet gas is most often dehydrated with a solid desiccant. Molecular sieves are generally specified because of their ability to dry the gas stream to a water dew point well below the required specification.

A Mercury Removal Unit (MRU) may then be required to remove mercury (Hg) to very low levels. Hg concentration below 1 Part Per Trillion by Volume (PPTV) or 0.001 Part Per Billion by Volume (PPBV) is often required to avoid mercury corrosion which would destroy downstream brazed aluminum exchangers. Typically removal is accomplished with an adsorbent bed using sulphur-impregnated activated carbon located just downstream of the dehydration unit. Depending on the feed composition, heavy hydrocarbons can be extracted at an intermediate temperature level during the chilling step. Tri-Ethylene Glycol (TEG), which is also commonly used for dehydration, has also been commercially demonstrated for bulk removal of aromatic hydrocarbons prior to the chilling/condensation step. (McKenzie et al.,1997)

1.3.1.1.3 J-T or Expander Chilling

Following pre-treatment, the dry, clean gas is successively chilled to condensation temperature by heat exchange with the product streams in brazed aluminum heat exchangers. The chilling process is accomplished by using any or all of the following:

- ❖ Adiabatic expansion (JT valve)
- ❖ Isentropic expansion (turbo expander).

1.3.1.1.4 Cryogenic Fractionation

The cryogenic fractionation section of the NRU is normally located inside a cold box. It is the heart of the NRU because it controls (1) the nitrogen in the methane-rich product stream, (2) the hydrocarbon losses in the rejected nitrogen stream, and (3) the overall thermal efficiency of the process.

1.3.1.1.5 Recompression

For typical applications, recompression of the sales gas (or fuel gas) is usually required unless the gas can be marketed at 20 barg or less. The main force for NRU separation is provided by the pressure differential between the feed gas and the product streams. The product streams, such as sales or fuel gas and N_2, when exit the unit at a pressure lower than the feed gas, possibly require recompression.

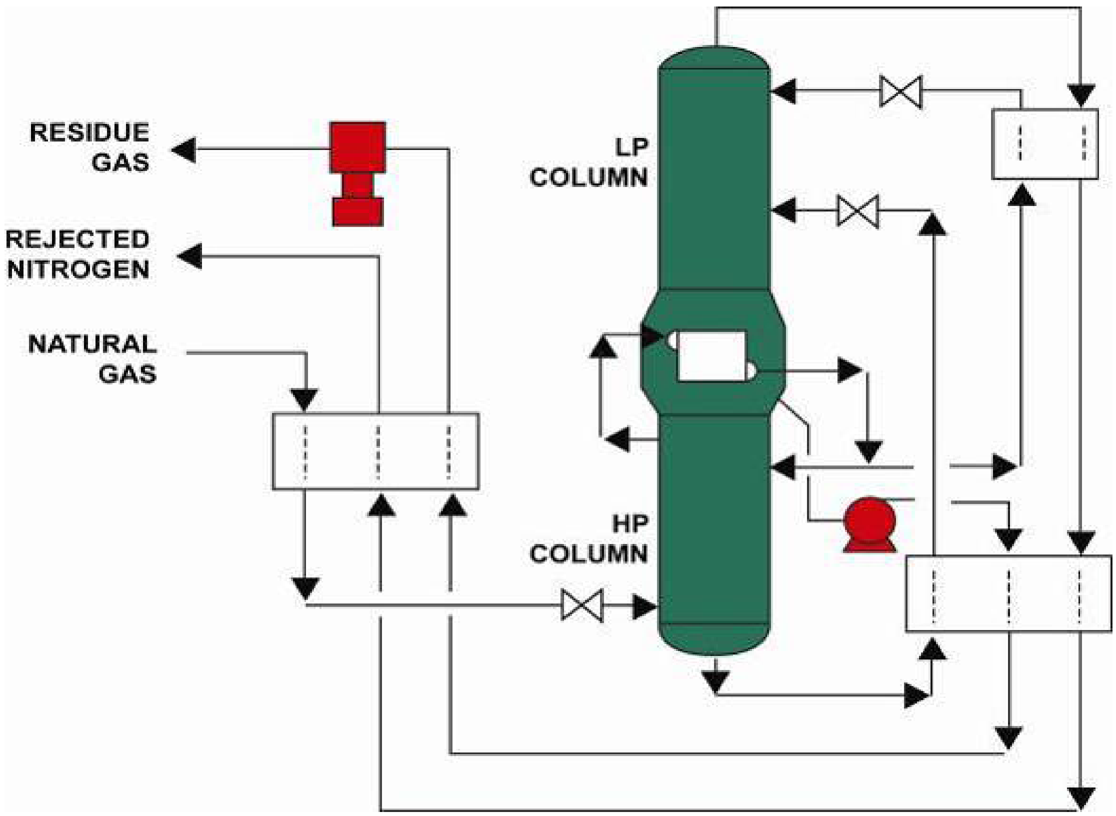


Figure 1.7 Double Columns Cryogenic Distillation (Elliot et al.,2008)

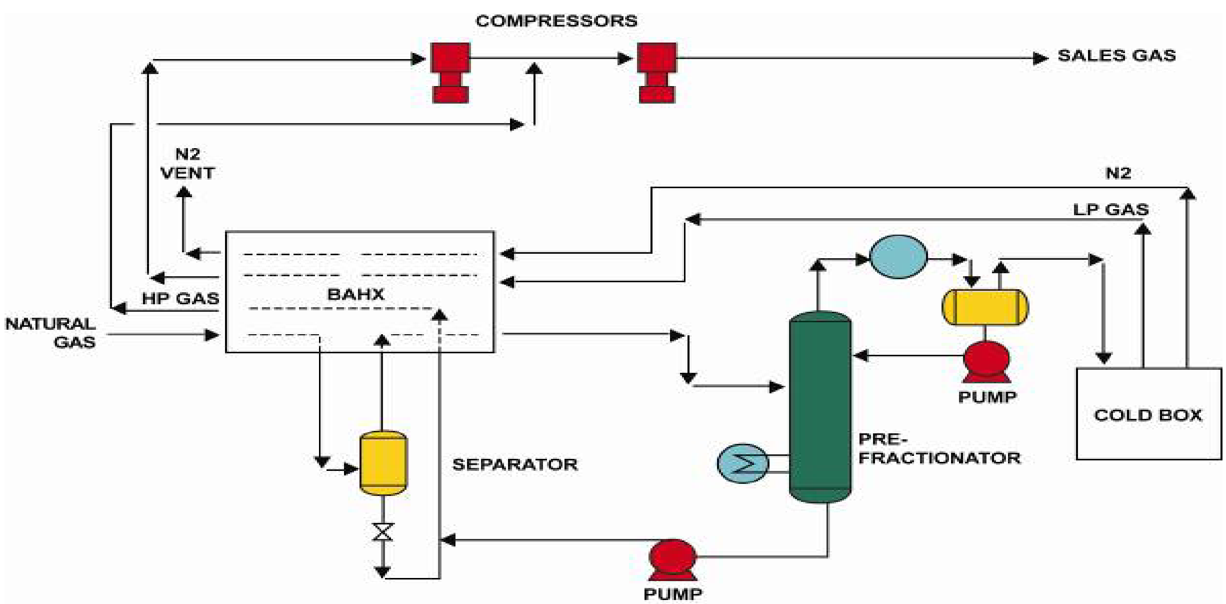


Figure 1.8 Pre-fractionator (Triple Columns) (Costain,2005)

1.3.1.2 Membrane Solution, Membrane Technology and Research (MTR)

(Membrane Technology and Research Inc., 1999)

In this technology, membranes are used to selectively permeate methane and reject nitrogen in the gas stream. The process relies on proprietary membranes that are significantly more permeable to methane, ethane, and other hydrocarbons than to nitrogen. (Elliot et al., 2008). As illustrated in Figure 1.9, MTR describes a two-stage membrane case that can produce pipeline-quality gas and nitrogen rich fuel from raw natural gas. Gas containing 15.0% nitrogen is firstly passed through a set of membrane modules. The permeated gas, which contains 4.0 mol.% nitrogen, is sent to the pipeline after compression. The nitrogen-rich residue gas then passes through a second set of membrane modules. This second set of modules produce a waste gas containing 50.0 mol.% nitrogen and a nitrogen-depleted gas containing about 10.0-20.0 mol.% nitrogen. The permeated gas is used as fuel. This case achieves about 90% hydrocarbon recovery of the feed gas heating British Thermal Unit (BTU) value (majority is methane) into the pipeline product. Recovery values as high as 95% or higher can be achieved depending on the composition of the inlet gas.

The pressure drops going through the membranes are at 12 bar to 50 bar per stage depending on the feed gas pressure. Another limitation for membranes is the maximum design pressure which is currently at 85 barg. Any feed pressure which is higher than 76.5 (90%of 85) barg needs to be throttled down before sending to the MTR.

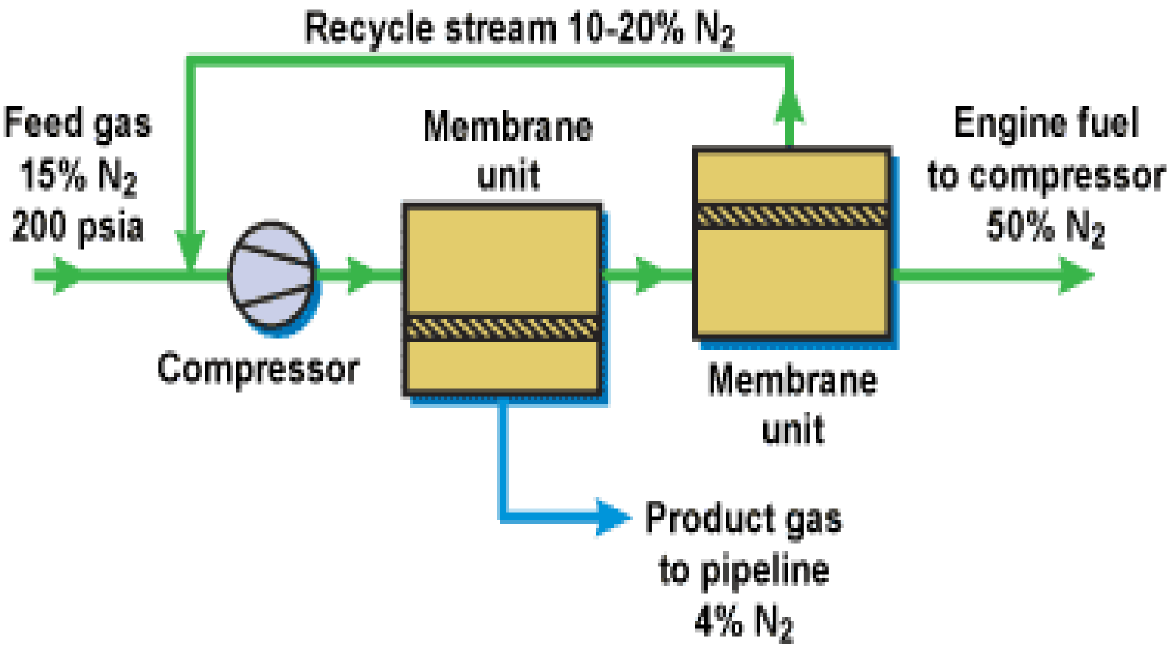


Figure 1.09 Membrane Technology and Research (MTR) (2-Stage Membrane,2009)

Figure 1.70 Nitro-Sep™ Process (MTR,2009)

An example of the MTR is the MTR's NitroSep™ system (Figure 1.10) which produces pipeline-quality or pipeline-acceptable gas and a nitrogen-rich fuel from raw natural gas.

1.3.1.3 Molecular Gate Systems

The Engelhard Molecular Gate system (Figure 1.11) offers a prefabricated, modular plant based on patented adsorbent materials. It is functioned to trap N_2 with this adsorbent while letting methane flow through. It has generated significant interest in the natural gas industry. It is easy to start-up. The unattended operation and cost-effectiveness are the advantages of the Molecular Gate technology.

Molecular Gate methane stream only has a minor pressure drop of about 0.7 bar. It often requires pre-treatment including inlet receiving, Acid Gas Removal Unit (AGRU) and Molecular Sieve Dehydration. The recovery of methane is about 90%. Because the sieve bed sizes are proportional to the gas volume being treated, this process has been used for smaller feed gas rate applications. Current flow is limited at 80 Million Standard Cubic Feet per Day (MMSCFD) per train due to a vessel diameter of 12.5 ft. The maximum design pressure is 55 barg. The optimum operating pressure is between 17 and 41 barg. The methane product is produced at low pressure of less than 55 barg. Also, the waste nitrogen stream may have a higher amount of hydrocarbons than allowed for venting of the nitrogen. If fuel use is not required for utilizing the waste nitrogen stream, hydrocarbon loss through venting of CO_2 mixed with N_2 could be a major concerns due to the greenhouse gas hydrocarbon penalty.

Figure 1.81 Molecular Gate® system, Removing the N_2 (or N_2 plus CO_2).

1.3.1.4 Solvent Absorption (Advanced Extraction Technologies AET)

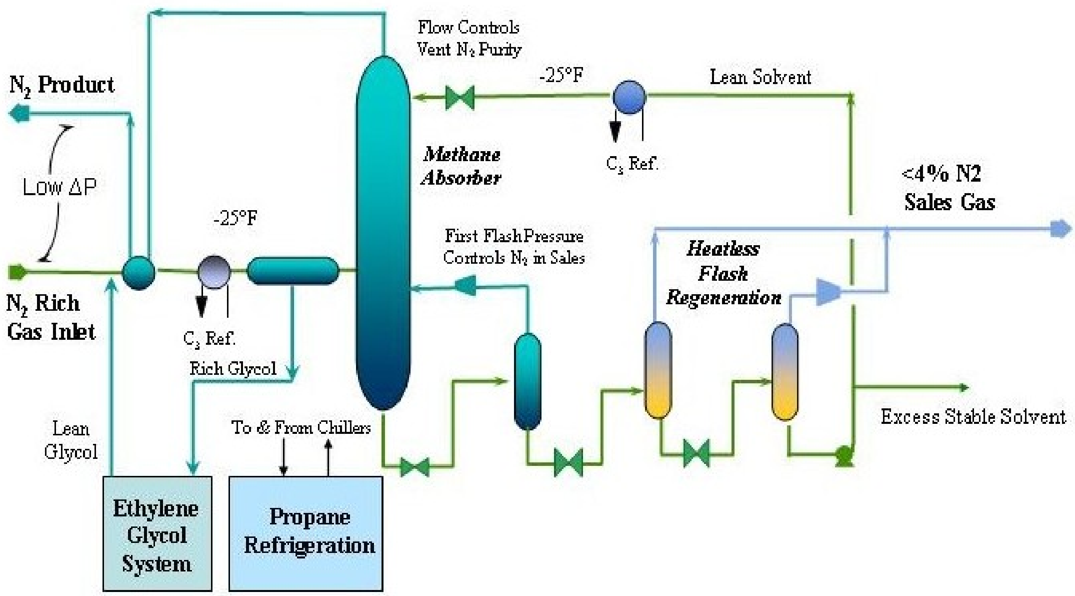


Figure 1.92 AET Process® NRU

This solvent absorption process as shown in Figure 1.12 has the advantage of not requiring CO_2 removal (AGRU) or deep dehydration. The hydrocarbon components are actually absorbed and regenerated at low pressure. For large capacity plants (>15 MMSCFD) AET may not be able to compete with Cryogenic fractionation with cold box according to some studies.

1.3.1.5 Nitrogen Sponge (IACX Energy)

The process of Nitrogen Sponge Unit (Figure 1.13) has been typically used under low pressure (around 4 barg) and low volumes (< 5 MMSCFD). IACX Energy introduced the Nitrogen Sponge™ process. This non-cryogenic and environmentally friendly nitrogen removal unit is a small scaled and extremely mobile. It removes nitrogen and water vapor from natural gas to meet stringent pipeline specifications. Inlet feed nitrogen concentrations can vary between 4%

and 40%. The Sponge will remove nitrogen with only minimal hydrocarbon losses. The maximum design pressure is 4 barg.

Figure.1.103 Rollout of a Nitrogen Sponge Unit (IACX Energy)

1.3.1.6 Pressure Swing Adsorption, Carbon Molecular Sieve (CMS)

Pressure swing adsorption is a technology used to separate nitrogen from other gases including natural gas components under pressure according to its molecular characteristics and attraction to an adsorbent material at near-ambient temperatures. Special adsorptive materials are used as a molecular sieve, adsorbing the hydrocarbon components at high pressure. The process then swings to low pressure to desorb the adsorbent material. Typical Carbon Molecular Sieve (CMS) uses this process to separate the methane from nitrogen and others. The adsorption/desorption cycle is quite similar to molecular sieve dehydration. Such a process could be instrumented quite easily for unattended operation. Methane is released during the desorption step at relatively low pressure near atmospheric (~1 barg) or even under vacuum in some cases. This technology also tolerates CO_2 and water but needs a larger bed. CMS is not economical to treat the high nitrogen feed gas rates due to the low methane product pressure. Extremely high recompression horse power is required for the methane product.

1.3.1.7 Lean Oil Absorption

This cryogenic absorption process uses chilled hydrocarbon oil to absorb the bulk of the methane and achieves a separation of nitrogen from natural gas. The absorbed methane is stripped off the oil in a regenerator and subsequently compressed back to the pipeline pressure. The need to absorb the bulk of methane requires large cryogenic oil circulation. This process has not been widely used commercially (Elliot et al., 2008,) and is not currently being marketed.

1.3.1.8 Chelating Chemical

The chelating chemical process is in the early research and developmental stage. This process uses a solvent containing a chelating agent to absorb nitrogen from the natural gas, leaving the methane and other hydrocarbons behind. The chelating agents are expensive and of questionable stability; there are no known research activities going on recently.

1.3.2 Technology Selection

As the NRU technologies vary widely, the selection of an optimum NRU technology may depend on the following design criteria. (Pervier et. al.,1983)

1) Feed gas nitrogen concentrations,
2) NRU inlet pressure,
3) NRU capacity,
4) Product specifications,
5) Approaches for the final disposition of the recovered hydrocarbon stream: (e.g., as fuel gas, re-injection or recycle back to feed gas),
6) Environmental NOx emissions impact,
7) Allowable methane concentration in the nitrogen vent.

The above items are generally the main factors considered in selecting a NRU technology. However, evaluations of other factors as shown below are also required to select a NRU technology,

1) Capital cost
2) Required compression power (the main operating cost)

3) Technology maturity
4) Hydrocarbon loss and the greenhouse gas penalty impact
5) Required operator attention
6) Required maintenance effort
7) Health, Environmental and Safety (HES) issues

Among the NRU technologies described above, the cryogenic fractionation has been widely used for providing an efficient and reliable means to upgrade natural gas. The use of membrane technology has progressed significantly in the last several years. While membranes (MTR) and Molecular Gate technologies have advanced, neither can produce high purity nitrogen when compared to cryogenic distillation. Cryogenic distillation can provide -

- High hydrocarbon recovery over 99+%.
- Minimal emissions of hydrocarbon methane Green House Gas (GHG) to atmosphere.
- High thermodynamic efficiency (lower power consumption).

A comparison summary of the above described NRU technologies is given in Table 1.1.

Table 1.1 NRU technologies Comparisons

NRU Technology	Technology Highlights	Application/ Limitation	Comments
Cryogenic Fractionation	J-T or expander, chilling and distillation at cryogenic temperatures. Re-compression is required. Cold box installation with Brazed Aluminum Heat Exchanger (BAHE).	Wide range feed gas inlet pressure and flow rate No design pressure limitation. May not be competitive for low gas throughput (<25 MMSCFD per Finn's [3] paper). Very low methane concentration (100 PPM to 1.5%) in N_2 vent stream.	Can achieve high hydrocarbon recovery of 99+%. Pre-treatment required including inlet receiving/compression, AGRU, Molecular Sieve Dehydration and MRU. Cryogenic distillation and re-compression also required. Many proven commercial installations. Multiple contractors can provide the EPC such as APCI, Bechtel/IPSI, Linde, KBR, BCCK, Costain and many other EPC companies worldwide.
Membranes (Membrane Technology and Research, MTR)	Single or multiple membranes modules used to separate nitrogen from hydrocarbon. Re-compression may be required, especially for multiple membrane modules installation.	Max. Design pressure is 85 barg. Currently. Max. Design through put is 100 MMSCFD/per train. Pressure drop for hydrocarbon is very high between 12 to 50 Bar per stage depending on feed N_2 concentration and pressure. Preferred N_2 concentration is 4% to 50%.	Hydrocarbon recovery is near 90% depending on the feed gas N_2 concentration. No pre-treatment required except for inlet receiving usually. CO_2 removal may be required depending on the feed CO_2 concentration. Many proven commercial installations. MTR is the only EPC contractor.

Table 1.1	Continued		NRU technologies Comparisons
Molecular Gate	Similar to Molecular Sieve Adsorption. Re-compression most likely required.	Max. Design pressure is 55 barg. Preferred operating pressure is between 17 and 41 barg. Not designed for and cannot be used to remove gas stream with more than 30% N_2 Max. Design through put is 80 MMSCFD/per train. Hydrocarbon pressure drop is low at about 0.7 Bar	Hydrocarbon recovery is about 90%. Pre-treatment required including inlet receiving, AGRU for CO2 removal and Molecular Sieve water Dehydration. Could remove N_2 and CO_2 in single step with larger bed. Many proven commercial installations. Guild associate is the EPC contractor.
Solvent Absorption (AET)	Separation of hydrocarbons from nitrogen using an absorbent solvent. The absorbed hydrocarbons are flashed off from the solvent by reducing the pressure on the processing stream in multiple gas de-compression steps.	Max. design pressure range is 70 barg. Currently. Largest installed capacity is 15 MMSCFD.	Can achieve high hydrocarbon recovery of 99+%. No pre-treatment required other than inlet receiving. Some commercial success with 50 mol. % nitrogen. For higher feed gas rate, higher recompression may be required for AET comparing with Cryogenic Distillation. AET is the EPC contractor.

Table 1.1	Continued		NRU technologies Comparisons
Nitrogen Sponge	Nitrogen sponge absorbs water and nitrogen	Max. Design pressure is 4 barg. Max. Design through put is 5 MMSCFD/per train.	Can achieve high hydrocarbon recovery of 92+%. Pre-treatment is not required other than inlet receiving, For low-pressure (around 4 barg), low-volume (<5 MMSCFD) natural gas streams only. This non-cryogenic, nitrogen rejection unit is for lower feed gas rate. Some commercial success. IACX energy is the EPC contractor.
Cryogenic Lean oil absorption	Absorption of methane into cryogenic lean oil.	No commercial applications. Wide range of feed gas pressures tolerated. (Elliot et al., 2008).	This is a new process and no commercial applications are operational. There are no marketing activities going on recently.
Pressure swing adsorption. Carbon Molecular Sieve (CMS)	Adsorbing the hydrocarbon components at high pressure. The process then swings to low pressure to desorb the adsorbent hydrocarbon material.	No commercial applications. (Elliot et al., 2008).	High recompression horse power is required for the hydrocarbon product.
Chelating solvent absorption	Selective absorption of nitrogen into a chelating solvent	No commercial applications. (Elliot et al., 2008).	This process is in the research and development stage. Stability of the solvent is suspect.

1.4 Objectives and Scope of Research.

The purpose of this study is to find the most popular and applicable EOS in the ultra-high pressure compression simulation industry for EOR purpose (Plocker et al.,2002). This will include checking with subject matter experts (SME) in gas processing, rotating equipment, flow assurance, reservoir engineering, and technical support of simulators professionals. Because the critical and fundamental thermodynamic related properties such as enthalpy, entropy, vapor pressure and density are shown to be related to the compressibility factor, process models need to be developed and used to evaluate different EsOS. With the selected pure CO_2, pure N_2, or hydrocarbon/injection gas (CO_2 or N_2, natural gas) mixtures, the predicted compressibility factors (Z) from different EsOS under various pressure and temperature conditions are compared with the gathered experimental data for the evaluations of EOS models (Kiseley et al., 2002). The proposed tasks are listed in the following.

a) Gather available actual experimental data about Z factor through literature search, requisition and research. For examples, there are many actual experimental data about Z factor. There are many research centers which can accurately measure those thermo-physical properties such as the density of gas. (Mantilla et al., 2010(a), 2010 (b)) and (Reamer et al.,1945,1951, 1952). Apparatuses for the accurate measurement of density of gases and liquids as well as for the measurement of viscosity of gases were operated in many countries. From density, the Z factor can be calculated. Those Z factors gathered for different gas composition at different pressures and temperatures can be used to compare to the Z factors calculated by different EsOS. The comparisons of Z factors can not only tell us how accurate the Ideal gas law is, but also serve as a correction factor for the Ideal gas law. The more accurate correlation between P, V, and T can be obtained.

b) Construct and evaluate a list of EsOS that can be applied to ultra-high pressure compression simulation.

c) Select the most appropriate process simulators for building the simulation model.

d) Establish the hydraulic profile for gas injection discharge including the 7000-ft water depth and 24,000-ft reservoir thickness and set the required discharge pressure.

e) Build the simulation model to test the identified EsOS . The model tested include the effects of

- Reservoir production,
- Oil production and oil pump-out,
- Water production and disposal including water treatment,
- Gas production and gas consumption,
- Injection gas make up,
- Injection of gas to reservoir, and
- Gas breakthrough and recycle.

As the simulation covers from almost atmospheric pressure to 12,000 psia, the Vapor Recovery Unit (VRU, 1 stage), Flash Gas Compressor

(FGC, 2 stages), Booster Gas Compressor (BGC, 2 stages) and Injection Gas Compressor (IGC, 3 stages) are also needed to be included.

f) Evaluate and compare the results (e.g., Z factor) obtained from use of the selected EsOS and actual experimental data to determine the most appropriate EOS to be used in ultrahigh pressure process simulations, equipment sizing and design purpose. The cases include using pure CO_2, pure N_2, and hydrocarbon/injection gas (CO_2 or N_2, natural gas) mixtures.

g) Examine the impact of different EsOS on the FGC, BGC and IGC horse power and the inter-stage cooler duty. This is to determine the impact of using different EsOS for the cost comparison.

1.5 Outline of the Dissertation

The general introduction of the study is described in Chapter 1. The problem statement, literature review which includes the EOR and three most popular gases CO_2, N_2 and natural gas served as EOR injection gas are also discussed in Chapter 1. For the offshore EOR, if the nitrogen is used as the injection gas, eventually the nitrogen will saturate, break through and come out with the oil and associate gas. Nitro Removal Unit (NRU) will be required to separate the nitrogen and hydrocarbon. Chapter 1 also provides all currently available NRU technologies. All of those available technologies are introduced by way of process flow diagrams, descriptions, technology highlights, pre-treatment requirements, strength and weakness and technology licensor/vendor lists.

Process modeling is important for conceptual design, optimization, and performance monitoring for oil and gas production, gas processing and petroleum refining. Furthermore, various Equations of State (EsOS) have been proposed for different systems and different industries. Chapter 2 presents process simulators and a list of available EsOS.

The methodology for evaluating identified EsOS with Aspen's HYSYS model is addressed in Chapter 3. This includes gathering available actual experimental data and simulating the EsOS model for the compressibility factor, Z. Those lab measured Z factors for different gas composition at different pressures and temperatures are compared with the Z factors calculated by different EsOS. The hydraulic profile for gas injection discharge including the 7000-ft water depth and 24,000-ft reservoir thickness are analyzed and set the required discharge pressure for injection compressor.

Simulation runs and results are reported in Chapter 4. The results (e.g., Z factor) obtained from use of the selected EsOS and actual experimental data are compared to evaluate the EOS model performance. The completed simulation model was also applied to examine the impact of different EsOS on the FGC, BGC and IGC horse power and the inter-stage cooler duty. This is to determine the impact of using different EsOS for the cost comparison. The presented study is summarized in Chapter 5 with conclusions, recommendation and future study. Following a complete list of references, an Appendix A is provided to summarize the calculation procedures given by Pratt (2001) for thermodynamic properties by the PR EOS. Example outputs from HYSYS model simulation printouts and samples of binary interaction parameters are presented respectively in Appendix B and Appendix C.

Chapter 2. Process Simulators and Equations of State (EsOS)

2.1 Process Simulators

Process simulators are tools for conceptual design, optimization, and performance monitoring for oil and gas production and gas processing. A list of available process simulators, including the name of the software and application areas are given in Table 2.1 below. (Wikipedia (c), 2014)

Because the critical and fundamental thermodynamic related properties such as enthalpy, entropy, vapor pressure and density are heavily depend on the use of EOS. Various EsOS models have been included in the process simulator to obtain the thermodynamic variables. Simulation by the selected process simulator can be carried out to evaluate the accuracy of different EsOS. It is aimed in this study to identify the best EOS, especially under the ultrahigh pressure condition for producing the most accurate compressibility Z. The engineering design will be based on the best simulator as well as the best EOS.

Table 2.1 Available Process Simulators

Software	Developer	Applications	Operative system	License
Ariane	ProSim	Utilities management and power plant optimization		
APMonitor		Data reconciliation, real-time optimization, dynamic simulation and nonlinear predictive control		

Aspen Plus	Aspen Technology	Process simulation and optimization		
Table 2.1		Continued		
Aspen HYSYS	Aspen Technology	Process simulation and optimization		
ASSETT	Kongsberg Oil & Gas Technologies AS	Dynamic process simulation		
BatchColumn	ProSim	Simulation and Optimization of batch distillation columns		
BatchReactor	ProSim	Simulation of chemical reactors in batch mode		
D-SPICE	Kongsberg Oil & Gas Technologies AS			
K-Spice	Kongsberg Oil & Gas Technologies AS	Dynamic process simulation and multiphase pipeline simulation		
CADSIM Plus	Aurel Systems Inc.	Steady-state and dynamic process simulation		
ChromWorks	ChromWorks, Inc.	Continuous/Batch chromatography process simulator		
CHEMCAD	Chemstations	Software suite for process simulation		
Cycle-Tempo	Asimptote	Thermodynamic analysis and optimization of systems for the production of electricity, heat and refrigeration		
COCO simulator	AmsterCHEM	Steady state simulation		free of charge
Design II for Windows	WinSim Inc.	Process simulation		

Table 2.1		Continued		
Distillation expert trainer	ATR	Operator training simulator for distillation process		
DWSIM	Daniel Medeiros, Gustavo León and Gregor Reichert	Process simulator	Windows, Linux, Mac	open-source
DynoChem	Scale-up Systems Ltd.			
EMSO	ALSOC Project	Modelling, simulation and optimization		
Dymola	CATIA Systems Engineering	Dynamic modelling and simulation software		
Flowtran simulation	Monsanto			
gPROMS	PSE Ltd	Advanced process simulation and modelling		
HSC Sim				
INDISS	RSI			
ICAS: integrated computer-aided system	CAPEC			
IDEAS	Andritz Automation			
iiSE Simulator	VRTech			
LIBPF		C++ LIBrary for process flow sheeting		
JModelica.org	Modelon AB			open-source

Table 2.1 Continued				
METSIM	Proware	General-purpose dynamic and steady state process simulation system	Windows	
MiMic	MYNAH Technologies			
Mobatec Modeller	Mobatec			
Clearview	Mapjects			
OLGA	SPT Group (Schlumberger)			
Omegaland	Yokogawa			
OpenModelica	Open-Source Modelica Consortium			open-source
PIPE-FLO Professional	Engineered Software Inc.			
PEL Software Suite				
Petro-SIM	KBC Advanced Technologies			
PETROX	Petrobras	General Purpose, Static, Sequential-Modular Process Simulator	Windows	internal users only
Prode Properties	Prode Software			
Prode simulator	Prode Software			

Table 2.1 Continued				
ProSim DAC	ProSim	Dynamic Adsorption Column Simulation		
ProSimPlus	ProSim	Process simulation and optimization		
ProSimulator	Sim Infosystems			
Pro-Steam	KBC Advanced Technologies			
ProMax	Bryan Research and Engineering			
TSWEET	Bryan Research and Engineering			
PROSIM				
PRO/II	SimSci			
DYNSIM	SimSci			
ROMeo (process optimizer)	SimSci			
RecoVR	VRTech			
Simulis Thermodynamics	ProSim	Mixture properties and fluid phase equilibria calculations		
SimCreate	TSC Simulation			
SPEEDUP	Roger W.H. Sargent and students			
SolidSim	SolidSim Engineering GmbH	Flow sheet simulation of solids processes		

Table 2.1 Continued				
SuperPro Designer	Intelligen			
SysCAD				
System7	Epcon International			
UniSim design	Honeywell			
Shadow plant	Honeywell			
Usim Pac	Caspeo			
VMGSim	Virtual Materials Group			
Wolfram SystemModeler	Wolfram Research		Windows, Mac, Linux	

2.2 Equations of State (EsOS)

As described by Peng and Robinson (Peng et al.,1976), In the field of physics and thermodynamics, an equation of state (EOS) is a relation between state variables and thermodynamic properties. More specifically, an EOS is a thermodynamic equation describing the state of matter under a given set of physical conditions. It is a constitutive equation which provides a mathematical relationship between two or more state functions associated with the matter, such as its temperature, pressure, volume, density or internal energy. EsOS are useful in describing the properties of fluids, mixtures of fluids, solids, and even the interior of stars." Use of a properly selected and tested EOS can provide important thermodynamic gas properties for the EOR studies.

The most prominent use of an EOS is to correlate densities of gases and liquids to temperatures and pressures (Edmister,1984). One of the simplest equations of state for this purpose is the ideal gas law, which is roughly accurate for weakly polar gases at low pressures and moderate temperatures. However, this equation becomes increasingly inaccurate at higher pressures and lower temperatures, and fails to predict condensation from a gas to a liquid. Therefore, a number of more accurate EsOS have been developed for gases and liquids. At present, there is no single equation of state that accurately predicts the properties of all substances under all conditions. Furthermore, there are nearly 30 different EsOS available for different systems and different industries in Chemical, Electrolyte, Environmental, Oil and Gas, Mineral and Metallurgical, Petrochemical, Power and Refining areas (Aspen HYSYS, 2011).

2.2.1 Activity Models

An activity coefficient is a factor used in thermodynamics to account for deviations from ideal behavior in a mixture of chemical substances. In an ideal mixture, the microscopic interactions between each pair of chemical species are the same (or macroscopically equivalent, the enthalpy change of solution and volume variation in mixing is zero) and, as a result, properties of the mixtures can be expressed directly in terms of simple concentrations or partial pressures of the substances present e.g., Raoult's law. Deviations from ideality are accommodated by modifying the concentration by an activity coefficient. The Activity Models handle highly non-idealized systems and are much more empirical in nature when compared to the property predictions in the hydrocarbon industry. Polar or non-idealized chemical systems are traditionally handled using dual model approaches. In this type of approach, an EOS is used for predicting the vapor fugacity coefficients and an activity coefficient model is used for the liquid phase. Since the experimental data for activity model parameters are fitted for a specific range, these property methods cannot be used as reliably for generalized application. Those EsOS include Chien Null, Extended NRTL, General NRTL, Margules, NRTL, UNIQUAC, Van Laar and Wilson.

2.2.2 Chao Seader & Grayson Streed Models

Both the Chao Seader and Grayson Streed EsOS are older and semi-empirical base models. The Grayson Streed correlation is an extension of the Chao Seader EOS with special emphasis on hydrogen. Only the equilibrium data produced by those correlations are used by HYSYS. The Lee-Kesler method is used for liquid and vapor enthalpies and entropies.

2.2.3 Vapor Pressure Models

Vapor Pressure K-value models may be used for ideal mixtures at low pressures. Ideal mixtures include hydrocarbon systems and mixtures such as ketones and alcohols where the liquid phase behavior is approximately ideal. The model equations were traditionally applied for heavier hydrocarbon fractionation systems and consequently provide a good means of comparison against rigorous models. The models may also be used as first approximations for non-ideal systems. They should not be considered for Vapor Liquid Equilibrium (VLE) predictions for systems operating at high pressures or systems with significant quantities of light hydrocarbons. Those EsOS are listed as Antoine, Braun K10 and Esso Tabular.

2.2.4 Miscellaneous Types Models

The Miscellaneous group contains Property Packages that are unique and do not fit into the groups previously mentioned. For example, for acid gas removal, many Amines related EsOS have been developed. Amine Package, DBR Amine Package, ASME Stream, Glycol Package, NBS Stream, MBWR and OLI_Electrolyte are considered as miscellaneous type EOS.

2.2.5 EsOS for Oil and Gas Hydrocarbon Industries

Some EsOS have proven to be very reliable in predicting the properties of most hydrocarbon based fluids over a wide range of operating conditions. The ten most popular EsOS used by the oil and gas industries are GERG-EOS, Benedict-Webb-Rubin-Starling (BWRS-EOS), Lee-Kessler Plocker (LKP-EOS), Peng-Robinson (PR-EOS), Kabadi-Danner (KD-EOS), Peng-Robinson-Stryjek-Vera (PRSV-EOS), Soave-Redlich-Kwong (SRK-EOS), Aspen RefProps (NIST-EOS), Generalized Cubic (GC-EOS), and Zudkevitch Joffee (ZJ-EOS). (Aspen HYSYS, 2011).

Historically, GERG-EOS is designed to provide high accuracy for typical natural gas components. While it is considered to be very accurate, it has not been widely implemented in most commercial process simulators. Furthermore, the PR-EOS has generally been the most widely used for oil, gas, and petrochemical industries. Compressor manufacturers, such as General Electric (GE) and Dresser-Rand (D-R), have tested the accuracy of EOS for high pressure compression applications and compared the accuracy of Relich-Kwong (RK-EOS), Lee-Kessler Plocker (LKP-EOS) and Peng-Robinson (PR-EOS) in predicting compressor performance. (Sandberg, 2005) (Kumar et al.,1999).

2.2.6 Equations Used for Different EsOS

The thermodynamic properties of mixtures can be calculated in a very convenient way from EOS. Most of these equations are explicit in pressure, as for example, the well-established PR EOS. Cubic equations with cubic power of Z such as the one used for PR EOS are still widely used in many technical applications due to their simple mathematical structure. For technical applications with high demands on the accuracy of the calculated mixture properties, these equations show major weaknesses with respect to the representation of thermal properties in the liquid phase and the description of caloric properties.

2.2.6.1 Ideal Gas Law (1834)

An ideal gas is defined as one in which all collisions between atoms or molecules are perfectly elastic and in which there are no intermolecular attractive forces. One can visualize it as a collection of perfectly hard spheres which collide but otherwise do not interact with each other. In such a gas, all the internal energy is in the form of kinetic energy and any change in internal energy is accompanied by a change in temperature. An ideal gas can be characterized by three state variables: absolute pressure (P), volume (V), and absolute temperature (T). The relationship between them may be deduced from kinetic energy theory as

$$PV = n\,RT, \tag{2-1}$$

where

P = Absolute pressure,

V = Volume,

n = number of moles,

R = universal gas constant. R=10.731 (ft^3 *psi)/(R^0 *lb-mol),

T = temperature.

2.2.6.2 Van der Waals (1873)

In 1873, J. D. Van der Waals introduced the first EOS derived by the assumption of a finite volume occupied by the constituent molecules. His new formula revolutionized the study of EOS, and was most famously continued via the Redlich-Kwong (RK) EOS and the Soave modification of Redlich-Kwong SRK EOS. This was the first EOS to describe the properties of fluids over a wide pressure range. It predicts the existence of a critical point, and also that when liquids exist. While it is an improvement on the Ideal Gas law, it is still not particularly accurate. The formulation of Van der Waals EOS is given as

$$P = \frac{RT}{V-b} - \frac{a}{V^2} \qquad (2.2a)$$

where

$a = \frac{27R^2T_c^2}{64P_c}$ and

(2.2b)

$$b = \frac{RT_c}{8P_c} \ . \qquad (2.2b)$$

And variables with subscript c indicate the one at the critical point (Temperature or Pressure)

2.2.6.3 Soave-Redlich-Kwong (1972)

In 1972 G. Soave replaced the 1/√(T) term of the Redlich-Kwong equation with a function α (T, ω) involving the temperature and the acentric factor. The resulting equation is also known as the Soave-Redlich-Kwong (SRK) equation. The α function was derived to fit the vapor pressure data of hydrocarbons and the equation does fairly well for those materials. The SRK equation is given as

$$P = \frac{RT}{V-b} - \frac{a}{V(V+b)} \ , \qquad (2.3a)$$

where

$a = 0.42748\frac{R^2T_c^2}{P_c}(1 + (0.480 + 1.574\omega - 0.176\omega^2)(1 - \sqrt{\frac{T}{T_c}})$ and (2.3b)

$b = 0.08664\frac{RT_c}{P_c}$, (2.3c)

ω = acentric factor for the species.

The acentric factor (omega) is a conceptual number introduced by Kenneth Pitzer in 1955 and was proven to be very useful in the description of matter. It has become a standard for the phase characterization of single & pure components. The other state description parameters are molecular weight, critical temperature, critical pressure, and critical volume. The acentric factor is said to be a measure of the non-sphericity (centricity) of molecules. Also the parameter " a " is given more complicated temperature dependence than that assumed in the Redlich-Kwong equation. The parameters giving the dependence of a on ω were found by fitting experimental data on a variety of compounds to the equation. This equation is still frequently used for predicting the properties of pure substances, mixtures and vapor-liquid equilibrium. It is not expected to be accurate for highly polar species or molecules that exhibit hydrogen bonding.

2.2.6.4 Peng-Robinson (1976)

The PR EOS was developed in 1976 at The University of Alberta in order to satisfy the following goals:

1. The parameters should be expressible in terms of the critical properties and the acentric factor.

2. The model should provide reasonable accuracy near the critical point, particularly for calculations of the compressibility factor and liquid density.

3. The mixing rules should not employ more than a single binary interaction parameter, which should be independent of temperature, pressure and composition (Reid et al., 1987).

4. The equation should be applicable to all calculations of all fluid properties in natural gas processes.

The PR equation in most cases exhibits performance similar to the SRK, although it is generally superior in predicting the liquid densities of many materials, especially nonpolar ones. This EOS is fairly similar to the SRK EOS, but with a modification of the denominator of the second term on the right hand side of equation (2.3a). Again, the parameter "a" has a temperature dependence, and the parameter giving its dependence on ω has been found by comparing the predictions of the equation with experimental boiling points. The Peng-Robinson equation is particularly accurate for predicting the properties of hydrocarbons including the behavior of mixtures and vapor-liquid equilibrium (VLE). It is not expected to be accurate when predicting properties of highly polar molecules, particularly those that are capable of hydrogen bonding.

The PR property package rigorously solves any single-, two-, or three-phase system with a high degree of efficiency and reliability and is applicable over a wide range of conditions:

- Temperature Range > -456 ^oF
- Pressure Range < 14,000 psia

Interaction parameter is a measure of the interaction energy between different groups. The PR property package also contains enhanced binary interaction parameters for all library hydrocarbon-hydrocarbon pairs (a combination of fitted and generated interaction parameters), as well as for most hydrocarbon-non-hydrocarbon binaries. For oil, gas, or petrochemical applications, the PR EOS is generally the recommended property package. The PR property package is used for the following simulations:

- Tri-Ethylene Glycol (TEG) Dehydration
- TEG Dehydration with Aromatics
- Cryogenic Gas Processing
- Air Separation
- Atmospheric Pressure (ATM) Crude Towers
- Vacuum Towers
- High H_2 Systems
- Reservoir Systems
- Hydrate Inhibition
- Crude Systems

The PR EOS applies functionality to some specific component-component interaction parameters. Key components receiving special treatment include He, H_2, N_2, CO_2, H_2S, H_2O, CH_3OH, Ethylene Glycol (EG), Di-Ethylene glycol (DEG), and Tri-Ethylene Glycol (TEG).

Formulations for pressure, P, and compressibility factor ,Z, used in HYSYS for the PR EOS are given as

$$P = \frac{RT}{V-b} - \frac{a}{V(V+b)+b(V-b)} \text{ and} \qquad (2.4)$$

$$Z^3 - (1-B)Z^2 + (A - 2B - 3B^2)\,Z - (AB - B^2 - B^3) = 0, \qquad (2.5)$$

where

Z=PV/ (RT), (2.6a)

$$A = \frac{aP}{(RT)^2}, \qquad (2.6b)$$

$$B = \frac{bP}{RT}\ , \qquad (2.6c)$$

$$b = \sum_{i=1}^{N} X_i(\,b_i) = \sum_{i=1}^{N} X_i \left(0.077796\,\frac{RT_{ci}}{P_{ci}}\right)\ , \qquad (2.6d)$$

$$a = \sum_{i=1}^{N}\sum_{j=1}^{N} X_i X_j \left(a_i^{0.5} a_j^{0.5}\right)\left(1 - k_{ij}\right), \qquad (2.6e)$$

$$a_i = a_{ci}\,\alpha_i, \qquad (2.6f)$$

$$a_{ci} = 0.457235\,\frac{(RT_{ci})^2}{P_{ci}}, \qquad (2.6g)$$

$\alpha_i^{0.5} = 1 + m_i (1 - T_{ri}^{0.5})$ or $\alpha_i = (1 + m_i \left(1 - T_{ri}^{0.5}\right))^2$ and (2.6h)

$m_i = 0.37464 + 1.54226\omega_i + 0.26992\omega_i^2,$ (2.6i)

N is the total number of the components.

The subscript i is the ith component of the gas mixture.

X_i is the mol fraction of the component.

k_{ij} is the interaction parameter between different component.

$T_r = T/T_c$ = reduced temperature.

When an acentric factor ω> 0.49 is present, HYSYS uses following corrected form for m_i:

$m_i = 0.379642 + (1.48503 - (0.164423 - 1.016666\omega_i)\omega_i)\omega_i$ (2.6j)

a, b, m_i, α_i, A, and B, are PR-EOS parameters and can be calculated by above formulas.

The compressibility factor (Z), also known as the compression factor, is a useful thermodynamic property for modifying the ideal gas law to account for the real gas behavior. In general, deviations from ideal behavior become more significant when the gas is closer to a phase change. This is at the lower temperature, or at higher pressure.

2.2.6.5 Benedict-Webb-Rubin-Starling (BWRS) (1940)

The BWRS EOS has been used in fluid dynamics applications (Benedict et al., 1940). Working at the research laboratory of M. W. Kellogg Limited, the three researchers (Manson Benedict, G. B. Webb, and L. C. Rubin) rearranged the Beattie-Bridgeman EOS and increased the number of experimentally determined constants. Professor Kenneth E. Starling of the University of Oklahoma later modified the Benedict–Webb–Rubin (BWR) EOS by using eleven compound-specific coefficients along with binary interaction parameters to formulate BWRS EOS. Although usually not the most convenient EOS, the viral equation is important because it can be derived directly from statistical mechanics. This equation is also called the Kamerlingh Onnes equation. If appropriate assumptions are made about the mathematical form of intermolecular forces, theoretical expressions can be developed for each of the coefficients.

The BWRS model is commonly used for compression applications and studies. It is specifically used for gas phase components. (Wu et.al,2003). The BWRS EOS can handle the complex thermodynamics that occur during compression and is useful in both upstream and downstream industries. The BWRS EOS can be expressed as

$$P = \rho RT + \left(B_0 RT - A_0 - \frac{C_0}{T^2} + \frac{D_0}{T^3} + \frac{E_0}{T^4}\right)\rho^2 + \left(bRT - a - \frac{d}{T}\right)\rho^3 + \alpha\left(a + \frac{d}{T}\right)\rho^6 + \frac{c\rho^3}{T^2}(1 + \gamma\rho^2)\exp(-\gamma\rho^2). \tag{2-7}$$

Here, ρ is the molar density which is related to the compressibility factor (Z). Ao, Bo, Co, Do, Eo, a, b, c and d are the BWRS EOS parameters and γ can be calculated by $= \frac{1}{\rho_c^2}$.

The BWRS EOS calculates fugacity coefficients, enthalpy departure, entropy departure, and molar volume for both the vapor and the liquid phases. The BWRS property package uses 11 pure-component parameters. Coefficients and binary interaction parameters are available for 15 compounds that are built-in to the property package and stored in the database. The 15 compounds are

- Methane
- Ethane
- Propane
- I-Butane
- n-Butane
- N_2
- CO_2
- H_2S
- I-Pentane
- n-Pentane
- n-Hexane
- n-Heptane
- n-Octane
- Ethylene
- Propylene

The coefficient for each compound is obtained from multi-property (vapor-liquid-equilibrium (VLE) , enthalpy, PVT, etc.) data regressions. Coefficients for chemicals common to natural gas mixtures are available from Starling book, page 270 (Starling, 1973). The value is ranging from 0.0000 to 0.2170. Sample of the interaction parameter is provided in the Appendix D for reference. Non hydrocarbon such as N_2, CO_2 and H_2S usually has higher interaction energy. If pure component coefficients are not supplied, they are automatically estimated using Tc, Vc and acentric factor with Han-Starling correlations proposed by Starling, or user specified coefficients for each compound.

2.2.6.6 Lee Kesler Plocker (LKP) (1978)

The Lee-Kesler Plocker model is the most accurate general method for non-polar substances and mixtures.(Li et al.,2011). LKP EOS is an extension of Lee-Kesler model, where the Vapor Liquid Equilibrium (VLE) is calculated by the LKP model and the Lee Kesler model is used to calculate enthalpy and entropy. The formulation of compressibility factor from LKP EOS is

$$Z = 1 + \frac{B}{V_r} + \frac{C}{V_r^2} + \frac{D}{V_r^5} + \frac{C}{T_r^3\, V_r^2} \left[\beta + \frac{\gamma}{V_r^2}\right] \exp\left[\frac{-\gamma}{V_r^2}\right], \qquad \text{(2-8)}$$

where

$$V_r = \frac{P_c\, V}{RT_c} \;, \qquad \text{(2-9a)}$$

$T_r = T/T_c$ = reduced temperature., (2-9b)

$$B = b_1 - \frac{b_2}{T_r} - \frac{b_3}{T_r^2} - \frac{b_4}{T_r^3} \;, \qquad \text{(2-9c)}$$

$$C = c_1 - \frac{c_2}{T_r} + \frac{c_3}{T_r^3}, \qquad \text{(2-9d)}$$

$$D = d_1 + \frac{d_2}{T_r} \;, \qquad \text{(2-9e)}$$

and $b_1, b_2, b_3, b_4, c_1, c_2, c_3, d_1, d_2, \beta\ \gamma$ and ω are the LKP EOS twelve parameters. Those parameters can be obtained in the API Data book (American Petroleum Institute), (API; 2005) or from Table 8 of Robert's (Robert, 2001) book.

2.2.6.7 GERG (2008)

(Kunz et al., 2007) and (Wagner; 2014)

A new EOS for the thermodynamic properties of natural gases, similar gases, and other mixtures, the GERG-2008 EOS, had been implemented from Europe recently. As a function of density, temperature and composition, GERG-2008 EOS is indicated in the Helmholtz free energy. It provides a robust new algorithm suitable for dry gas and as opposed to American Gas Association (AGA-8) for wet gas and liquids, e.g., Liquefied Natural Gas (LNG). The equation is based on 21 natural gas components: methane, nitrogen, carbon dioxide, ethane, propane, n-butane, isobutene, n-pentane, isopentane, n-hexane, n-heptane, n-octane, n-nonane, n-decane, hydrogen, oxygen, carbon monoxide, water, hydrogen sulfide, helium, and argon. Those components are listed in the AGA-8 algorithm.

2.2.6.7.1 Structure of the GERG-2008 EOS

The GERG EOS equations are based on a multi-fluid mixture model which is indicated in the dimensionless form of reduced Helmholtz free energy $\alpha = a/(RT)$ with the independent mixture variable of the density ρ, the temperature T and the composition x (mole fractions) of the mixture. Symbol a is the Helmholtz free energy. The equations related to GERG EOS model is given as

$$\alpha(\delta,\tau,x) = \alpha^{\circ}(\rho,T,x) + \sum_{i=1}^{N} x_i \ \alpha_i^r(\delta,\tau) + \Delta\alpha^r(\delta,\tau,x), \quad (2\text{-}10)$$

where

ρ = density

T= temperature

x = composition (mole fractions)

$\alpha^{\circ}(\rho,T,x)$ = properties of the Ideal gas mixture.

α_i^r= residual part of the reduced Helmholtz free energy for component i

$\sum_{i=1}^{N} x_i \ \alpha_i^r(\delta,\tau)$ is the contribution of pure substance.

$\Delta\alpha^r(\delta,\tau,x)$ = Departure function.

$\delta = \rho/\rho_r(x)$ = Reduced mixture density.

$\tau = T_r(x)/T$ = Inverse reduced mixture temperature.

N = Number of components in the mixture.

Those reducing functions of δ and τ for the density and temperature depend only on the composition of the mixture. Three more elements as shown below are needed to set up a multi-fluid mixture model:

(1) Pure substance equations of state for all components;

(2) Reducing functions for density and temperature; and

(3) Departure functions.

The reducing functions as well as the departure function were developed to describe the behaviour of the mixture, substance and mixture specific parameters. From the reducing functions, the reducing values ρ_r and T_r for the density and the temperature of the mixture can be calculated. They depend on the mixture composition and are reduced to the critical properties ρ_c and T_c, respectively, for the pure components. As noted in equation 2-10, the departure function depends on the reduced mixture density ρ_r , the inverse reduced mixture temperature τ , and the composition x of the mixture. For the mixture in a mul-fluid system, the departure function as proposed by Wagner; (2014) can be expressed as

$$\Delta\alpha^r(\delta,\tau,x) = \sum_{j=i+1}^{N} \quad \sum_{i=1}^{N-1} \Delta\alpha_{ij}^r \quad (\delta,\tau,x). \qquad (2\text{-}11)$$

Equation (2-11) is a double summation over all binary specific and generalized departure functions developed for the binary subsystems.

In order to obtain a reference EOS that yields accurate results for various types of natural gases and other multi-component mixtures over wide ranges of composition, the reducing and departure functions were developed using only data for binary mixtures. The 21 pure components are covered by GERG-2008 result in 210 possible binary mixture combinations. Departure functions

$\Delta\alpha_{ij}^{r}\ \ (\delta, \tau, x)$ were developed only for such binary mixtures for which accurate experimental data existed. For binary mixtures with limited or poor data, no departure functions has been developed, and only the parameters of the reducing functions $\rho_r(x)$ und $T_r(x)$ were fitted. In the case of very poor data, simplified reducing functions without any fitting were used. The multi-fluid model used enables a simple inclusion of additional components in future developments. This means that, for example, fitted parameters of the existing equation of state do not have to be refitted when incorporating new components. This also holds for the departure function with its optimized structure which remains unchanged when expanding the model.

In terms of the performance of GERG-2008 EOS, in the gas region, the uncertainties in density and speed of sound are 0.1%, in enthalpy differences (0.2-0.5)% and in heat capacities (1-2)%. In the liquid region, the uncertainty in density is (0.1-0.5)%, in enthalpy differences (0.5-1)% and in heat capacities (1-2)%. In the two-phase region, vapour pressures are calculated with a total uncertainty of (1-3)%, which corresponds to the uncertainties of the experimental VLE data. For mixtures with limited or poor data, the uncertainty values stated above can be somewhat higher. These accuracy statements are based on the fact that GERG-2008 represents the corresponding experimental data to within their experimental uncertainties (with very few exceptions).

Over the entire composition range, GERG-2008 covers the gas phase, liquid phase, supercritical region, and VLE states for mixtures of these components. The normal range of validity of GERG-2008 includes temperatures from -370 ^oF to -10 ^oF and pressures up to 5,076 psia. The extended validity range reaches from - 400 ^oF to 240 ^oF and up to 10,152 psia. In principle, the given numerical information enables the use of GERG-2008 for all of the various technical applications. Moreover, the equation can be reasonably extrapolated beyond the extended range, and each component can basically cover the entire composition range, i.e., (From 0 to100 %).

2.2.7 Methods to Calculate the Z Factor

Different from the ideal gas law (PV=nRT), the introduction of compressibility factor, Z, making the formula become PV=ZRT. This equation covers wide range of composition, temperature and pressure. The calculations of Z-factors fall into three main methods.

1. By measuring the density in the laboratory at certain composition, temperature and pressure. The volume of 1 lb-mole of this gas is given by V =ZRT/P. Knowing the density, Z can be calculated by Z=PV/RT=P/ρ RT. For any new research and study, this is method to obtain the Z factor.
2. By using one of the EsOS as described in previous section 2.2.6. This is the most accurate and convenient method nowadays with computer and simulator.
3. By curve fitting using the Standing- Katz isotherms as shown on Figure 2.1 (Standing- Katz, 1942).

The Standing-Katz Z-factor chart is based on the method 1 performed on gas mixture. After many decades, the Z-factor chart, although has some limitations, is still widely used as a practical source for obtaining natural gas compressibility factors. A generalized Z chart for 10 most common gases is also provided in Figure 2.2 (Ortega, 2014). As an example showing the procedure of finding the Z factor using the Z factor chart, let us consider a natural gas with the following composition:

Table 2.2 Gas compositions for Z factor calculation

Component	Mole Fraction, X_i
N_2	0.0224
CO_2	0.0180
H_2S	0.0352
CH_4	0.8383
C_2H_6	0.0510
C_3H_8	0.028
$i\text{-}C_4H_{10}$	0.003
$n\text{-}C_4H_{10}$	0.003
$i\text{-}C_5H_{12}$	0.0002
$n\text{-}C_5H_{12}$	0.0002
C_6H_{14}	0.0001
C_7+	0.0006

where

CH_4 = methane=C_1 , C_2H_6= ethane=C_2, C_3H_8= propane=C_3

With the reservoir temperature at 350 ^oF and reservoir pressure of 8,500 psia, the following properties such as reduced temperature and reduced pressure can be calculated. Finally, we can find the Z-factor from Standing-Katz chart.

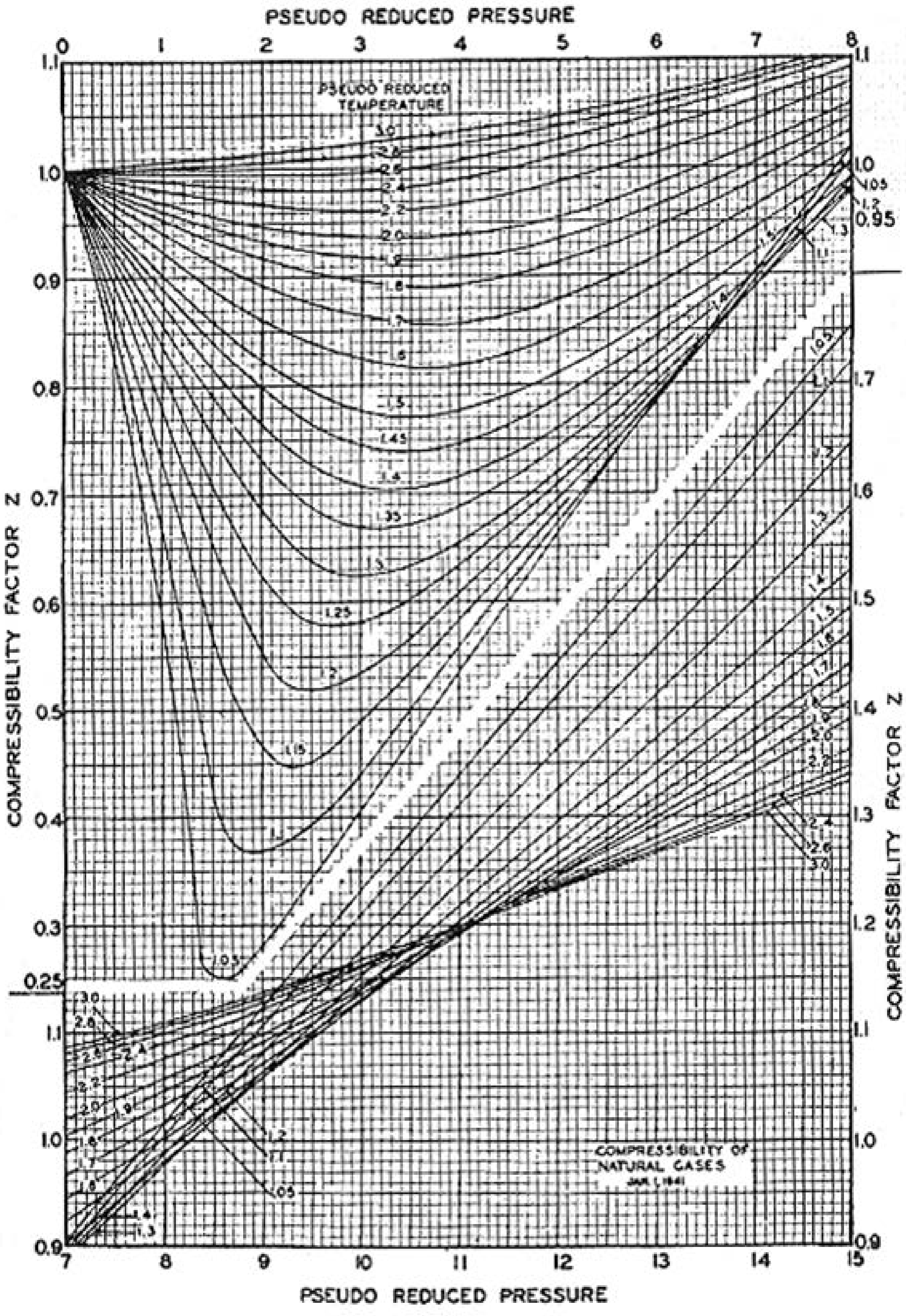


Figure 2.1 Standing-Katz Z Factor Chart (Standing-katz,1942)

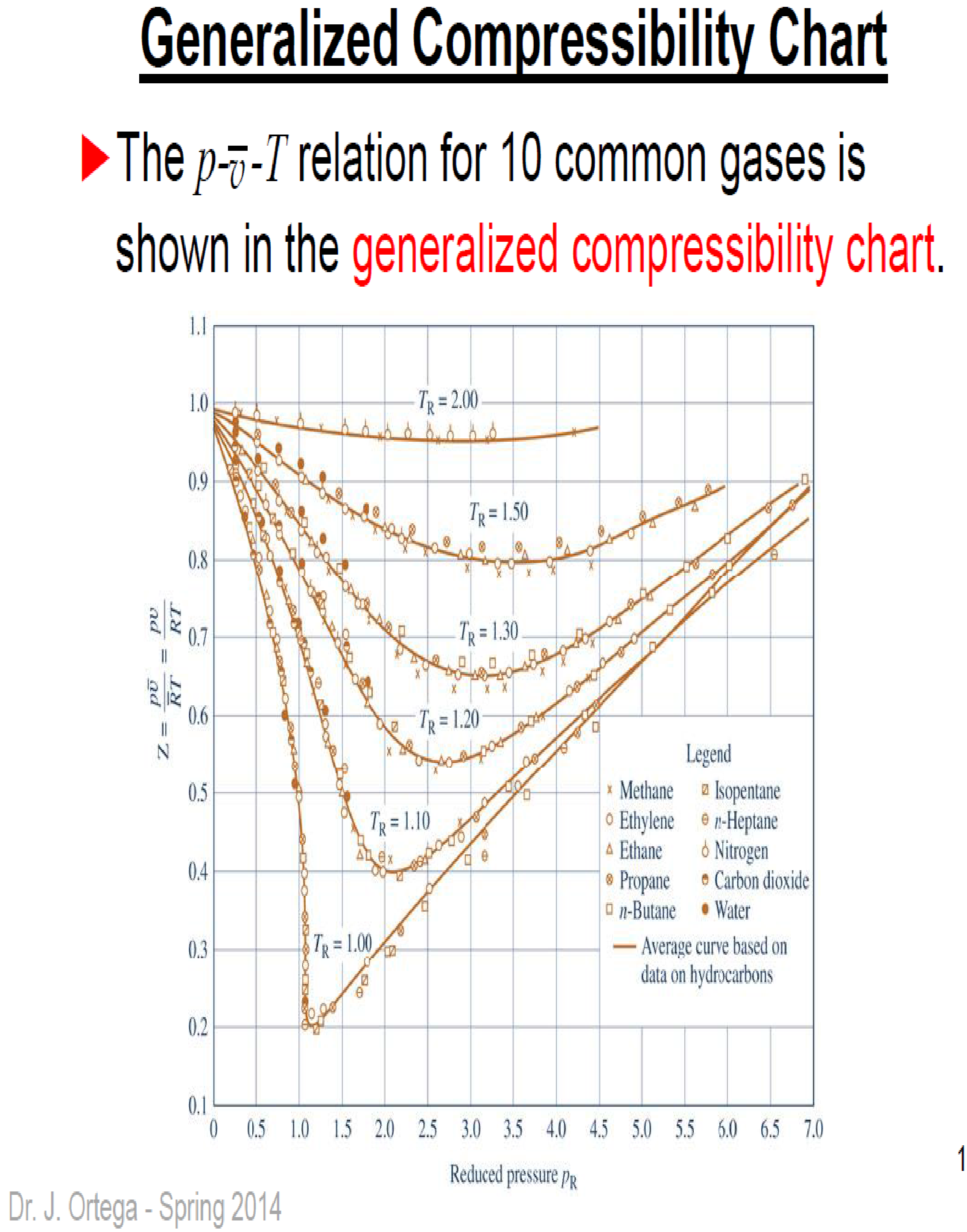


Figure 2.2 Generalized Z Chart for 10 Common Gases (Ortega, 2014).

Table 2.3 Z factor and MW, P_c and T_c Calculation

Component	Mol.% (X_i)	MW	Mol.%* MW X_i *MW	P_c	X_i *P_c	T_c	X_i *T_c ^oR
C1	0.8383	16.04	13.446	673	564.18	344	288.38
C2	0.0510	30.07	1.534	709	36.16	550	28.05
C3	0.0280	44.09	1.235	618	17.30	666	18.65
i-C4	0.0030	58.12	0.174	530	1.59	733	2.20
n-C4	0.0030	58.12	0.174	551	1.65	766	2.30
i-C5	0.0002	72.15	0.014	482	0.10	830	0.17
n-C5	0.0002	72.15	0.014	485	0.10	847	0.17
n-C6	0.0001	86.17	0.009	434	0.04	915	0.09
n-C7	0.0006	100.2	0.060	397	0.24	973	0.58
n-C8	0.0000	114.2	0.000	361	0.00	1024	0.0
N_2	0.0224	28.02	0.628	492	11.02	227	5.08
CO_2	0.0180	44.01	0.792	1072	19.30	548	9.86
H_2S	0.0352	34.08	1.200	1306	45.97	673	23.69
Total	1.000		19.28		698		379

1. The mixture molecular weight is 19.28 as calculated in the Table 2.3.

2. The specific gravity is 19.28/ 28.97 = 0.666

3. The reduced pressure and temperature without adjustment are

P_r= P/P_c=8500/698= 12.2

T_r =T/T_c= (350+ 460)/379 = 2.14

From Figure 2-1 the Standing and Katz Z-factor is obtained to be 1.265. The results of calculated Z factor for other pressures are shown in Table 2.4

Table 2.4 Z factor at different pressure

P, psia	14.7	100	300	500	1000	4000	6000	8500
Z	l.000	1.000	0.989	0.983	0.972	1.016	1.114	1.265

The results in Table 2.4 show that the compressibility factors decreases with an increase of pressure until it reach a minimum at about 1,000 psia. The compressibility factor then increase with further increase of pressure. As indicated in the Table 2.4, the Z factors reduce from 1.000 to 0.972 at the pressure of 1,000 psia and then increase to 1.265 at 8,500 psia.

Chapter 3. Methodology

3.1 EsOS Selected for Evaluation

Among the EsOS described in Chapter 2, engineering groups such as the Gas Technology, Rotating Equipment, Flow Assurance, Reservoir Engineering SMEs and Aspen Technology Technical Support Professionals suggest that the highly popular and potential EsOS applicable in ultrahigh pressure compression simulation are GERG, BWRS, LKP, and PR models. (Colby, G. M.,1987) These four models are selected for simulation and evaluation. Table 3.1 gives a description of each of the EsOS analyzed. Stream component composition, temperature and pressure will be specified to match the experimental condition. By using different EOS in the simulator, the Z factor can be calculated. In addition, the computed compressibility factors (Z) from the four EsOS are compared with the experimental data obtained from a wide variety of sources (Mantilla, et al., 2010) and (Reamer, et al., 1951). Those data sources present P-ρ-T data for gases such as CO_2, N_2 and mixture measured with a high-pressure single-sinker Magnetic Suspension Densimeter (MSD).(Hacum et al.,1988) The data covered different isotherms at different temperatures. The MSD technique yields data with less than 0.03 % relative uncertainty over the pressure range from 1,450 to 29,006 psia.

Table 3.1 Descriptions of 4 EsOS for This Research

Equation of State	Description
GERG-2008 (GERG) (2008)	This model was originally developed in Europe for their gas transmission industry and has been expanded to higher pressures and other gases. The fact that the National Institute of Standards and Technology (NIST) have strongly endorsed its use. It is designed to provide high accuracy of typical natural gas components. The GERG-2008 is a standard (ISO-20765) international reference equation suitable for natural gas applications. It is considered to be very accurate but has not been widely implemented in commercial process simulators. Only one process simulator, Aspen Technology provides this EOS. (Aspen HYSYS 2014)
Benedict-Webb-Rubin-Starling (BWRS) (1940)	This model is commonly used for compression applications and studies. It is specifically used for gas phase components that handle the complex thermodynamics during compression and is useful for upstream and downstream industries. This EOS has been historically used by General Electric (GE) and Dresser Rand (D-R) for compressor calculations due to its greater accuracy in purely gas phase applications.
Lee-Kesler-Plocker (LKP) (1978)	This model is the most accurate general method for polar substances and mixtures. This EOS has been used by General Electric (GE) and Dresser Rand (D-R) compressor vendor for compressor calculations.
Peng Robinson (PR) (1976)	This model is ideal for Vapor Liquid Equilibrium (VLE) calculations and liquid densities for hydrocarbon systems. It is the most widely used EOS for the oil, gas and petrochemical industries as it describes the single, two or multiphase behavior accurately and reliably.

3.2 Selection of Process Simulator and Hydraulic Discharge Pressure

Process simulation through applicable software or models increases in-depth knowledge for process industries and helps engineers to not only to plan the system successfully, but also create sustainable designs. However, not all process simulators are developed with similar applications. Many simulators also provide the dynamic simulation model as well as operator training model. In general, process simulators can provide insight into processes that:

- Optimizes process design, engineering, operational analysis and commissioning time which allows a process to become profitable sooner.
- Increases profit potential with advanced planning & scheduling applications that consider the different feedstock processing requirements and processing capabilities.
- Increases plant availability, monitors performance, and assists in troubleshooting operational issues, resulting in minimal downtime.
- Minimizes unplanned outages, it allows the workforce to adeptly deal with plant disturbances.

The most common usage includes the rigorous heat and material balance (H&MB) calculations. Typical equipment provided by simulator includes process reactor, separator, piping, reactors, distillation columns, heat exchanger, tank and pumps. Software typically includes chemical and physical properties components, mixtures, reactions, and mathematical models that allow a process model to be calculated by computers. In this study, the HYSYS simulator provided by Aspen was used to simulate the designed process system and the corresponding Z factor under the selected EsOS for comparison. Among the software available to the industries for the simulation of the material and energy balances of chemical processing plants, only the Aspen HYSYS 2012 simulator has the GERG-2008 EOS as a source of thermodynamic EOS. In other word, other simulators do not provide GERG EOS and will not be able to obtain the GERG EOS results. Furthermore, HYSYS is a worldwide available program. The cost is slightly higher than the other simulators but it is acceptable and reasonable.

Because of the density and molecular weight differences between CO_2, natural gas, and N_2, the estimated compressor discharge pressure required to get into the reservoir is 9,000, 14,000 and 12,000 psia respectively. The reservoir pressure is about 20,000 psia. At those ultrahigh pressure conditions, the compressibility factor (Z), is a useful thermodynamic property for modifying the ideal gas law to account for the real gas behavior. The calculated compressibility factor (Z) from the different EsOS at different pressure, temperature and composition are compared with experimental data to evaluate the accuracy and capability of the EsOS.

3.3 Steps in Developing Aspen HYSYS Model.

Steps in developing the Aspen's HYSYS model for this study are listed as below.

1. Select the units to work with, e.g., specify the popular English unit used in USA such as pounds for weight, psia for pressure and ^oF for temperature.

2. Select the thermodynamic EsOS to be used for predicting physical properties. The EsOS include GERG, BWRS, LKP, and PR models.

3. Specify the chemical species and component mole fraction that are present in the process. This includes all hydrocarbon and impurities such as N_2, CO_2 and H_2S.

4. Specify the process conditions such as pressure, temperature and flow rate.

5. Build the model by adding streams and equipment one at a time. This includes different streams and equipment such as separator, compressor, pump, heat exchanger and distillation tower.

6. Add recycle loops, to take care the gas breakthrough from reservoir.

7. Use the HYSYS utilities to get additional information such as the mechanical design of distillation column trays or hydrate prediction.

8. Run the model. Print necessary reports which are the results of the simulation. This includes the streams properties, equipment data sheet and Heat and Material Balance (H&MB).

3.4 Offshore Oil/Gas Production and EOR Gas Injection

The individual module process flow diagram (PFD) and overall simulation PFD used for simulation are presented as in Figure 3.1 to Figure 3.7. Figures 3.1, 3.2 and 3.3 provide the configurations of different compressor schemes including the flash gas compressor (FGC), the booster gas compressor (BGC), and injection gas compressor (IGC) configuration. Typically, in one stage of compression, with the compressor, it also includes the suction drum to remove any liquids to protect the compressor and the compressor discharge cooler to cool down the gas to prevent the damage of the compressor seal gas system. Multiple stages of compression which include FGC,BGC and IGC, are required to compresses the gas from very low pressure (about 30 psia, 15 psig) to ultrahigh pressure (12,000 psia or 11,985 psig).

There are 2, 2 and 3 stages respectively for FGC, BGC and IGC systems depending on the compressor compression ratio (discharge pressure/suction pressure) required. Typical centrifugal compressor compression ratio is limited about 3 (between 2 to 4) depending on the heat capacity ratio. One of the N_2 simulation cases shows that FGC used two stages to compress from 27.6 Pisa to about 118.9 psia. BGC also used two stages to compress from 109.6 psia to about 1,115.1 psia. After the gas dehydration, the IGC needs to use three stages to compress from 1,096.2 psia to about 12,000 psia (Figure 3.3). Because the critical pressures of the CO_2, N_2 and methane (close to natural gas) are 1,070.0 psia, 492.8 psia and 667.0 psia respectively, the IGC compression basically occurs in the dense phase. Some of the inputs and outputs such as stream properties, equipment data sheet and H&MB from the HYSYS simulations are provided in the appendix C.

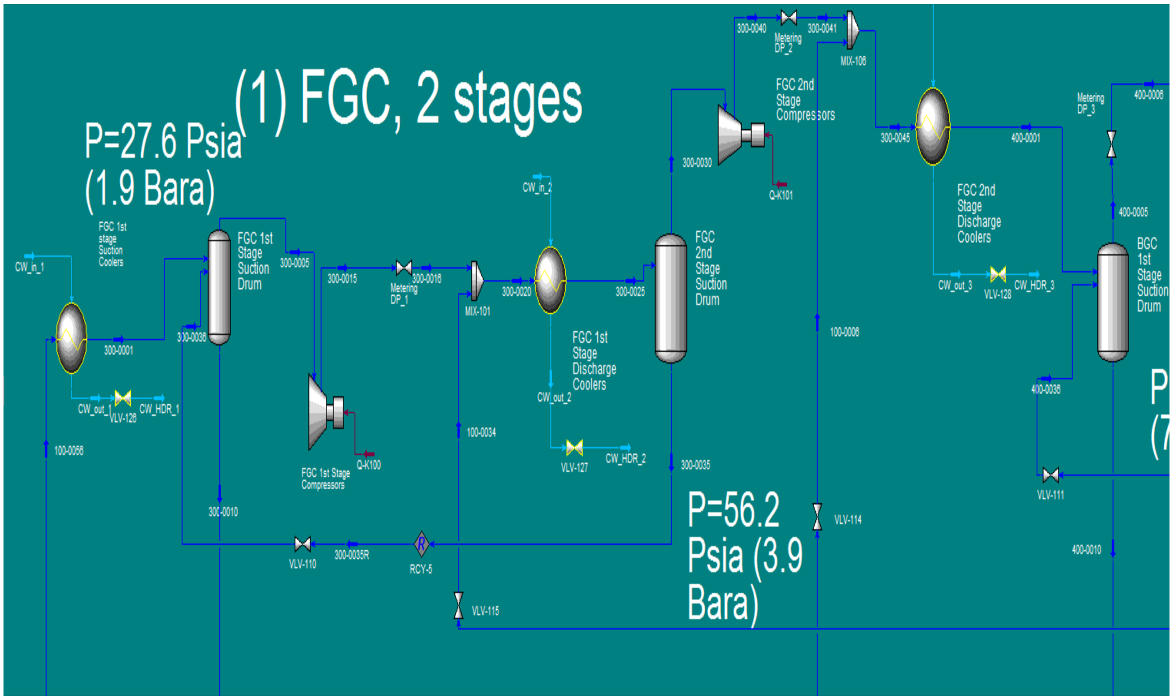


Figure 3.1 Offshore 2 Stages Flash Gas Compressor (FGC)

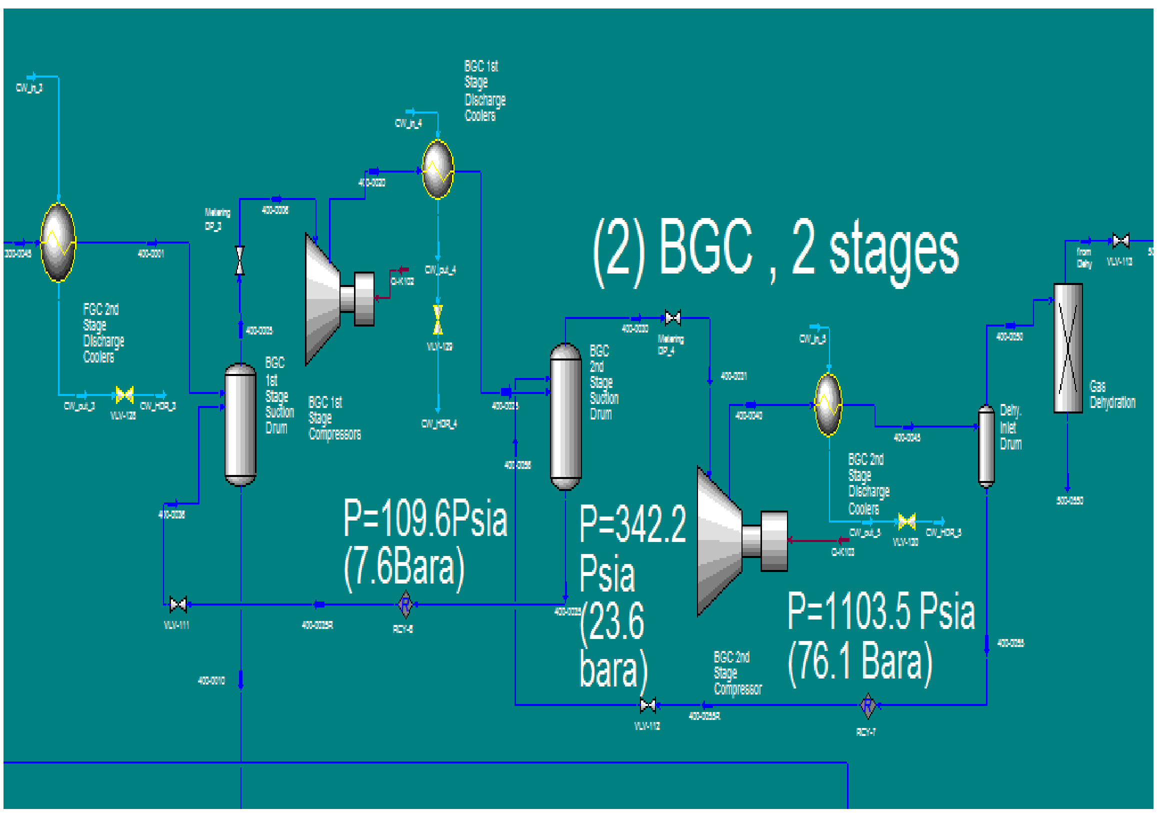


Figure 3.2 Offshore 2 Stages Booster Gas Compressor (BGC)

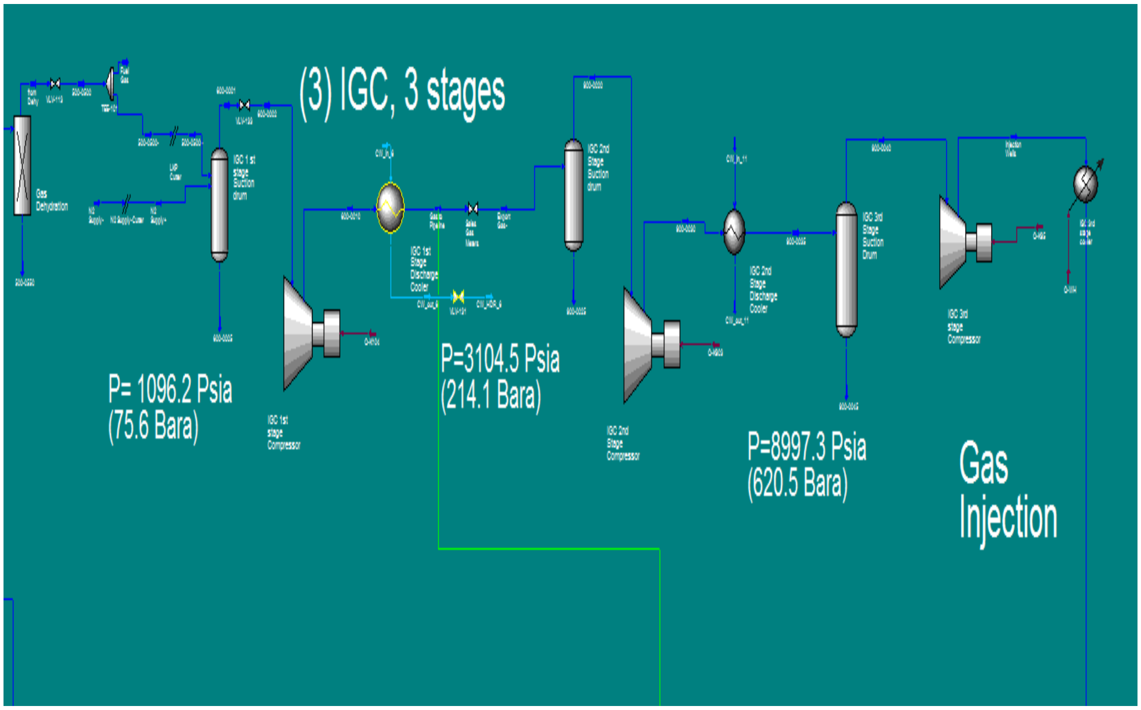


Figure 3.3 Offshore 3 Stages Injection Gas Compressor (IGC)

The simulation module for oil production and oil pump out is shown in Figure 3.4. Basically, to carry out the simulation, the system includes a series of three phase separator (Hydrocarbon gas, liquids (oil) and water), heat exchangers and pumps. Oil required pump to increase the pressure for shipping purpose. Water production and disposal including water treatment can be simulated with separator, filter and hydrocarbon removal unit as illustrated in Figure 3.5.

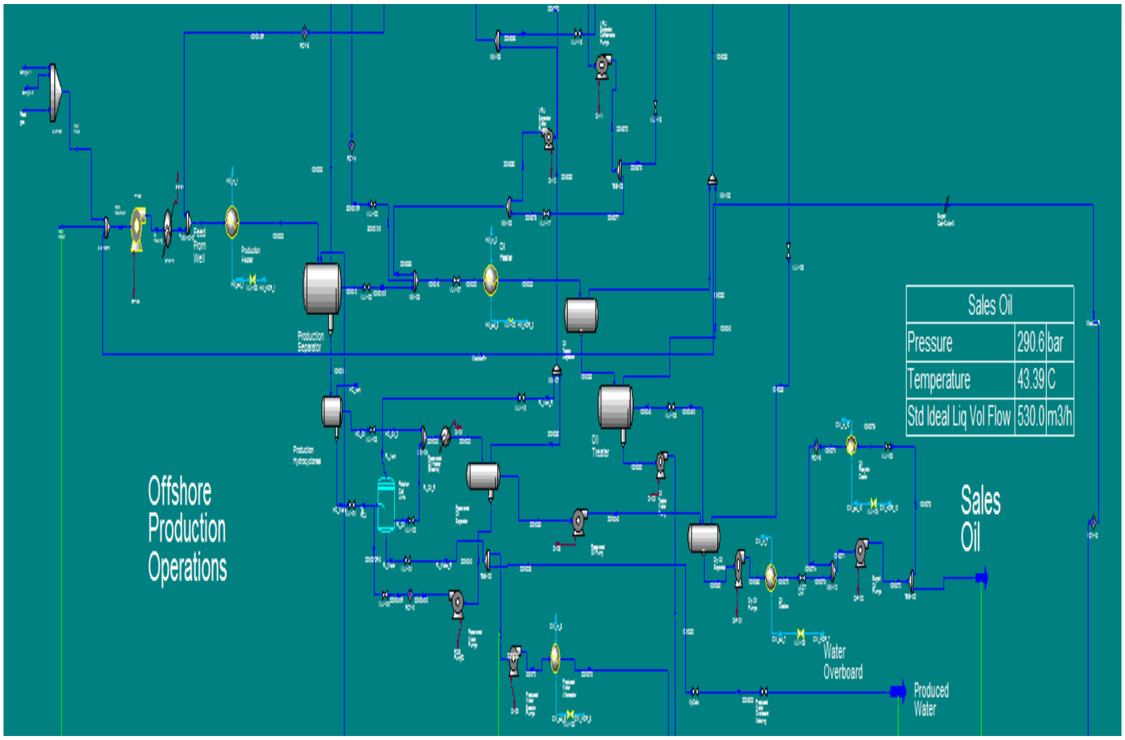


Figure 3.4 Offshore Oil Production Facilities

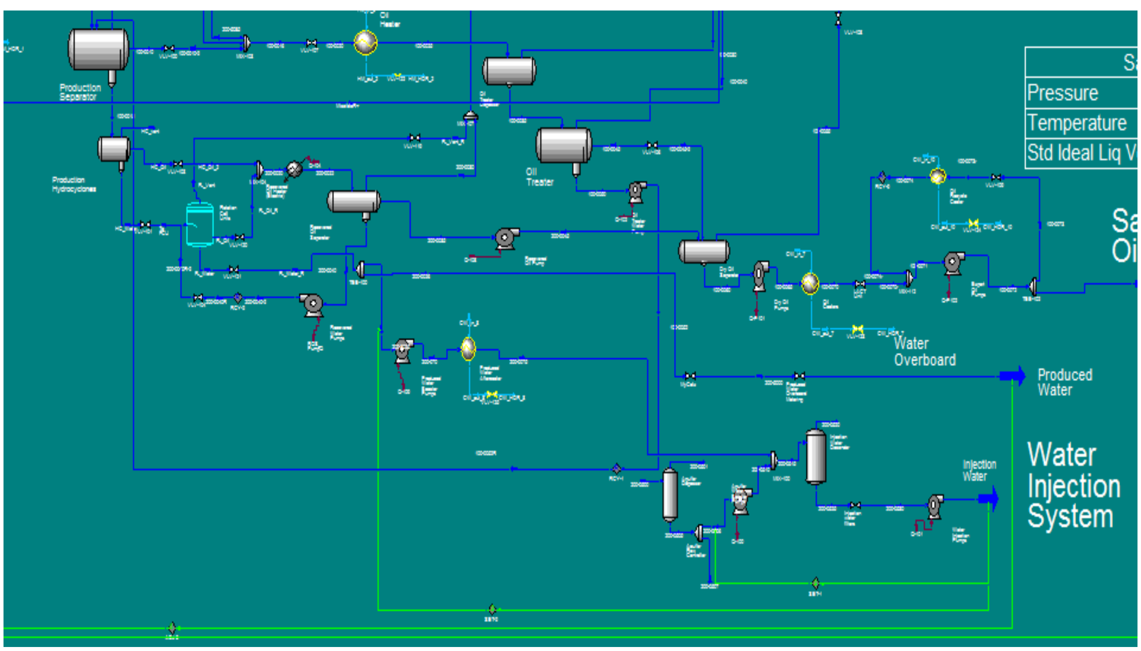


Figure 3.5 Offshore Water Production and Treatment

There are vent gases that come out from very low pressure separator, storage tank or water treating facilities. These gases are collected by the vent gas system and then compressed by the Vapor Recovery System (VRS) as shown in Figure 3.6. This system includes the suction drum and compressor but no discharge air cooler because of the low compression ratio.

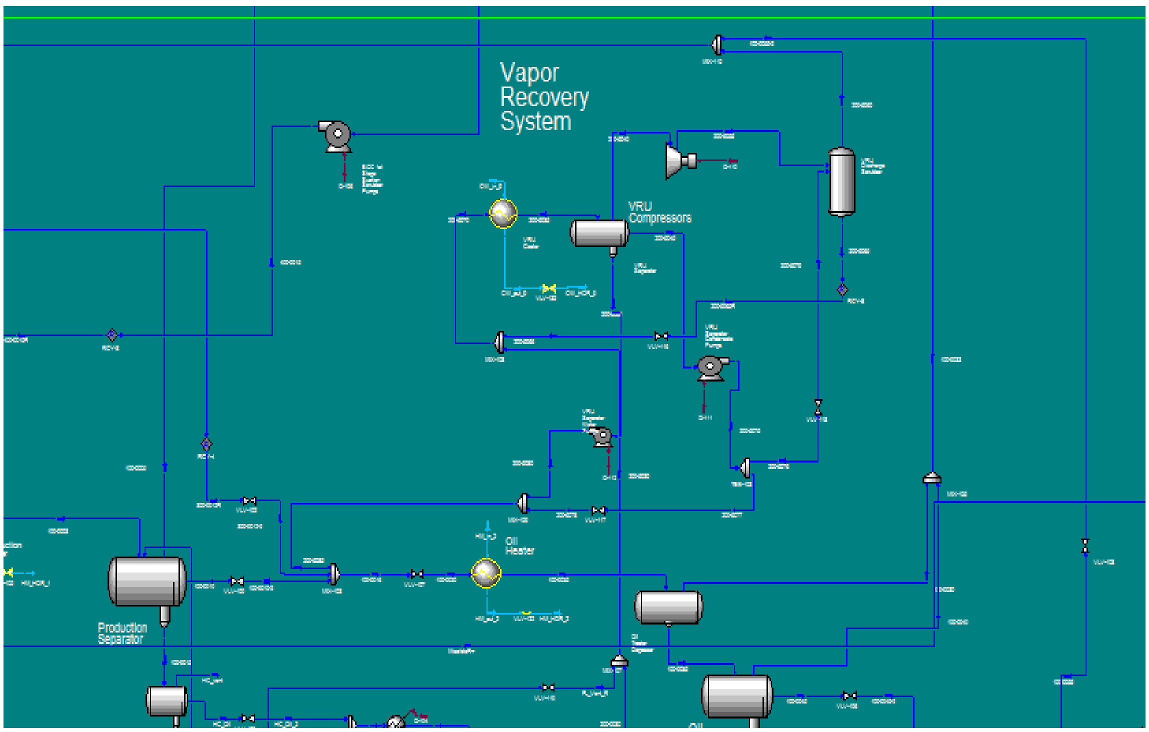


Figure 3.6 Offshore Vapor Recovery System (VRS)

The overall simulation PFD, which includes all those modules in Figure 3.1 to 3.6 is in Figure 3.7. The simulation PFD given in this figure represents a complete system for offshore oil/ gas production and EOR gas injection.

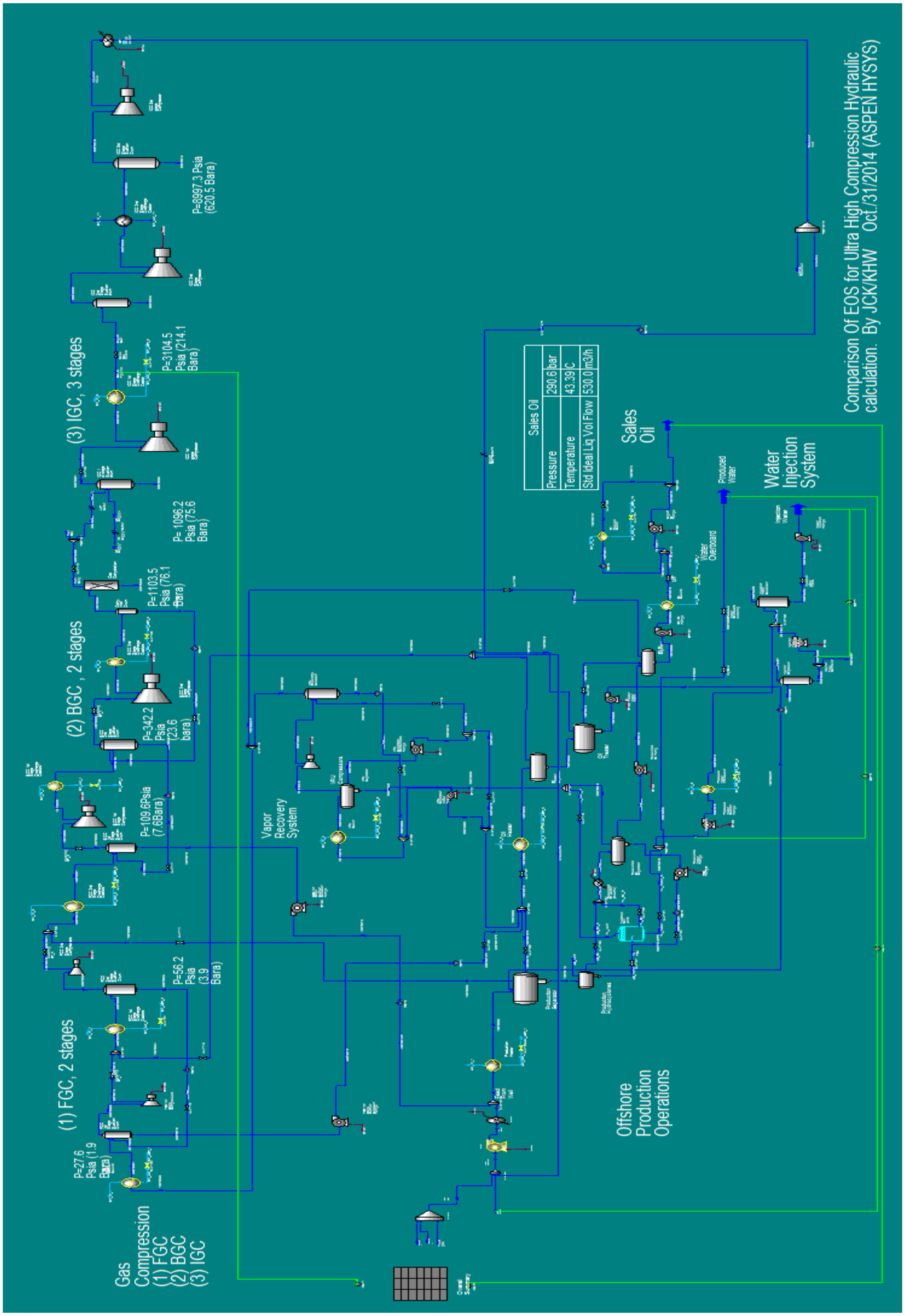


Figure 3.7 Offshore Overall Simulation Process Flow Diagram

Chapter 4. Results

For EOR applications, the composition of the produced gas can vary significantly from pure hydrocarbon gas before the breakthrough of injection gas to very high concentrations (80%+) of the injection gas (CO_2, N_2, or natural gas) in the later year of the EOR operation. To examine the effect of injection gas on the process of EOR operation in terms of the use of identified EsOS, the following basis in the simulations were considered.

1. Evaluation considerations included pure CO_2, pure N_2, and hydrocarbon/ injection gas (CO_2 or N_2, natural gas) mixtures over a wide range of temperatures 77 ^oF to 350 ^oF and pressures 200 psia to12, 000 psia.

2. Mixtures of C_3H_8/CO_2 (C_3/CO_2), C_2H_6/CO_2 (C_2/CO_2), and C_2H_6/N_2 (C_2/N_2) were selected as proxy for the gas stream. Molecular Weight (MW) similarity is the basis (Staby et al,1991).

3. The dimensionless compressibility factors (Z) using each of the identified four EsOS was computed to compare to the experimental data (Brugge,1997).

4.1 Z Factor for Different EsOS Comparison

The computed compressibility factors (Z) were compared to experimental data obtained from a wide variety of sources (Mantilla et al., 2010) and (Reamer et al., 1951) to evaluate the accuracy of the identified EsOS models. Figures 4.1 through 4.17 show the comparisons of the experimental data to EOS predictions for pure CO_2, pure N_2, propane (C_3)/CO_2 mixtures, ethane (C_2)/CO_2 mixtures, and ethane (C_2)/N_2 mixtures over a wide range of temperatures and pressures.

Considering the pure CO_2 as the injected gas, the variations of compressibility factor versus gas pressure from the EsOS of GERG, BWRS, LKP and PR for a temperature of 98 ^oF are presented in Figure 4.1. The results for pure CO_2 but under a higher temperature consideration, i.e. 350 ^oF are given in Figure 4.2. The pressure range for results in Figure 4.1 covers from 300 psia to 11,000 psia. For case shown in Figure 4.2, the pressure ranges from 700 psia to 11,000 psia. The measured data are also included in Figures 4.1 and 4.2 for comparisons. (Hwang et al.,1997). From Figures 4.1 and 4.2, we notice that GERG associated EOS can produce the most accurate results. The BWRS and LKP are slightly less accurate in predictions, while the PR is the least accurate model.

For the cases of pure $N_{2,}$ the computed compressibility factors are plotted versus gas pressure in Figures 4.3, 4.4 and 4.5 respectively for the conditions of T=77 ^oF,1,450 psia≤ P≤ 12,000 psia; T=170 ^oF,400 psia≤ P≤ 11,000 psia; T=260 ^oF,150 psia≤ P≤ 11,600 psia. The gathered data are also included in those figures for comparisons. The results indicate again that GERG produces the most accurate solutions. The LKP also gives good results when compared to the data while the BWRS and PR results are deviated from the data. Furthermore, as indicated in Figures 4.3, 4.4 and 4.5 the compressibility factors for pure N_2 get larger as the pressure get higher. However as in Figures 4.1, and 4.2, the compressibility factors firstly show the decreasing trend then increase with further increase of pressure. For example, in Figure 4.2 the compressibility factors decreases as pressure increase from 700 psia to about 3,800 psia. Then the compressibility factor reversely shows the increasing trend as pressure increase from 3,800 psia to 11,000 psia.

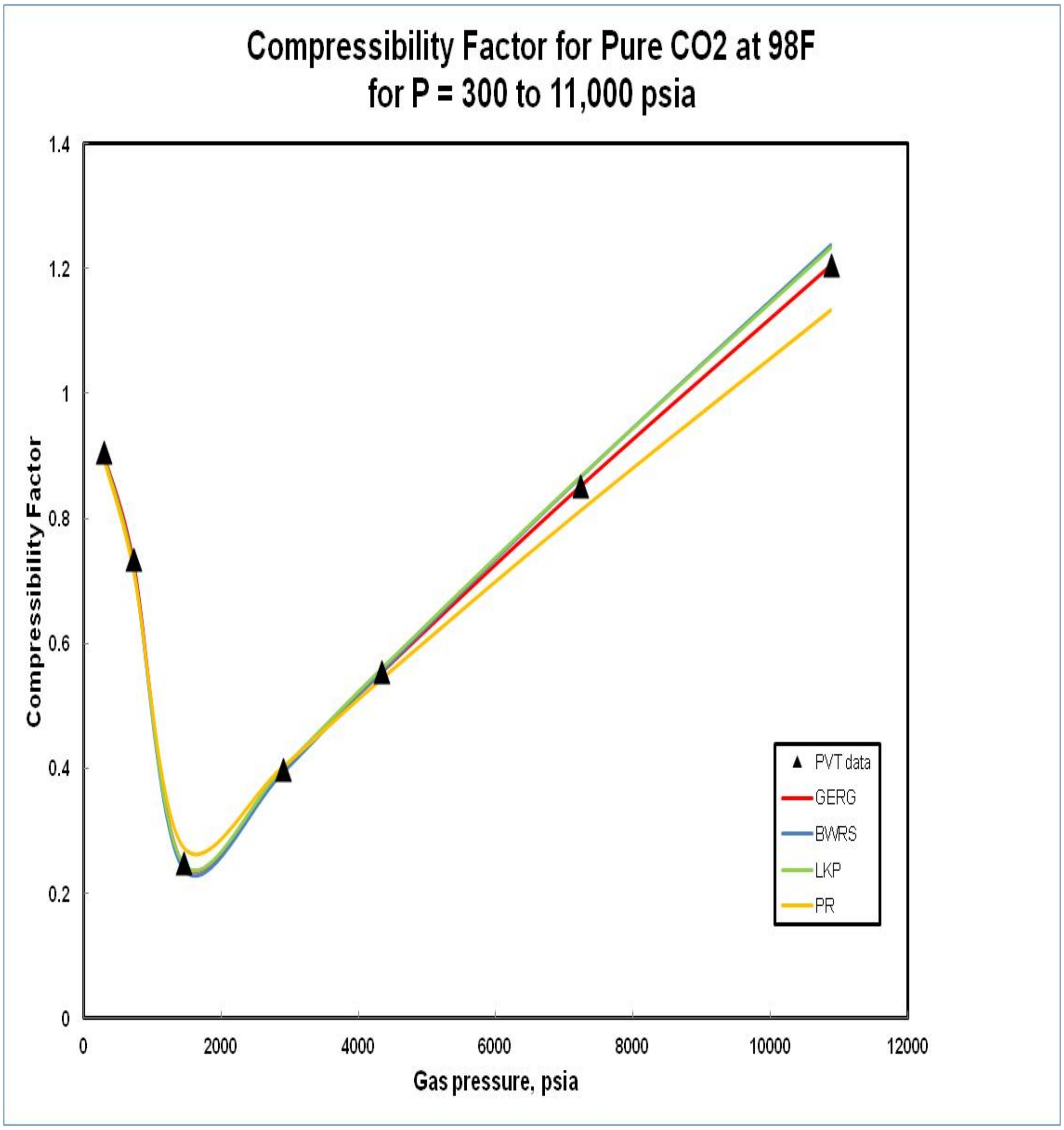


Figure 4.1 Compressibility Factor for Pure CO_2 at 98 ^oF

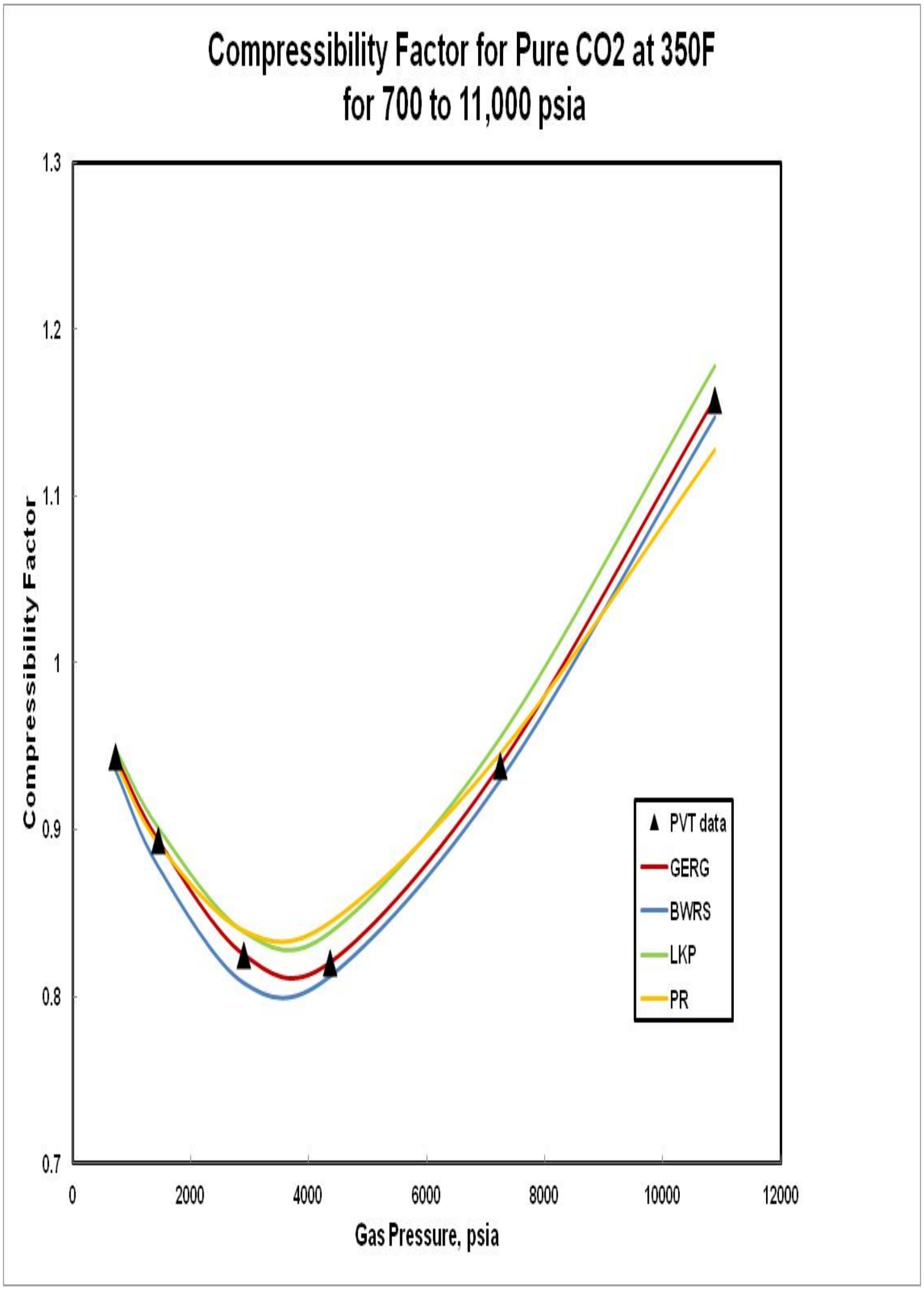


Figure 4.2 Compressibility Factor for Pure CO_2 at 350 ^oF

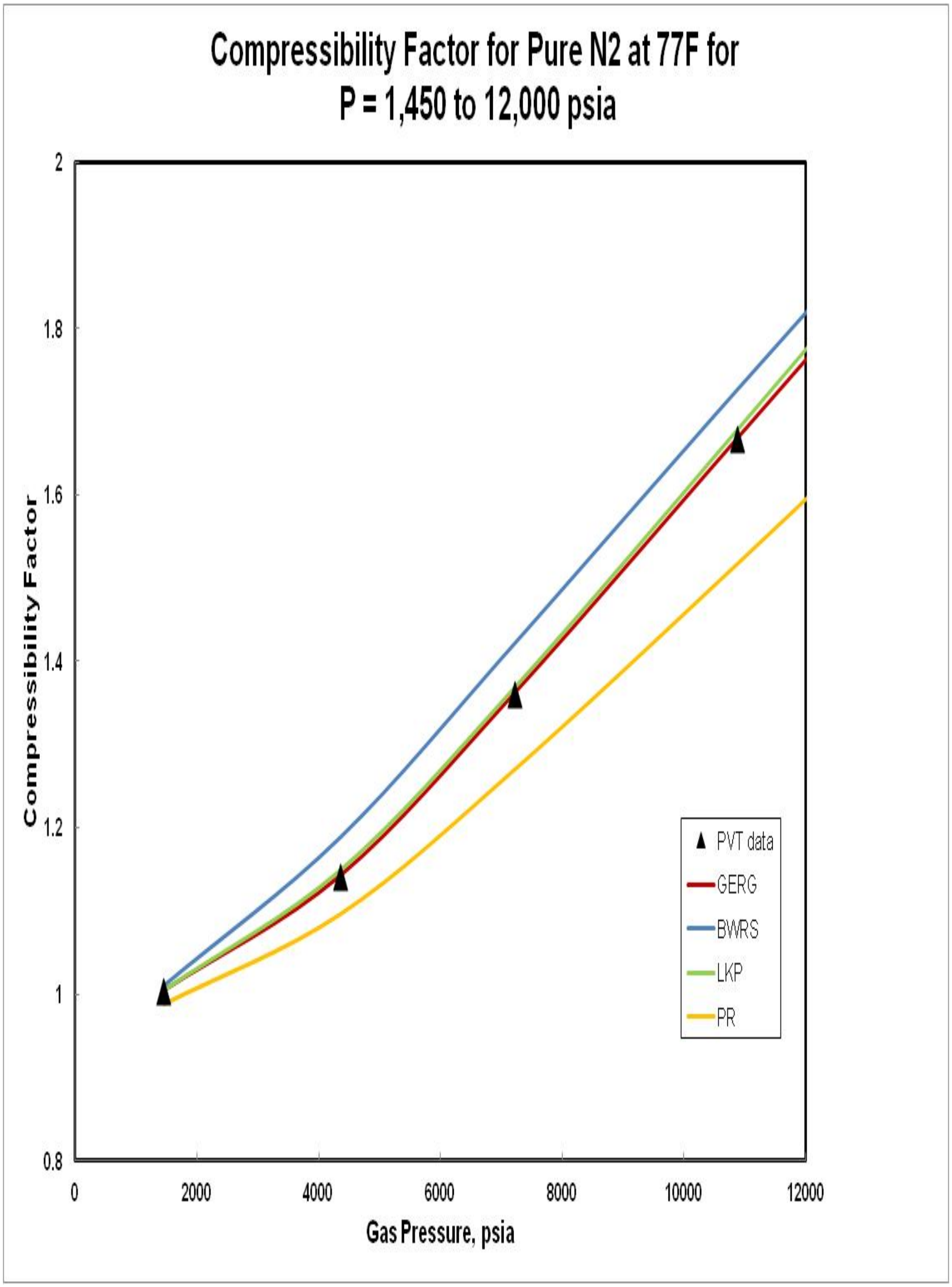


Figure 4.3 Compressibility Factor for Pure N_2 at 77 ^oF

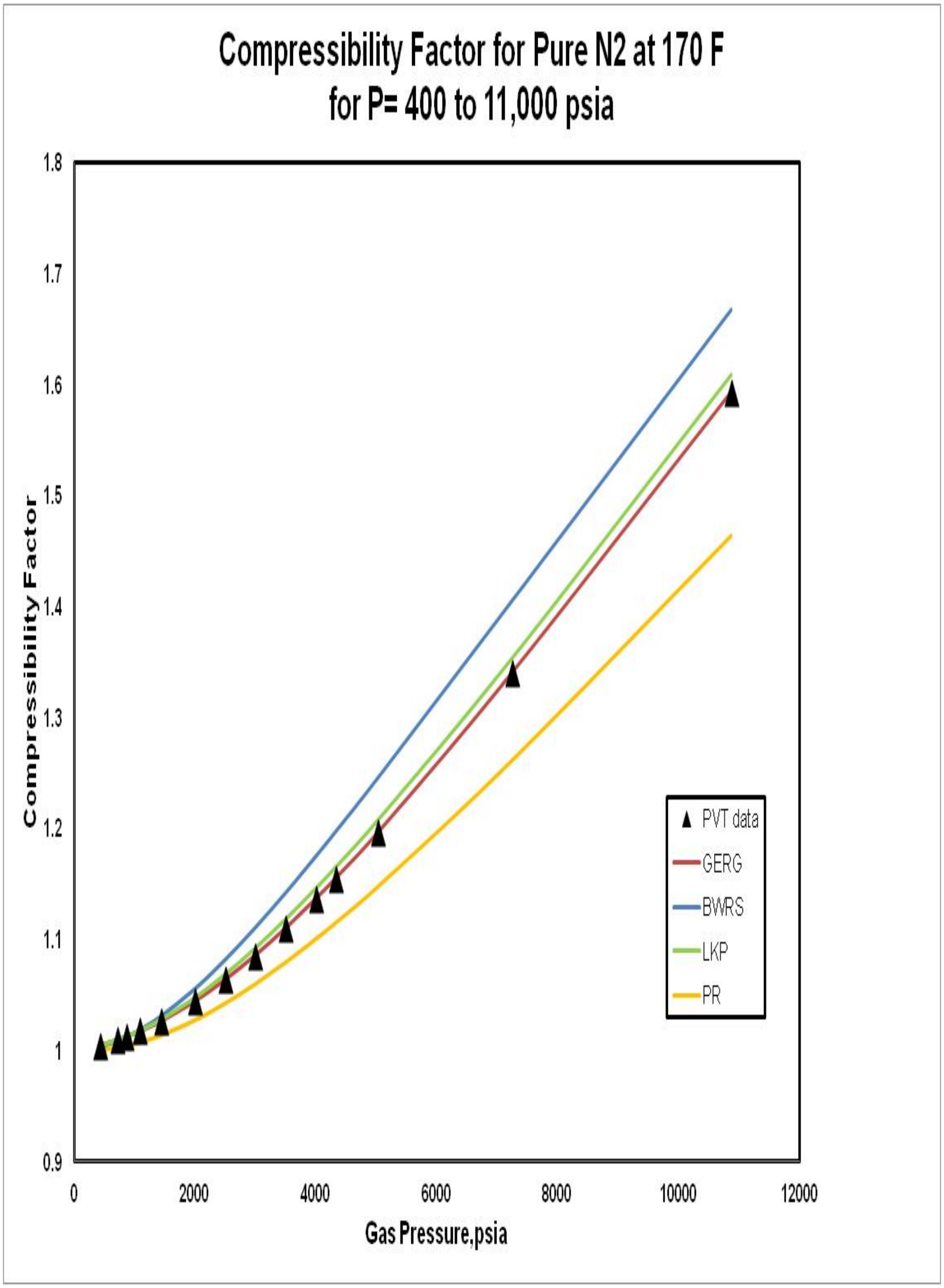


Figure 4.4 Compressibility Factor for Pure N_2 at 170 ^oF

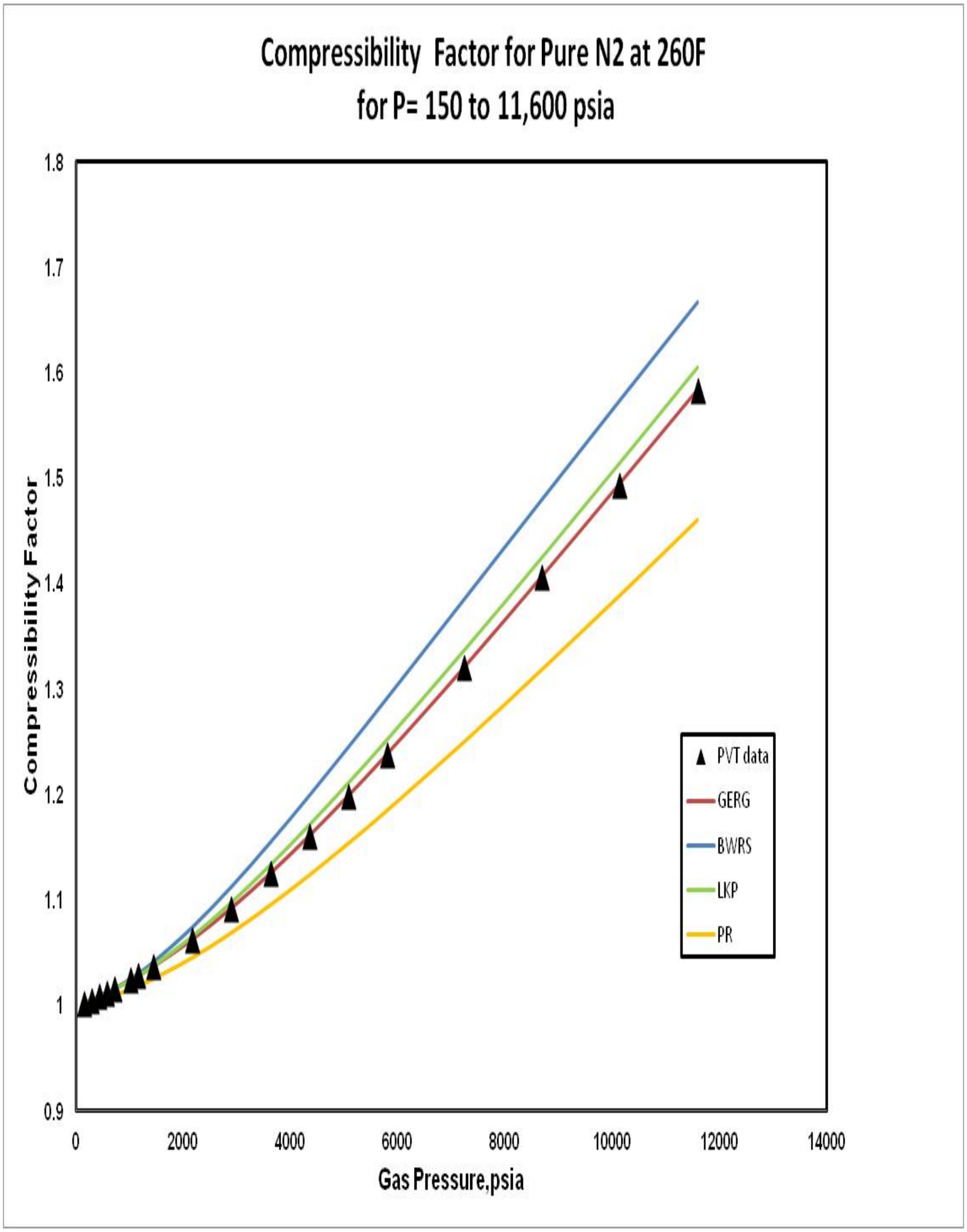


Figure 4.5 Compressibility Factor for Pure N_2 at 260 ^oF

Figures 4.6 and 4.8 present respectively the results of compressibility factors for the case of 20% C_3 /80% CO_2 and 80% C_3 /20% CO_2. The results in Figure 4.6 show that the compressibility factors decreases with an increase of C_3 /CO_2 pressure until it reach a minimum at about 1,200 psia. The compressibility factors then increase with further increase of pressure. Figures 4.8 reveals similar variation trend of compressibility factor as in Figure 4.6, however, the Z factor approaches a minimum when gas pressure reaches about 500 psia. For these relatively low temperature cases at 100 ^{o}F, the GERG results fit best to the data. In general, the BWRS and LKP also give reasonable predictions. The PR model produces the results with largest errors.

When the temperature increases to 340 ^{o}F, the variations of compressibility factor for 20% C_3/80% CO_2 and 80% C_3/20% CO_2 are presented in Figure 4.7 and 4.9 respectively . For the case of 20% C_3/80% CO_2 (Figure 4.7), GERG and LKP produce similar results, which fit best to the data. BWRS results are under predicted. For the case of 80% C_3/20% CO_2 (Figure 4.9), the results obtained from GERG, BWRS and LKP are similar and fit well with the data. For both cases, PR results are least accurate.

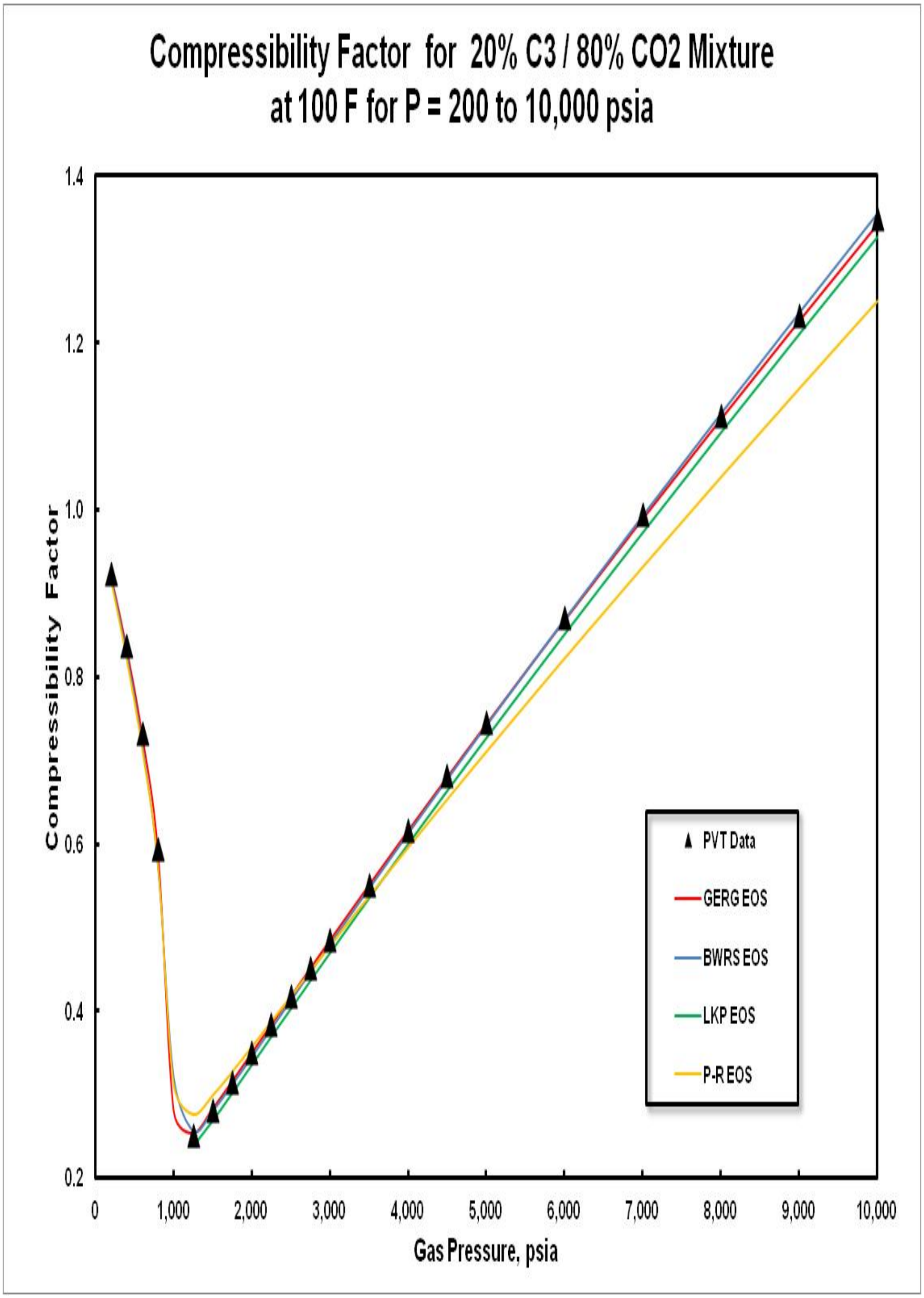


Figure 4.6 Compressibility Factor for 20% C3/80% CO_2 at 100 ^{o}F

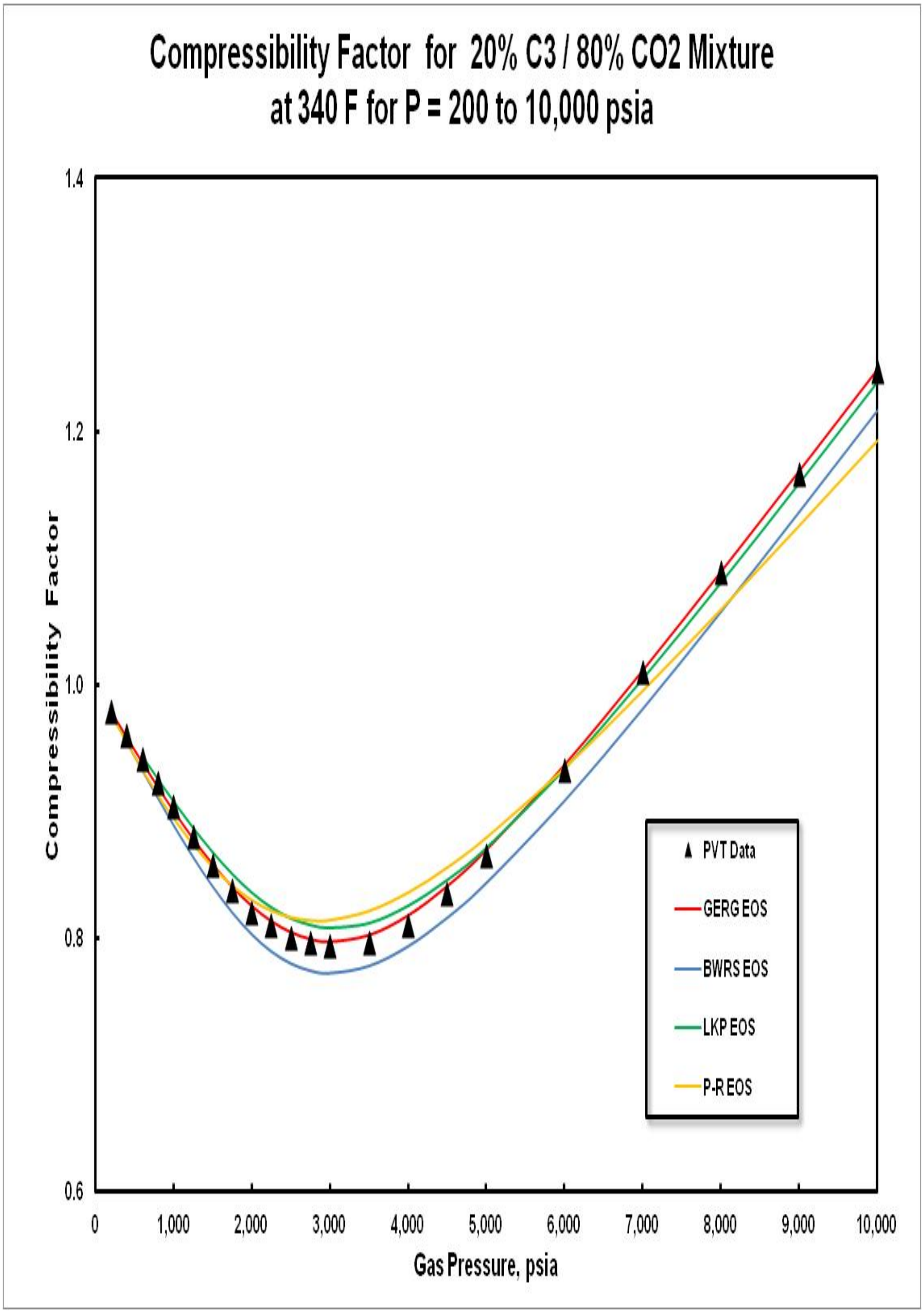


Figure 4.7 Compressibility Factor for 20% C3/80% CO_2 at 340 ^oF

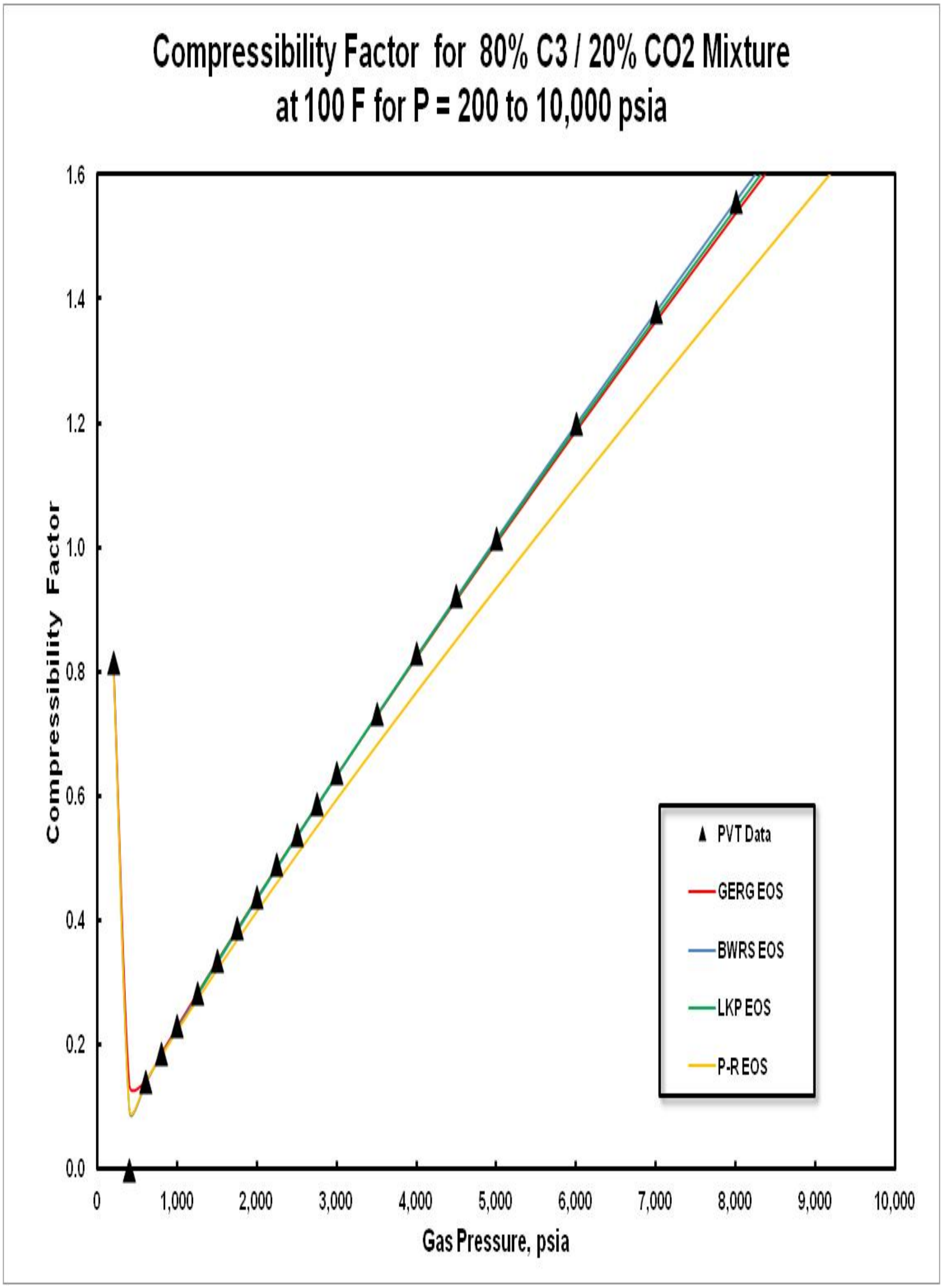


Figure 4.8 Compressibility Factor for 80% C_3/20% CO_2 at 100 ^oF

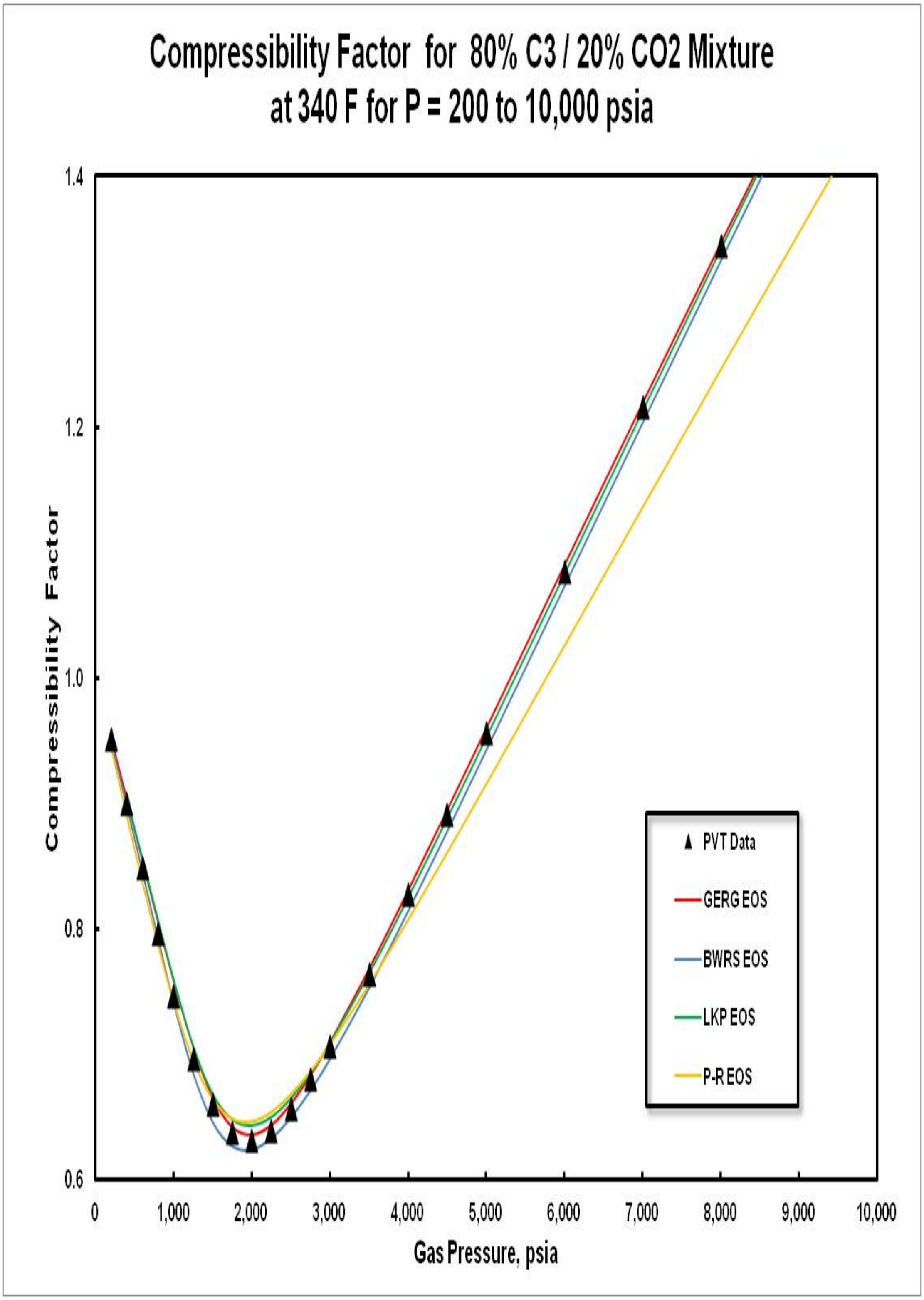


Figure 4.9 Compressibility Factor for 80% C_3/20% CO_2 at 340 ^oF

For the pressure range from 200 psia to 10,000 psia, considering C_2/CO_2, but changing the mixture to make it different from the results given in Figure 4.6 to 4.9, the cases with 33% C2/67% CO2 and 67% C2/33% CO2 were also investigated. The computed compressibility factors are presented in Figure 4.10 to 4.13. For the ethane (C_2)/ CO_2 mixtures at 100 ^oF (Figures 4.10 and 4.12), the LKP and BWRS were the most accurate with the GERG giving slightly over-estimated results. The PR has the least accuracy of all the EsOS tested. However, at 340 ^oF (Figures 4.11 and 4.13), the LKP is the most accurate model. The GERG and the BWRS are slightly less accurate in calculation, while the PR was the least accurate model.

For the ethane (C_2)/ N_2 mixtures at 100 ^oF, the results of compressibility factors are presented in Figures 4.14 for the 27% C_2/73% N_2 case and Figure 4.16 for 73% C_2/27% N_2 case. Overall it is noted that GERG, LKP, and BWRS can produce reasonable results when compared to the experimental data. Again the PR model fails to provide good results.

Similar to the ethane (C_2)/ N_2 mixtures tested in Figures 4.14 and 4.16 but increasing the temperature to 340 ^oF , the results of compressibility factors are presented in Figures 4.15 for the 27% C_2/73% N_2 case and Figure 4.17 for 73% C_2/27% N_2 case. Basically the GERG, BWRS and LKP models generate similar results and fit reasonably well with data, although the LKP gives the best fitted results. The PR results however are deviated away from the data and cannot produce reasonable estimation of the compressibility factor under the cases of C2/N2 mixture.

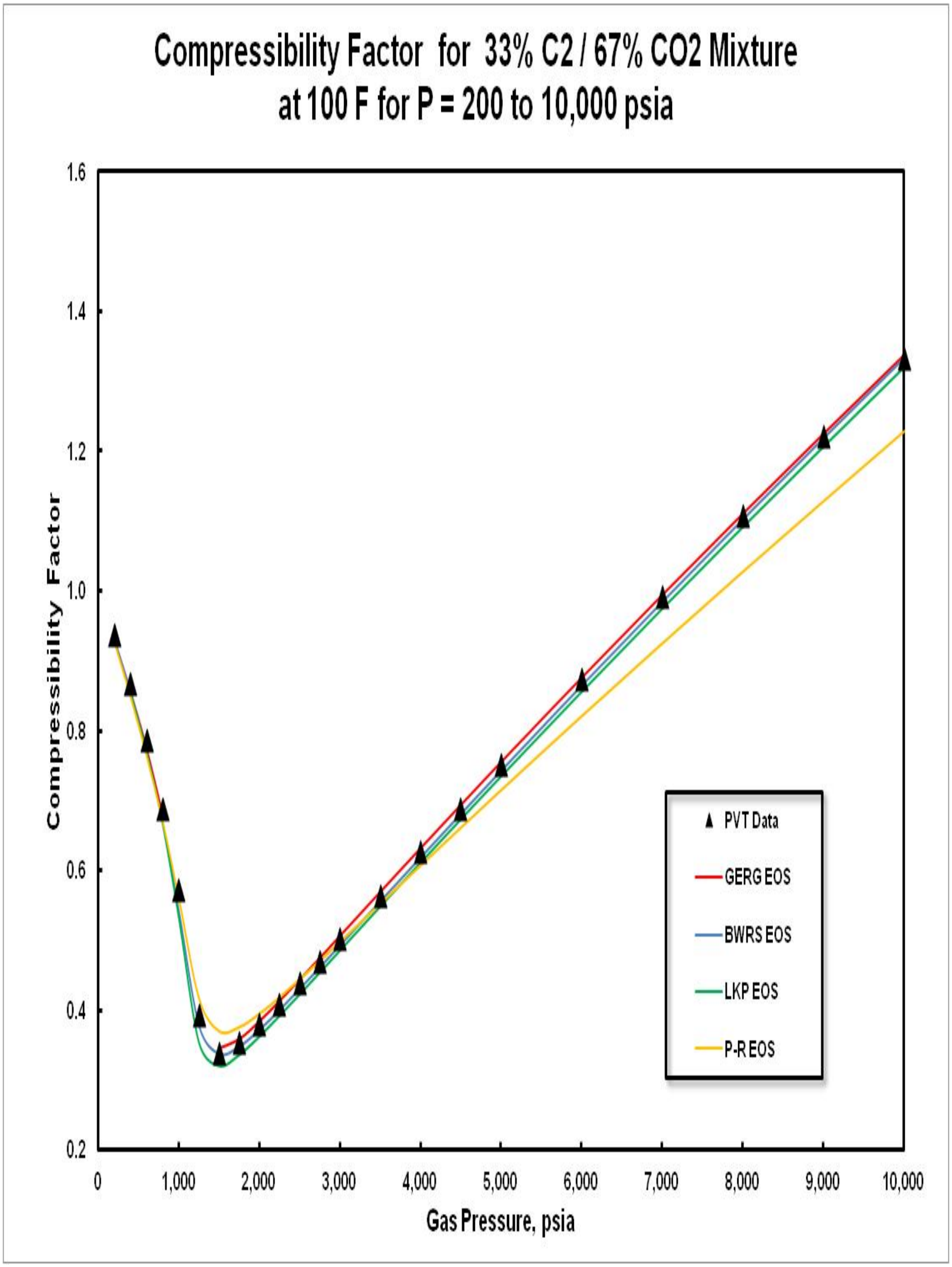


Figure 4.10 Compressibility Factor for 33% C_2/67% CO_2 at 100 ^oF

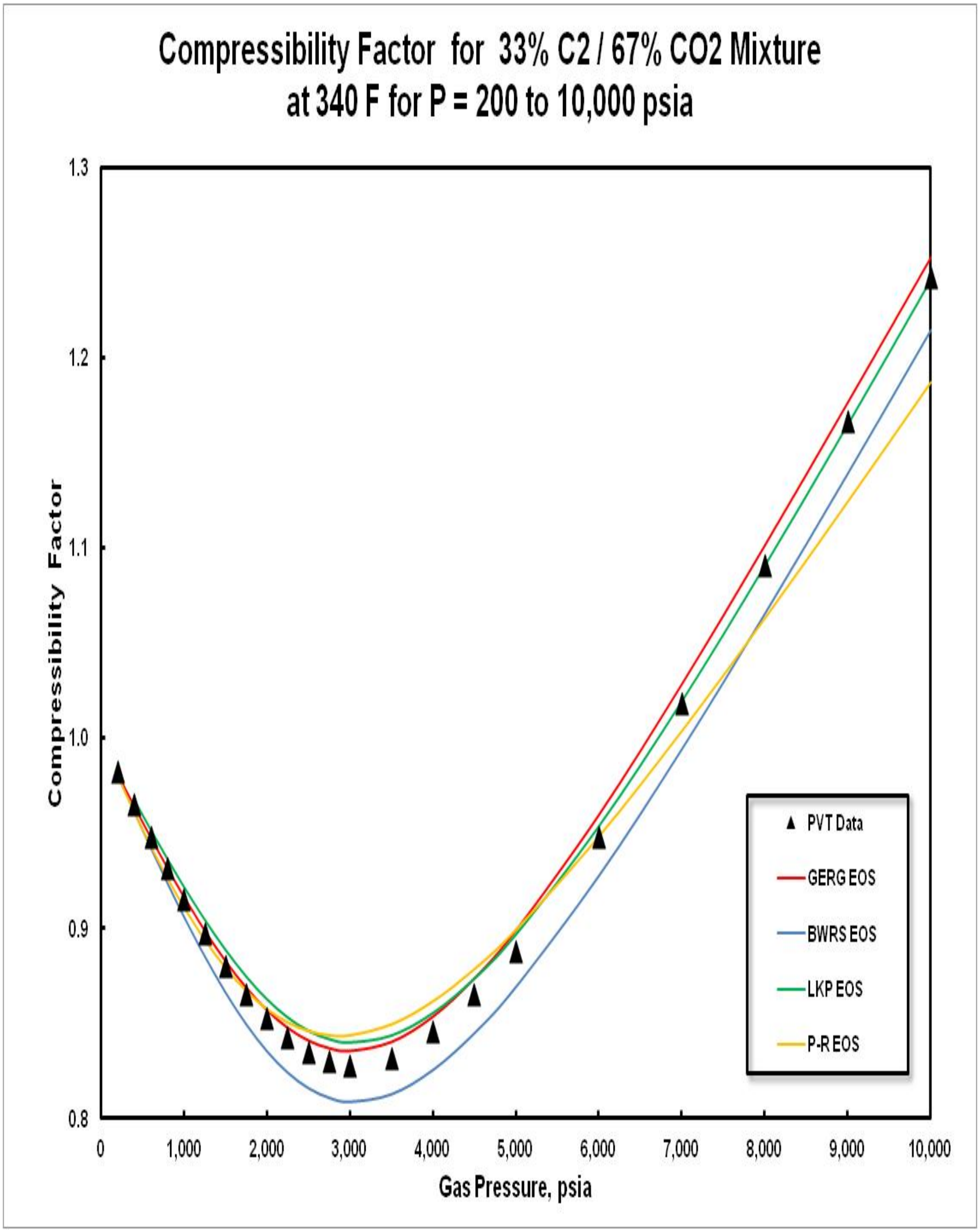


Figure 4.11 Compressibility Factor for 33% C_2/67% CO_2 at 340 ^oF

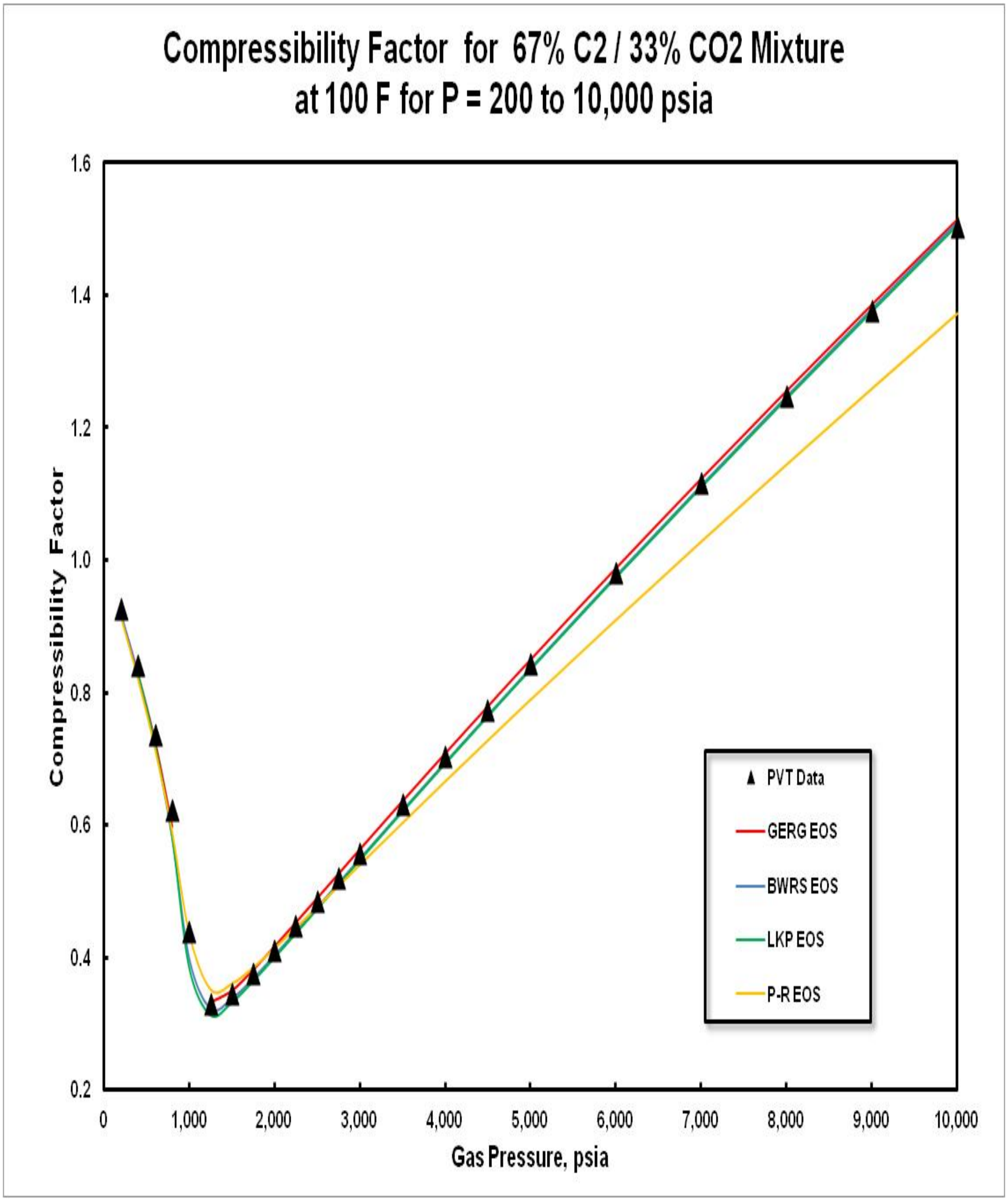


Figure 4.12 Compressibility Factor for 67% C_2/33% CO_2 at 100 ^oF

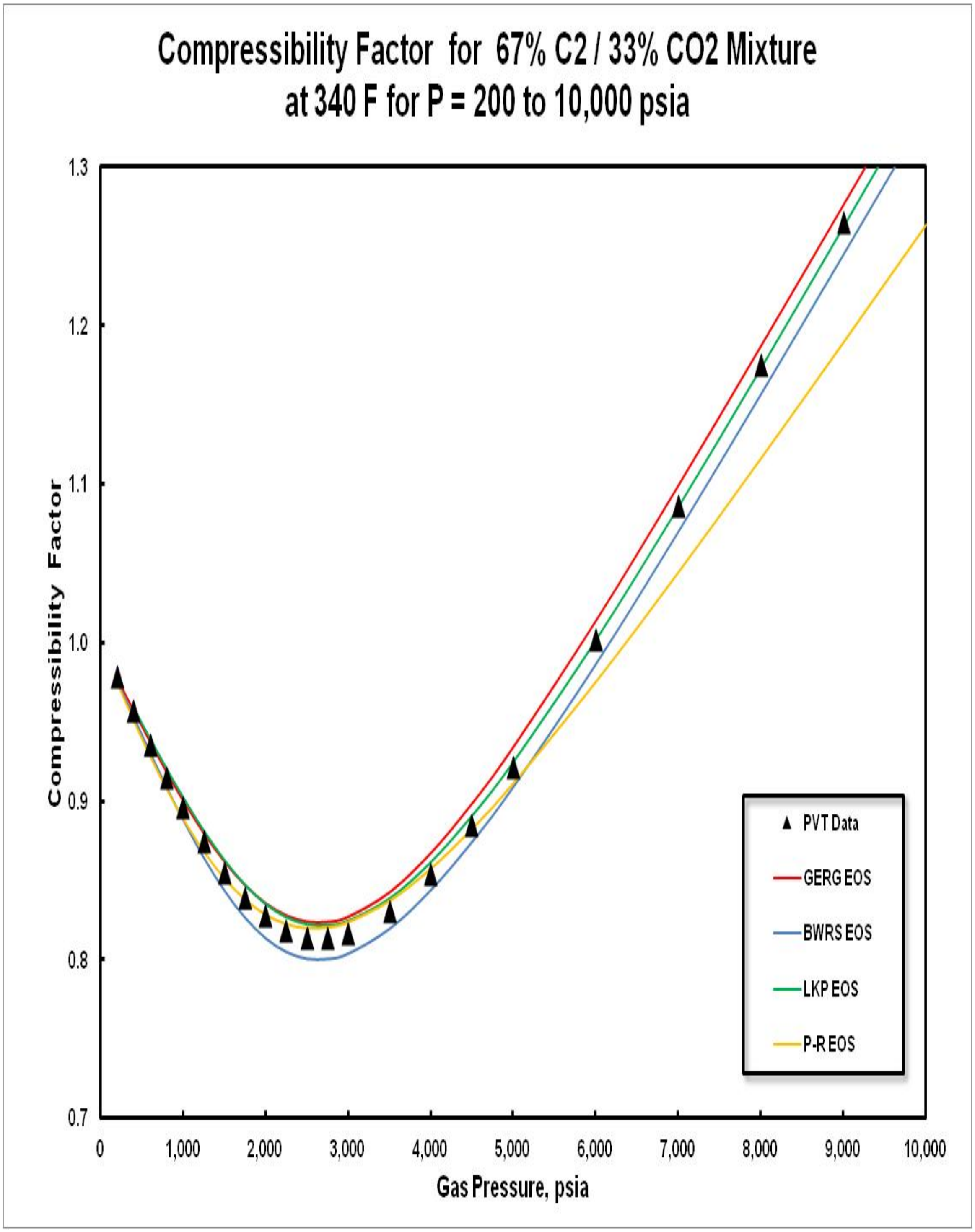


Figure 4.13 Compressibility Factor for 67% C_2/33% CO_2 at 340 ^oF

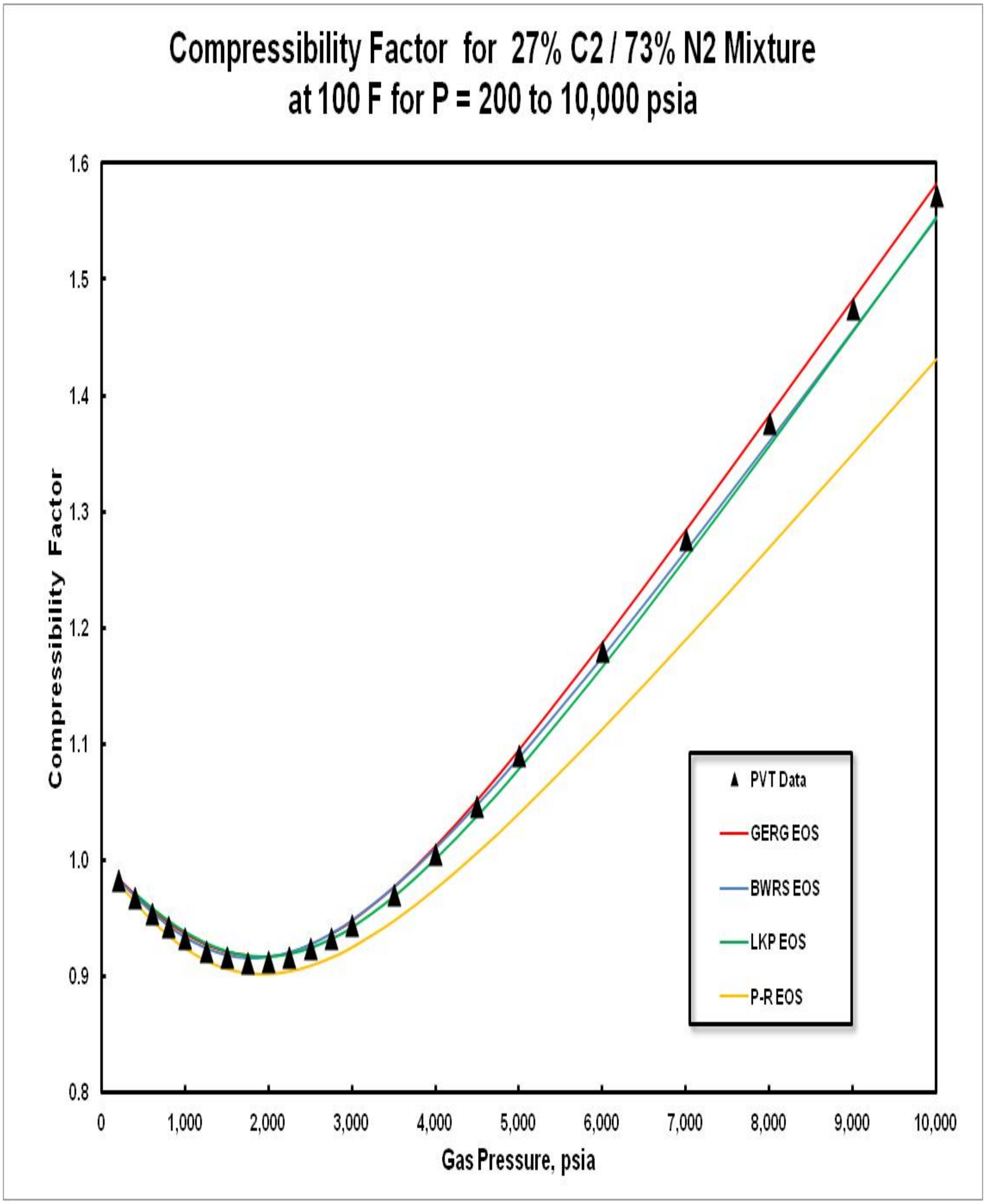


Figure 4.14 Compressibility Factor for 27% C_2/73% N_2 at 100 ^oF

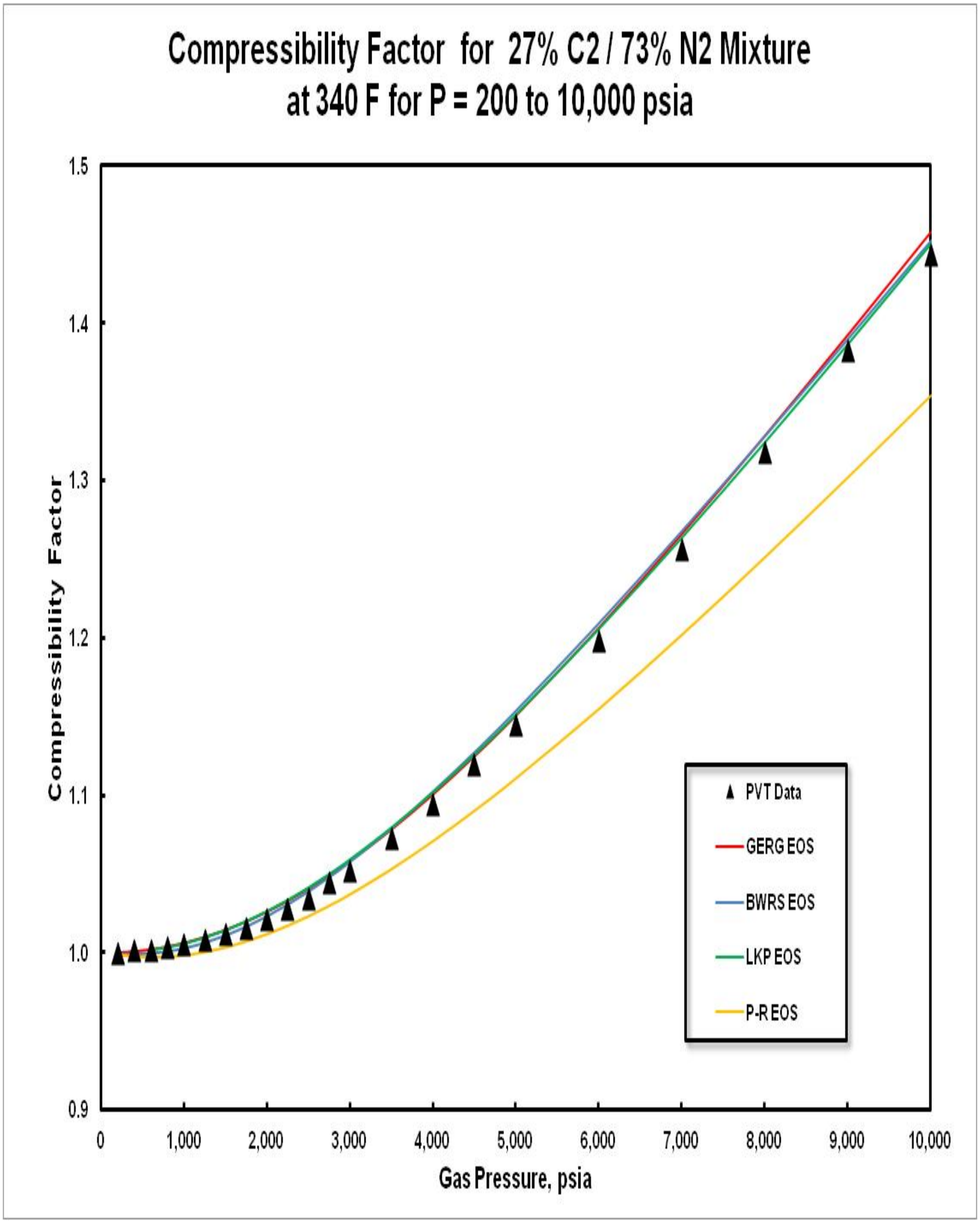


Figure 4.15 Compressibility Factor for 23% C_2/73% N_2 at 340 ^oF

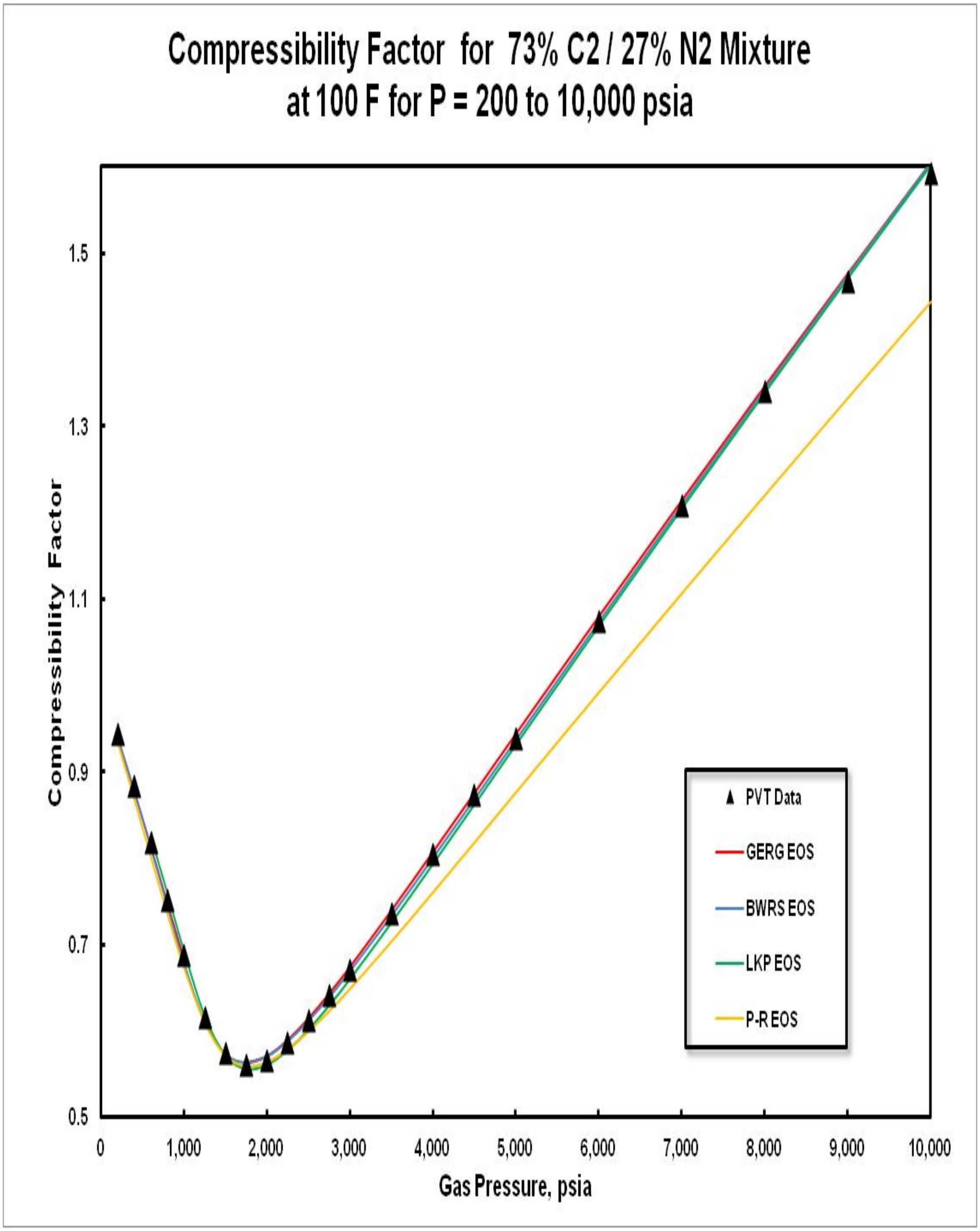


Figure 4.16 Compressibility Factor for 73% C_2/27% N_2 at 100 ^oF

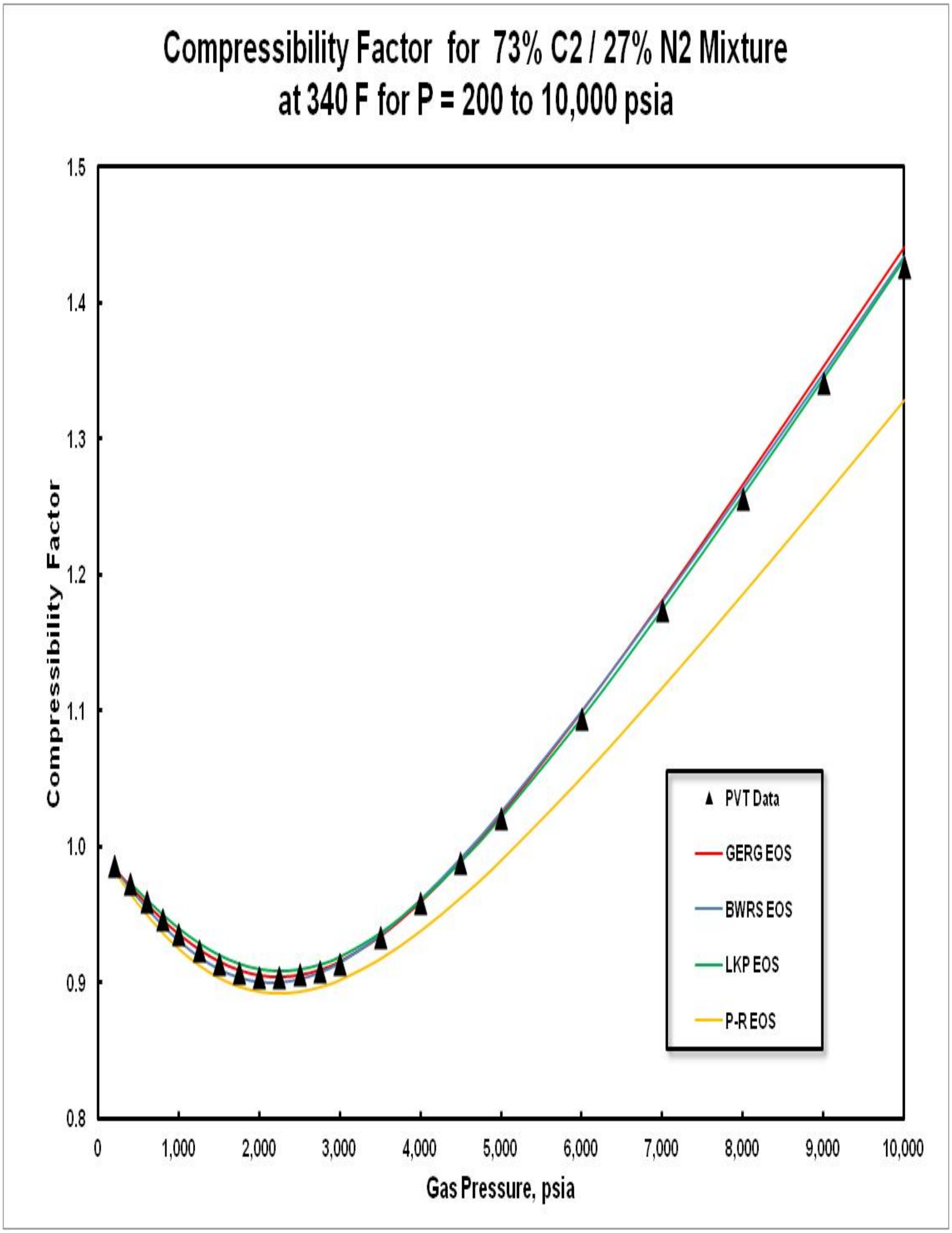


Figure 4.17 Compressibility Factor for 73% C_2/27% N_2 at 340 ^oF

In summary, from Figures 4.1 to 4.5, it is evident that for pure CO_2 and pure N_2 cases, all the equations of states (EsOS) tested represent the data very well when pressures is less than 1,000 psia and below. However, when the pressure increases to above 1000 psia (e.g., between 1,000 to 12,000psia) the GERG can provide the most accurate predictions when compared to the experimental data. The LKP and BWRS are slightly less accurate, and the PR was the least accurate EOS in estimating the compressibility factors. Furthermore, for the pure N_2 case, the Z factor increase when the pressure increase. For the pure CO_2 case, the Z factor actually reduce it value first to a minimum and then increase with the pressure. The Standing-Katz Z factor chart has shown the similar pattern. Nevertheless, the gas going to the production platform for injection purpose in general will contain different components and may not be pure CO_2, Natural gas or $N_{2.}$ Therefore most of the EOR injection gas will have the similar pattern as CO_2.

For the hydrocarbon/CO_2 and hydrocarbon/N_2 mixtures (Figures 4.6 to 4.17) at the pressure range of 1,000 psia and below, the four EsOS – GERG, LKP, BWRS and PR can generally provide good estimation of compressibility factors. Relatively, the results from GERG, LKP and PR fit better to the data. For 1,000 to12,000 psia pressure ranges at 100 ^oF, the GERG generally give the most accurate results and compare well with the experimental data. The LKP and BWRS also give good predictions while the PR model produces the results with the largest error. Between 1,000 and 12,000psia at 340^oF the LKP prove to give the most accurate representation of the experimental data. The results from

GERG and BWRS are reasonable but not as accurate as those from LKP. The PR is identified again as the least accurate EOS.

For N_2 as the injection gas, some of the Z factor average deviations are plotted for comparison purpose. For the 27% C_2/73% N_2 case at different temperature of 100 ^oF, 220 ^oF and 340 ^oF, the compressibility factor average deviation percentage versus the pressure is plotted in Figure 4.18. It is evident that the GERG produce the most accurate representation of the experimental data and as a result has the lowest deviation which is less than 1.00% even at high pressure region. The results from LKP and BWRS are slightly less accurate but in the acceptable range, and the PR is the least accurate EOS with some absolute deviation reach nearly 9.0%. Especially, for the temperature of 340 ^oF and at high pressure condition above 5,000 psia, the PR has the error greater than about 4.5%. For compressor simulation and actual compressor operation, the compressor discharge temperature could reach 340 ^oF. In other word, using the PR EOS actually could under estimate the design duty requirement for all discharge cooler.

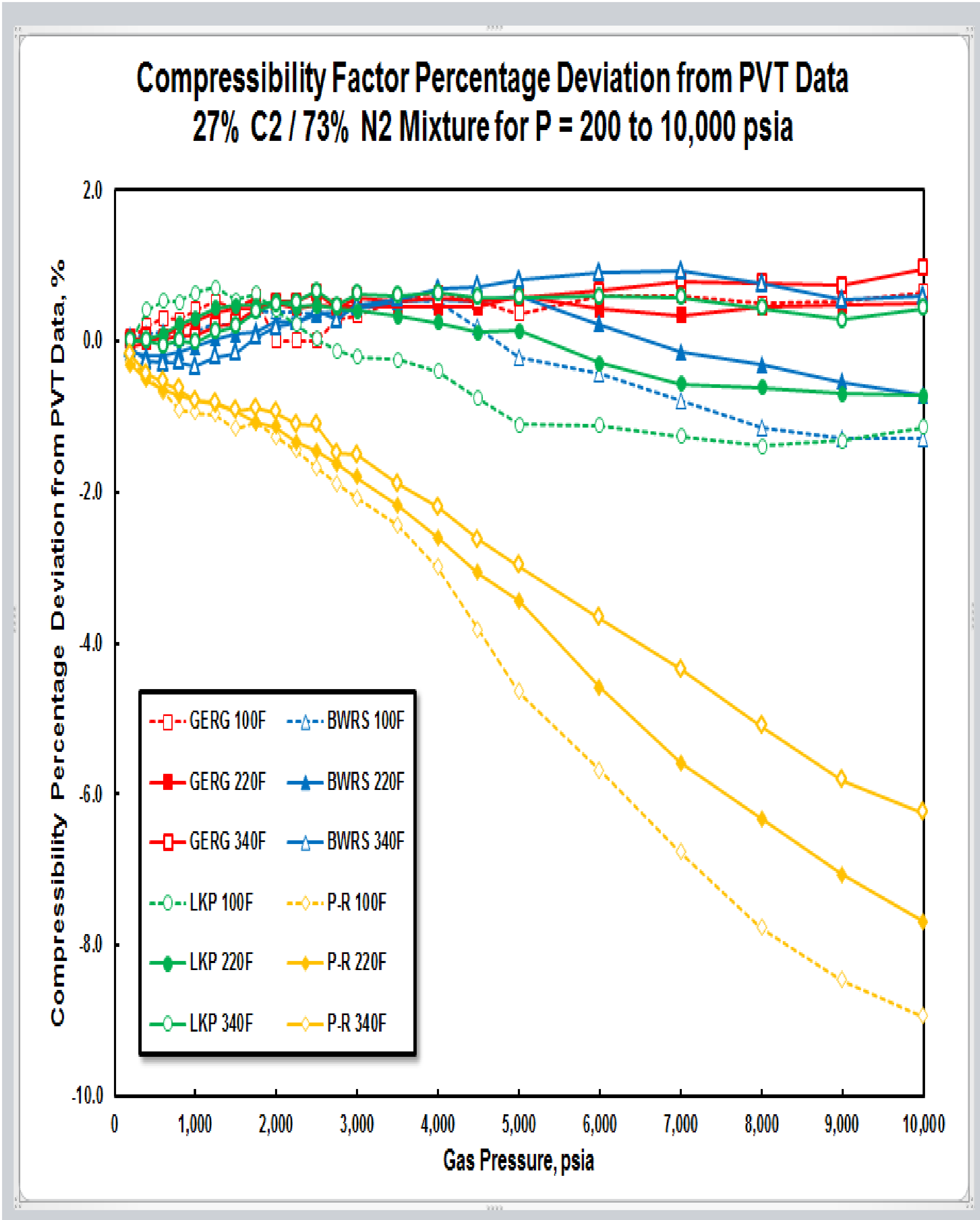


Figure 4.18 Z factor average deviation for 27% C2/73% N_2 mixture

4.2 Impact of Different EsOS on the FGC, BGC and IGC.

From study presented in previous section (section 4.1) we note that GERG, BWRS and LKP models generally produce similar and more accurate results in compressibility factor. However the PR model in most cases gives poor prediction. The horsepower of compressor and cooling duty actually reflect directly the cost impact. It would be interested in examining the difference of horsepower and cooling duty outputs from FGC, BGC and IGC by using one of the EOS from GERG, BWRS and LKP models against the PR EOS. However, the GERG was not selected as it was not available for the complicated operation such as compressor and recycle loop unit operation in HYSYS simulator. Rather the LKP EOS was selected together with PR EOS to examine the compressor and cooling duty impact. The compressor power computed from LKP and PR EsOS for each stage of FGC, BGC and IGC are summarized in Table 4.1. The more accurate LKP EOS estimates the required total power as 68,310 horse power (HP). However the less accurate PR EOS predicts the total power of 64,620 HP which is underestimated by 5.4%.

Table 4.1 Compressor Horsepower Required by PR and LKP EOS

	FGC 1st HP	**FGC 2nd HP**	**BGC 1st HP**	**BGC 2nd HP**	**IGC 1st HP**	**IGC 2nd HP**	**IGC 3rd HP**	**Total HP, IGC**
PR EOS	**37**	**59**	**15,870**	**15,050**	**19,350**	**21,550**	**23,720**	**64,620**
LKP EOS	**37**	**59**	**15,870**	**15,050**	**19,710**	**22,510**	**26,090**	**68,310**
% Shortage	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**1.8%**	**4.3%**	**9.1%**	**5.4%**

For the cooling duty, the results from LKP and PR EsOS for each stage of FGC, BGC and IGC are presented in Table 4.2. The LKP EOS estimates the required total cooling duty of 176.9 MMBTU/Hr. However the PR EOS predicts the total cooling duty of 171.2 MMBTU/Hr. which is underestimated by 3.2%. Therefore it is critically important to select the most accurate EOS for engineering design.

Table 4.2 Compressor Discharge Cooler Duty Required by PR and LKP

Duty in MMBtu/Hr.	**FGC 1^{st} Duty**	**FGC 2^{nd} Duty**	**BGC 1^{st} Duty**	**BGC 2^{nd} Duty**	**IGC 1^{st} Duty**	**IGC 2^{nd} Duty**	**IGC 3^{rd} Duty**	**Total Duty IGC**
PR EOS	**0.5**	**57.0**	**50.2**	**46.8**	**67.4**	**60.0**	**43.8**	**171.2**
LKP EOS	**0.5**	**57.0**	**50.2**	**46.8**	**68.9**	**62.0**	**46.0**	**176.9**
% Shortage	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**2.1%**	**3.2%**	**4.8%**	**3.2%**

Higher duties mean larger equipment which required larger platform. For a multiple billion dollar offshore EOR project, the cost impacts due to the difference of estimated total compressor horsepower and cooling duty can be very high ,e.g., in the multiple million dollar range. Furthermore, as seen in the comparison results, it is recommended to not only use the LKP EOS for design purposes. It is also recommended that a 10% process margin as minimum which is an industry standard to account for the uncertainties MUST be added. Please note that this is not including the mechanical margin that manufacture implemented.

Chapter 5. Conclusions, Recommendation and Further Research.

5.1 Conclusions

Offshore EOR in deep water is one of the ways to go for next decade to produce oil. Today many operations are deeper than 7,000 feet of water. Massive production platforms are required. By using EOR, 30 to 60 % or more of the reservoir's original oil can be extracted compared with 20 to 40 % using the primary and secondary recovery methods. The study reservoir pressure is about 20,000 psi. Because of the density and molecular weight differences between CO2, natural gas, and N2, the estimated compressor discharge pressure required to get into the reservoir is 9,000, 14,000 and 12,000 psia respectively.

An engineering design starts with EOS selection. An EOS that can adequately model the PVT and calculations at ultra-high pressure nearly 12,000 psi is required to do the offshore EOR simulation. GERG, BWRS, LKP, and PR four EsOS are selected for simulation and evaluation. By using different EOS in the simulator, the Z factor can be calculated. In addition, the computed compressibility factors (Z) from the four EsOS are compared with the experimental data in order to evaluate the accuracy of the related EOS. For this study, the HYSYS simulator has been selected to simulate the designed process system.

It is evident that for pure CO2 and pure N2 cases, all the equations of states (EsOS) tested represent the data very well when pressures is less than

1,000 psia and below. However, when the pressure increases to above 1000 psia (e.g., between 1,000 to 12,000 psia) the GERG can provide the most accurate predictions. The LKP and BWRS are slightly less accurate, and the PR was the least accurate EOS in estimating the compressibility factors.

For the hydrocarbon/CO2 and hydrocarbon/N2 mixtures at the pressure range of 1,000 psia and below, the four EsOS – GERG, LKP, BWRS and PR can generally provide good estimation of compressibility factors. For 1,000 to 12, 000 psia pressure ranges at 100 ^{o}F, the GERG generally give the most accurate results and compare well with the experimental data. The LKP and BWRS also give good predictions while the PR model produces the results with the largest error. Between 1,000 and 12,000psia at 340^{o}F the LKP prove to give the most accurate representation of the experimental data. The results from GERG and BWRS are reasonable but not as accurate as those from LKP. The PR is identified again as the least accurate EOS.

This study finds that overall the GERG produces the most accurate representation of the experimental data and as a result has the lowest deviation which is less than 1.00% even at high pressure region. The results from LKP and BWRS are slightly less accurate but in the acceptable range, and the PR is the least accurate EOS with some absolute deviation reach nearly 9.0%. The required horsepower of a compressor and cooling duty actually reflect directly the cost impact. The LKP EOS was selected together with PR EOS to examine the compressor and cooling duty impact. The more accurate LKP EOS estimates the required total horsepower (HP) of a system designed for the power requirement study to be 68,310 HP. However the less accurate PR EOS predicts 64,620 HP as the required total compressor power which is underestimated by 5.4%. The LKP EOS estimates the required total cooling duty of 176.9 MMBTU/Hr. However the PR EOS predicts the total cooling duty to be 171.2 MMBTU/Hr. which is underestimated by 3.2%. Therefore it is critically important to select the most accurate EOS for engineering design. Higher duties mean larger equipment which required larger platform. For a multiple billion dollar offshore EOR project, the cost impacts due to the difference of estimated total compressor horsepower and cooling duty can be very high,e.g., in the multiple million dollar range.

5.2 Recommendations.

It is interesting to note that the Peng Robinson EOS (PR-EOS), although is widely used in the oil, gas and petrochemical industries due to its capability of describing in general the single, two or multiphase behaviors reasonably well, is not the EOS to be used for ultrahigh pressure compression application because the Z factor deviation could reach as high as 9% and the required compressor power could be underestimated. After evaluating the compressibility factor predictions over the wide range of temperatures and pressures as presented in this study it is recommended that for low pressure system and up to 1,000 psia two EsOS – LKP and PR which predict the experimental data well and can be used for the simulations of production operations. In fact, nowadays, many companies prefer the use of PR for oil and gas simulation purpose. GERG is considered to be very accurate but has not been widely implemented in commercial process simulators. Only one process simulator HYSYS provides this EOS.

For the consideration of high pressure system from 1,000 and Up to 12,000 psia, the LKP would be suggested for the simulations of the operating systems (primarily gas compression). The LKP is selected over the GERG because:

a. The LKP predicts the compressibility factors of pure CO_2, pure N_2, hydrocarbon/CO_2, hydrocarbon/N_2 at 100^{o}F fairly well,
b. The LKP gives the best prediction of the compressibility factors of the hydrocarbon/CO_2, hydrocarbon/N_2 mixtures at 340^{o}F, and
c. The GERG has not been implemented in most commercial simulators.

For simulations using different EOS package, at appropriate sections of the simulation, a “stream cutter” or “EOS cutter” could be inserted to transform the properties of a stream in a given EOS package to another EOS. The results of the initial implementation of this concept have been accepted as satisfactory for design. Furthermore, as seen in the comparison results, it is recommended to use the LKP EOS for design purposes. It is also suggested that a 10% process margin as minimum which is an industry standard to account for the uncertainties in the EOS MUST be added. It should be noted that this does not include the mechanical margin that manufacture implemented.

5.3 Further Research

The GERG EOS is the newest and only available in 2008. It provides 21 pure components for binary mixture combination. The fact is that the National

Institute of Standards and Technology (NIST) have strongly endorsed the usage of GERG especially for the gas industry. It is considered to be very accurate but has not been widely tested and implemented in commercial process simulators. Only one process simulator, Aspen Technology HYSYS provides this EOS. However, there are some computational related issues need to be resolved to make this EOS more flexible. In contrast, the most popular EOS is PR model which is fully developed and available for the industry since 1976. Most of the simulators providers have the PR EOS available for selection. However, this study proves that under the ultrahigh pressure conditions, the PR EOS fails to provide good estimations on compressibility factor and compressor power for systems especially with hydrocarbon/CO_2 and hydrocarbon/N_2 mixtures. Further research on the PR EOS should be carried out to define the limitation of the model. In addition, more research on improving the implementation capability of the GERG model should be considered. As the technology advanced, the computer system with better and faster computational capability and with more robust data bank from HYSYS model for GERG, further study to use the GERG model for more process simulations and testing is recommended. More comparisons between LKP and GERG on the actual design calculations are required to further define the design capabilities of the LKP and GERG models and to potentially reduce the design margin.

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Appendices

Appendix A. Procedure of Using Equation of State to Determine the Thermodynamic Properties Containing Derivatives (Pratt, 2001)

Summarized below is a procedure and applied examples presented by Pratt (2001) for the determination of thermodynamic properties involving derivatives, such as $(\partial P/\partial V)_T$, $(\partial T/\partial P)_V$, and $(\partial V/\partial T)_P$, using the formulation of equation of state. This calculation procedure provides a useful and simple tool for engineers to use in their design and process analyses. To demonstrate the methods, Pratt (2001) adopted Peng-Robinson (PR) EOS applied to a binary vapor hydrocarbon mixture.

The PR EOS as described in Chapter 2 is written as

$$P = \frac{RT}{V-b} - \frac{a}{V(V+b)+b(V-b)} \quad , \tag{A1}$$

where

R = universal gas constant

T = absolute temperature

V = molar volume

$a = a_c\left[1 + m\,[1 - \sqrt{T/T_c}\,]\right]$

$a_c = 0.45723553\ R^2T_c^2/P_c$

$m = 0.37464 + 1.54226\ \omega - 0.26992\ \omega^2$

$b = 0.077796074\ RT_c/P_c$

As an example, Pratt (2001) considered a binary vapor mixture of n-butane and n-pentane at 390 °K and 11 bar where 35.63 mole % is n-butane. The critical properties for the two components indicated above are given in Table A.1 (Smith et al., 1996).

Table A.1

Critical Property Data for n-butane and n-pentane

	n-butane	n-pentane
T_c(°K)	425.1	469.7
P_c(bar)	37.96	33.7
ω	0.200	0.252

For convenience, the PR EOS can be written in a cubic polynomial form for the compressibility factor Z = PV/RT as

$$\mathrm{f(Z)} = \mathrm{Z}^3 + \alpha \mathrm{Z}^2 + \beta \mathrm{Z} + \gamma = 0, \tag{A2}$$

where

$\alpha = B - 1$

$\beta = A - 2B - 3B^2$

$\gamma = B^3 + B^2 - AB$

and

$A = aP/(RT)^2$

B = bP / RT

Under the case of an N-component fluid with composition, { w_i }, the mixture parameters, a and b, can be calculated from the following empirical formula

$$a = \sum_{i-l}^{N} \sum_{j-l}^{N} w_i\ w_j \sqrt{a_i a_j}\ (1 - k_{ij}) \quad \text{and} \quad b = \sum_{i=l}^{N} w_i\, b_i \qquad \text{(A3)}$$

In principle, the binary interaction coefficient, k_{ij}, is exactly zero for i = j and k_{ij} is close to zero for hydrocarbons when i≠j. It is therefore reasonable to take k_{ij} = 0. From Eq. (A1), we have the pure component parameters using R=83.14 cm^3-bar/mol-K as

a_1 = 15911115 cm^6-bar/mol^2 a_2 = 23522595 cm^6-bar/mol^2

b_1 = 72.43235 cm^3/mol b_2 = 90.14847 cm^3/mol. , and

Then, the use of Eq. (A3) gives

a = 2063 1852 cm^6-bar/mol^2 b = 83.836216 cm^3/mol

The compressibility factor, Z, can be calculated by solving Eq. (A2). For the example case, the largest of the three real roots of the vapor phase of the compressibility factor is determined to be 0.7794. As a result, the molar volume, V , of the vapor mixture is ZRT/P = 2297.54 cm^3/mol. By knowing the molar volume and compressibility, the thermodynamic properties containing derivatives, $(\partial P/\partial V)_T$, $(\partial T/\partial P)_V$, and $(\partial V/\partial T)_P$, can be calculated from the following equations,

$$\left(\frac{\partial P}{\partial V}\right)_T = \frac{-RT}{(V-b)^2} + \frac{2a(V+b)}{[(V(V+b)+b(V-b)]^2} \qquad \text{(A4)}$$

$$\left(\frac{\partial T}{\partial P}\right)_V = 1/\left(\frac{\partial P}{\partial T}\right)_V = 1/[\frac{R}{V-b} - \frac{a'}{V(V+b)+b(V-b)}] \tag{A5}$$

and

$$\left(\frac{\partial P}{\partial V}\right)_T \left(\frac{\partial T}{\partial P}\right)_V \left(\frac{\partial V}{\partial T}\right)_P = -1 \tag{A6}$$

where

$$a' = \frac{da}{dT}$$

The computed values are

$$\left(\frac{\partial P}{\partial V}\right)_T = -0.0035459 \text{ bar} / (\text{cm}^3/\text{mol})$$

$$\left(\frac{\partial T}{\partial P}\right)_V = 2.99558 \text{ K/bar}$$

$$\left(\frac{\partial V}{\partial T}\right)_P = 12.26396 \text{ cm}^3/(\text{mol} - \text{K}).$$

With formulations provided by Pratt (2001), other thermodynamic properties, such as the heat capacities of C_v and C_P can also be computed.

Appendix B. HYSYS Simulation Model Outputs Summary

Stream Summaries Printouts

aspentech	CHEVRON USA Burlington, MA USA
Case Name:	PHD.HSC
Unit Set:	NewUser
Date/Time:	Mon Apr 06 10:04:42 2015

Material Stream: Feed From Well

Fluid Package: Main Basis
Property Package: Peng-Robinson

CONDITIONS

		Overall	Vapour Phase	Liquid Phase	Aqueous Phase
Vapour / Phase Fraction		0.2979	0.2979	0.0876	0.6145
Temperature:	(C)	42.11	42.11	42.11	42.11
Pressure:	(bar)	12.05	12.05	12.05	12.05
Molar Flow	(MMSCFD)	579.1	172.5	50.74	355.9
Mass Flow	(kg/h)	1.082e+006	2.444e+005	5.181e+005	3.193e+005
Std Ideal Liq Vol Flow	(m3/h)	1344	413.5	611.0	320.0
Molar Enthalpy	(Btu/SCF)	-253.6	-40.23	-494.2	-322.7
Molar Entropy	(kJ/kgmole-C)	121.7	150.9	469.2	58.03
Heat Flow	(kJ/h)	-6.456e+009	-3.051e+008	-1.102e+009	-5.049e+009
Liq Vol Flow @Std Cond	(m3/h)	1358 *	2.026e+005	606.0	314.7

PROPERTIES

		Overall	Vapour Phase	Liquid Phase	Aqueous Phase
Molecular Weight		37.51	28.45	205.0	18.02
Molar Density	(kgmole/m3)	1.498	0.4693	4.067	55.21
Mass Density	(kg/m3)	56.20	13.35	833.7	994.7
Act. Volume Flow	(m3/h)	1.925e+004	1.831e+004	621.4	321.0
Mass Enthalpy	(kJ/kg)	-5968	-1248	-2127	-1.581e+004
Mass Entropy	(kJ/kg-C)	3.245	5.304	2.289	3.221
Heat Capacity	(kJ/kgmole-C)	95.92	40.68	411.3	77.74
Mass Heat Capacity	(kJ/kg-C)	2.557	1.430	2.006	4.315
LHV Molar Basis (Std)	(Btu/SCF)	---	---	---	3.286e-005
LHV Mass Basis (Std)	(kJ/kg)	---	---	---	1.610e-003
Phase Fraction [Vol. Basis]		0.3076	0.3076	0.4544	0.2380
Phase Fraction [Mass Basis]		0.2259	0.2259	0.4789	0.2952
Partial Pressure of CO2	(bar)	2.241e-002	---	---	---
Cost Based on Flow	(Cost/s)	0.0000	0.0000	0.0000	0.0000
Act. Gas Flow	(ACT_m3/h)	1.831e+004	1.831e+004	---	---
Avg. Liq. Density	(kgmole/m3)	21.45	20.78	4.136	55.39
Specific Heat	(kJ/kgmole-C)	95.92	40.68	411.3	77.74
Std. Gas Flow	(STD_m3/h)	6.820e+005	2.032e+005	5.975e+004	4.191e+005
Std. Ideal Liq. Mass Density	(kg/m3)	804.7	591.1	848.0	998.0
Act. Liq. Flow	(m3/s)	0.2618	---	0.1726	8.918e-002
Z Factor		---	0.9792	0.1130	8.323e-003
Watson K		10.59	10.09	11.66	6.682
User Property		---	---	---	---
Partial Pressure of H2S	(bar)	0.0000	---	---	---
Cp/(Cp - R)		1.095	1.257	1.021	1.120
Cp/Cv		1.031	1.299	1.162	1.156
Heat of Vap.	(Btu/SCF)	107.2	---	---	---
Kinematic Viscosity	(cSt)	---	1.173	7.336	0.6294
Liq. Mass Density (Std. Cond)	(kg/m3)	796.5	1.206	854.9	1015
Liq. Vol. Flow (Std. Cond)	(m3/h)	1358	2.026e+005	606.0	314.7
Liquid Fraction		0.7021	0.0000	1.000	1.000
Molar Volume	(m3/kgmole)	0.6674	2.131	0.2459	1.811e-002
Mass Heat of Vap.	(kJ/kg)	2522	---	---	---
Phase Fraction [Molar Basis]		0.2979	0.2979	0.0876	0.6145
Surface Tension	(dyne/cm)	---	---	20.07	69.12
Thermal Conductivity	(W/m-K)	---	2.784e-002	0.1108	0.6341
Viscosity	(cP)	---	1.565e-002	6.117	0.6261
Cv (Semi-Ideal)	(kJ/kgmole-C)	87.61	32.36	403.0	69.42

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CHEVRON USA
Burlington, MA
USA

Case Name:	PHD.HSC
Unit Set:	NewUser
Date/Time:	Mon Apr 06 10:04:42 2015

Material Stream: Feed From Well (continued)

Fluid Package: Main Basis
Property Package: Peng-Robinson

PROPERTIES

		Overall	Vapour Phase	Liquid Phase	Aqueous Phase
Mass Cv (Semi-Ideal)	(kJ/kg-C)	2.336	1.138	1.966	3.853
Cv	(kJ/kgmole-C)	93.06	31.32	353.9	67.22
Mass Cv	(kJ/kg-C)	2.481	1.101	1.726	3.731
Cv (Ent. Method)	(kJ/kgmole-C)	---	---	---	66.39
Mass Cv (Ent. Method)	(kJ/kg-C)	---	---	---	3.685
Cp/Cv (Ent. Method)		---	---	---	1.171
Reid VP at 37.8 C	(bar)	149.2	---	2.604	---
True VP at 37.8 C	(bar)	567.2	---	11.79	7.343
Liq. Vol. Flow - Sum(Std. Cond)	(m3/h)	2.036e+005	2.026e+005	606.0	314.7
Viscosity Index		5.591e-002	---	---	---
HHV Molar Basis (Std)	(Btu/SCF)	---	---	---	46.46
HHV Mass Basis (Std)	(kJ/kg)	---	---	---	2276
CO2 Loading		---	---	---	---
CO2 App ML Con	(kgmole/m3)	---	---	1.134e-003	3.926e-004
CO2 App WT Con	(kgmol/kg)	---	---	1.360e-006	3.947e-007
Phase Fraction [Act. Vol. Basis]		0.9510	0.9510	3.228e-002	1.668e-002
Mass Exergy	(kJ/kg)	52.69	---	---	---

COMPOSITION

Overall Phase

Vapour Fraction 0.2979

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
Nitrogen	5357.2284	0.1857	150072.0405	0.1387	186.1072	0.1384
CO2	16.8164	0.0006	740.0849	0.0007	0.8967	0.0007
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Methane	1847.5811	0.0641	29640.5585	0.0274	99.0018	0.0736
Ethane	546.2138	0.0189	16424.5955	0.0152	46.1776	0.0343
Propane	497.6064	0.0173	21942.9482	0.0203	43.3075	0.0322
i-Butane	80.2894	0.0028	4666.7403	0.0043	8.3043	0.0062
n-Butane	278.5297	0.0097	16189.2621	0.0150	27.7583	0.0206
i-Pentane	122.1746	0.0042	8815.0178	0.0081	14.1393	0.0105
n-Pentane	221.3295	0.0077	15969.1469	0.0148	25.3588	0.0189
n-Hexane	304.9254	0.0106	26277.8311	0.0243	39.6548	0.0295
C7s*	241.1101	0.0084	23221.3133	0.0215	32.9964	0.0245
C8s*	196.3197	0.0068	21597.1355	0.0200	29.8002	0.0222
C9s*	140.9362	0.0049	17287.2376	0.0160	23.0434	0.0171
C10s*	125.3411	0.0043	16795.7046	0.0155	21.5890	0.0161
C11s*	98.8982	0.0034	14538.0343	0.0134	18.4268	0.0137
C12s*	82.9171	0.0029	13349.6569	0.0123	16.6881	0.0124
C13s*	76.8226	0.0027	13443.9543	0.0124	16.5782	0.0123
C14s*	67.4653	0.0023	12818.4029	0.0118	15.5955	0.0116
C15s*	56.6735	0.0020	11674.7420	0.0108	14.0335	0.0104
C16s*	52.1418	0.0018	11575.4904	0.0107	13.7983	0.0103
C17s*	45.1448	0.0016	10699.3088	0.0099	12.6335	0.0094
C18s*	42.6960	0.0015	10716.6973	0.0099	12.5798	0.0094
C19s*	41.4903	0.0014	10911.9413	0.0101	12.7343	0.0095
C20s*	33.2774	0.0012	9151.2769	0.0085	10.6165	0.0079
C21s*	29.7524	0.0010	8657.9359	0.0080	9.9863	0.0074
C22s*	27.7679	0.0010	8469.2140	0.0078	9.7127	0.0072
C23s*	24.4162	0.0008	7764.3504	0.0072	8.8536	0.0066

* Specified by user.

aspentech	CHEVRON USA Burlington, MA USA	Case Name: PHD.HSC Unit Set: NewUser Date/Time: Mon Apr 06 10:13:05 2015

Material Stream: Feed From Well (continued)

Fluid Package: Main Basis
Property Package: Peng-Robinson

COMPOSITION

Overall Phase (continued)

Vapour Fraction 0.2979

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
C28s*	16.5165	0.0006	6408.4046	0.0059	7.1526	0.0053
C29s*	15.6616	0.0005	6295.9666	0.0058	7.0037	0.0052
C30L+*	284.1999	0.0099	207014.0696	0.1914	206.9647	0.1539
C30H+*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O	17791.0530	0.6168	320507.6077	0.2963	321.1544	0.2389
Argon	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Oxygen	0.0004	0.0000	0.0131	0.0000	0.0000	0.0000
Total	28843.5543	1.0000	1.081822497e+06	1.0000	1344.4302	1.0000

Vapour Phase

Phase Fraction 0.2979

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
Nitrogen	5315.7366	0.6187	148909.7319	0.6092	184.6658	0.4466
CO2	15.9860	0.0019	703.5396	0.0029	0.8524	0.0021
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Methane	1817.7246	0.2116	29161.5740	0.1193	97.4020	0.2356
Ethane	512.6425	0.0597	15415.1100	0.0631	43.3395	0.1048
Propane	416.9553	0.0485	18386.4776	0.0752	36.2883	0.0878
i-Butane	55.4807	0.0065	3224.7609	0.0132	5.7384	0.0139
n-Butane	176.3189	0.0205	10248.3598	0.0419	17.5719	0.0425
i-Pentane	52.1292	0.0061	3761.1756	0.0154	6.0329	0.0146
n-Pentane	82.4024	0.0096	5945.4162	0.0243	9.4412	0.0228
n-Hexane	52.1916	0.0061	4497.7655	0.0184	6.7874	0.0164
C7s*	20.0849	0.0023	1934.3784	0.0079	2.7487	0.0066
C8s*	6.2664	0.0007	689.3713	0.0028	0.9512	0.0023
C9s*	1.8065	0.0002	221.5833	0.0009	0.2954	0.0007
C10s*	0.6485	0.0001	86.8986	0.0004	0.1117	0.0003
C11s*	0.2293	0.0000	33.7110	0.0001	0.0427	0.0001
C12s*	0.0948	0.0000	15.2611	0.0001	0.0191	0.0000
C13s*	0.0451	0.0000	7.9000	0.0000	0.0097	0.0000
C14s*	0.0199	0.0000	3.7767	0.0000	0.0046	0.0000
C15s*	0.0066	0.0000	1.3506	0.0000	0.0016	0.0000
C16s*	0.0024	0.0000	0.5391	0.0000	0.0006	0.0000
C17s*	0.0009	0.0000	0.2084	0.0000	0.0002	0.0000
C18s*	0.0004	0.0000	0.0930	0.0000	0.0001	0.0000
C19s*	0.0002	0.0000	0.0475	0.0000	0.0001	0.0000
C20s*	0.0001	0.0000	0.0201	0.0000	0.0000	0.0000
C21s*	0.0000	0.0000	0.0078	0.0000	0.0000	0.0000
C22s*	0.0000	0.0000	0.0035	0.0000	0.0000	0.0000
C23s*	0.0000	0.0000	0.0016	0.0000	0.0000	0.0000
C24s*	0.0000	0.0000	0.0007	0.0000	0.0000	0.0000
C25s*	0.0000	0.0000	0.0003	0.0000	0.0000	0.0000
C26s*	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000
C27s*	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000
C28s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C29s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C30L+*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C30H+*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O	65.1071	0.0076	1172.9104	0.0048	1.1753	0.0028
Argon	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

* Specified by user.

aspentech

CHEVRON USA
Burlington, MA
USA

Case Name:	PHD.HSC
Unit Set:	NewUser
Date/Time:	Mon Apr 06 10:13:05 2015

Material Stream: Feed From Well (continued)

Fluid Package: Main Basis
Property Package: Peng-Robinson

COMPOSITION

Vapour Phase (continued)

Phase Fraction 0.2979

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
Oxygen	0.0004	0.0000	0.0129	0.0000	0.0000	0.0000
Total	8591.8814	1.0000	244421.9879	1.0000	413.4809	1.0000

Liquid Phase

Phase Fraction 8.761e-002

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
Nitrogen	40.1814	0.0159	1125.6028	0.0022	1.3959	0.0023
CO2	0.7044	0.0003	30.9985	0.0001	0.0376	0.0001
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Methane	29.8558	0.0118	478.9744	0.0009	1.5998	0.0026
Ethane	33.5713	0.0133	1009.4853	0.0019	2.8382	0.0046
Propane	80.6511	0.0319	3556.4706	0.0069	7.0192	0.0115
i-Butane	24.8087	0.0098	1441.9794	0.0028	2.5660	0.0042
n-Butane	102.2108	0.0404	5940.9023	0.0115	10.1863	0.0167
i-Pentane	70.0454	0.0277	5053.8422	0.0098	8.1064	0.0133
n-Pentane	138.9271	0.0550	10023.7308	0.0193	15.9175	0.0261
n-Hexane	252.7338	0.1000	21780.0656	0.0420	32.8674	0.0538
C7s*	221.0252	0.0875	21286.9348	0.0411	30.2477	0.0495
C8s*	190.0533	0.0752	20907.7643	0.0404	28.8490	0.0472
C9s*	139.1297	0.0551	17065.6543	0.0329	22.7480	0.0372
C10s*	124.6926	0.0493	16708.8059	0.0323	21.4773	0.0352
C11s*	98.6689	0.0390	14504.3233	0.0280	18.3840	0.0301
C12s*	82.8223	0.0328	13334.3958	0.0257	16.6690	0.0273
C13s*	76.7775	0.0304	13436.0543	0.0259	16.5685	0.0271
C14s*	67.4454	0.0267	12814.6262	0.0247	15.5909	0.0255
C15s*	56.6669	0.0224	11673.3914	0.0225	14.0319	0.0230
C16s*	52.1394	0.0206	11574.9513	0.0223	13.7976	0.0226
C17s*	45.1439	0.0179	10699.1004	0.0207	12.6332	0.0207
C18s*	42.6956	0.0169	10716.6044	0.0207	12.5797	0.0206
C19s*	41.4901	0.0164	10911.8938	0.0211	12.7343	0.0208
C20s*	33.2773	0.0132	9151.2567	0.0177	10.6165	0.0174
C21s*	29.7523	0.0118	8657.9281	0.0167	9.9863	0.0163
C22s*	27.7679	0.0110	8469.2105	0.0163	9.7127	0.0159
C23s*	24.4162	0.0097	7764.3488	0.0150	8.8536	0.0145
C24s*	22.0564	0.0087	7300.6814	0.0141	8.2871	0.0136
C25s*	20.6543	0.0082	7125.7302	0.0138	8.0520	0.0132
C26s*	18.8761	0.0075	6776.5027	0.0131	7.6230	0.0125
C27s*	18.6708	0.0074	6982.8971	0.0135	7.8200	0.0128
C28s*	16.5165	0.0065	6408.4045	0.0124	7.1526	0.0117
C29s*	15.6616	0.0062	6295.9666	0.0122	7.0037	0.0115
C30L+*	284.1999	0.1125	207014.0696	0.3996	206.9647	0.3387
C30H+*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O	2.7349	0.0011	49.2694	0.0001	0.0494	0.0001
Argon	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Oxygen	0.0000	0.0000	0.0002	0.0000	0.0000	0.0000
Total	2527.0249	1.0000	518072.8178	1.0000	610.9672	1.0000

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aspentech	CHEVRON USA Burlington, MA USA	Case Name: PHD.HSC Unit Set: NewUser Date/Time: Mon Apr 06 10:13:05 2015

Material Stream: Feed From Well (continued)

Fluid Package: Main Basis
Property Package: Peng-Robinson

COMPOSITION

Aqueous Phase Phase Fraction 0.6145

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
Nitrogen	1.3103	0.0001	36.7058	0.0001	0.0455	0.0001
CO2	0.1260	0.0000	5.5469	0.0000	0.0067	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Methane	0.0006	0.0000	0.0101	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0002	0.0000	0.0000	0.0000
Propane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
i-Butane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
n-Butane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
i-Pentane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
n-Pentane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
n-Hexane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C7s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C8s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C9s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C10s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C11s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C12s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C13s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C14s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C15s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C16s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C17s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C18s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C19s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C20s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C21s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C22s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C23s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C24s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C25s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C26s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C27s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C28s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C29s*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C30L+*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C30H+*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O	17723.2110	0.9999	319285.4279	0.9999	319.9298	0.9998
Argon	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Oxygen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	17724.6480	1.0000	319327.6908	1.0000	319.9820	1.0000

K VALUE

COMPONENTS	MIXED	LIGHT	HEAVY
Nitrogen	302.0	38.91	8369
CO2	45.38	6.675	261.7
H2S	---	---	---
Methane	143.5	17.91	5.940e+006
Ethane	35.99	4.491	2.097e+008
Propane	12.19	1.521	1.988e+010
i-Butane	5.271	0.6577	5.301e+012

* Specified by user.

aspentech	CHEVRON USA Burlington, MA USA	Case Name:	PHD.HSC
		Unit Set:	NewUser
		Date/Time:	Mon Apr 06 10:13:05 2015

Material Stream: Feed From Well (continued)

Fluid Package: Main Basis
Property Package: Peng-Robinson

K VALUE

COMPONENTS	MIXED	LIGHT	HEAVY
n-Butane	4.066	0.5074	3.278e+012
i-Pentane	1.754	0.2189	1.179e+015
n-Pentane	1.398	0.1745	1.035e+015
n-Hexane	0.4868	6.074e-002	4.835e+017
C7s*	0.2142	2.673e-002	1.674e+020
C8s*	7.772e-002	9.698e-003	1.378e+023
C9s*	3.060e-002	3.819e-003	1.694e+025
C10s*	1.226e-002	1.530e-003	---
C11s*	5.478e-003	6.836e-004	---
C12s*	2.698e-003	3.366e-004	---
C13s*	1.386e-003	1.729e-004	---
C14s*	6.947e-004	8.668e-005	---
C15s*	2.727e-004	3.403e-005	---
C16s*	1.098e-004	1.370e-005	---
C17s*	4.592e-005	5.729e-006	---
C18s*	2.044e-005	2.551e-006	---
C19s*	1.027e-005	1.282e-006	---
C20s*	5.187e-006	6.472e-007	---
C21s*	2.127e-006	2.654e-007	---
C22s*	9.760e-007	1.218e-007	---
C23s*	4.725e-007	5.896e-008	---
C24s*	2.307e-007	2.879e-008	---
C25s*	1.067e-007	1.331e-008	---
C26s*	4.900e-008	6.115e-009	---
C27s*	2.115e-008	2.639e-009	---
C28s*	9.630e-009	1.202e-009	---
C29s*	4.314e-009	5.383e-010	---
C30L+*	2.411e-020	3.008e-021	---
C30H+*	---	---	---
H2O	8.657e-003	7.002	7.578e-003
Argon	---	---	---
Oxygen	174.8	21.98	1.917e+004

UNIT OPERATIONS

FEED TO		PRODUCT FROM		LOGICAL CONNECTION
Heat Exchanger:	Production Heater	Mixer:	MIX-101-2	

UTILITIES

(No utilities reference this stream)

PROCESS UTILITY

DYNAMICS

Pressure Specification	(Inactive): 12.05 bar						
Flow Specification	(Inactive)	Molar:	579.1 MMSCFD	Mass:	1.082e+006 kg/h	Std Ideal Liq Volume:	1344 m3/h

User Variables

NOTES

Description

* Specified by user.

aspentech	CHEVRON USA Burlington, MA USA	Case Name: PHD.HSC Unit Set: NewUser Date/Time: Mon Apr 06 10:13:05 2015

Material Stream: Feed From Well (continued)

Fluid Package: Main Basis
Property Package: Peng-Robinson

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Licensed to: CHEVRON USA * Specified by user.

Oil Production Separator Printouts

aspentech	CHEVRON USA Burlington, MA USA	Case Name:	PHD.HSC
		Unit Set:	NewUser
		Date/Time:	Mon Apr 06 10:33:51 2015

3 Phase Separator: Production Separator

CONNECTIONS

Inlet Stream

Stream Name	From Unit Operation	
100-0003	Heat Exchanger:	Production Heater
100-0052R	Recycle:	RCY-1

Outlet Stream

Stream Name	To Unit Operation	
100-0005	Valve:	VLV-114
100-0010	Valve:	VLV-100
100-0015	3 Phase Separator:	Production Hydrocyclones

Energy Stream

Stream Name	From Unit Operation

PARAMETERS

Vessel Volume:	---	Level SP:	50.00 %	Liquid Volume:	---		
Vessel Pressure:	8.598 bar	Pressure Drop:	0.0000 psi	Duty:	0.0000 kJ/h	Heat Transfer Mode:	Heating

User Variables

RATING

Sizing

Cylinder		Horizontal		Separator has a Boot:	Yes
Boot Diameter:	---	Boot Height:	---		
Volume:	---	Diameter:	---	Length:	---

Nozzles

Base Elevation Relative to Ground Level	0.0000 m *	Diameter	---	Length	---

		100-0003	100-0052R	100-0005
Diameter	(m)	5.000e-002	5.000e-002	5.000e-002
Elevation (Base)	(m)	0.0000	0.0000	0.0000
Elevation (Ground)	(m)	0.0000	0.0000	0.0000
Elevation (% of Height)	(%)	---	---	---

		100-0010	100-0015	
Diameter	(m)	5.000e-002	5.000e-002	
Elevation (Base)	(m)	0.0000	0.0000 *	
Elevation (Ground)	(m)	0.0000	0.0000	
Elevation (% of Height)	(%)	---	---	

Level Taps: Level Tap Specification

Level Tap	PV High	PV Low	OP High	OP Low

Level Taps: Calculated Level Tap Values

Level Tap	Liquid Level	Aqueous Level

Options

PV Work Term Contribution	(%)	100.00 *	

CONDITIONS

Name	100-0003	100-0052R	100-0010	100-0005	100-0015
Vapour	0.3459	0.0000	0.0000	1.0000	0.0000

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Licensed to: CHEVRON USA * Specified by user.

3 Phase Separator: Production Separator (continued)

CONDITIONS

Temperature	(C)	87.7778 *	86.8898 *	87.7241	87.7241	87.7241
Pressure	(bar)	8.5978	8.5978 *	8.5978	8.5978	8.5978
Molar Flow	(MMSCFD)	579.1055	74.0845 *	112.3008	200.2723	340.6168
Mass Flow	(kg/h)	1081822.4966	66562.7124	534916.9078	307397.7272	306070.5740
Std Ideal Liq Vol Flow	(m3/h)	1344.4302	66.7103	600.3517	504.0313	306.7574
Molar Enthalpy	(Btu/SCF)	-246.8	-318.8	-403.7	-63.03	-318.7
Molar Entropy	(kJ/kgmole-C)	140.4	68.46	263.5	166.8	68.65
Heat Flow	(kJ/h)	-6.2825e+09	-1.0383e+09	-1.9931e+09	-5.5494e+08	-4.7728e+09

PROPERTIES

Name		100-0003	100-0052R	100-0010	100-0005	100-0015
Molecular Weight		37.51	18.04	95.63	30.82	18.04
Molar Density	(kgmole/m3)	0.8211	53.16	8.765	0.2914	53.11
Mass Density	(kg/m3)	30.80	958.9	838.3	8.981	958.2
Act. Volume Flow	(m3/h)	3.513e+004	69.42	638.1	3.423e+004	319.4
Mass Enthalpy	(kJ/kg)	-5807	-1.560e+004	-3726	-1805	-1.559e+004
Mass Entropy	(kJ/kg-C)	3.743	3.795	2.755	5.411	3.805
Heat Capacity	(kJ/kgmole-C)	98.51	78.73	234.0	48.81	78.76
Mass Heat Capacity	(kJ/kg-C)	2.626	4.365	2.447	1.584	4.366
LHV Molar Basis (Std)	(Btu/SCF)	---	---	---	---	---
LHV Mass Basis (Std)	(kJ/kg)	---	---	---	---	---
Phase Fraction [Vol. Basis]		0.3750	0.0000	0.0000	1.000	0.0000
Phase Fraction [Mass Basis]		0.2842	0.0000	0.0000	1.000	0.0000
Partial Pressure of CO2	(bar)	1.426e-002	0.0000	0.0000	1.426e-002	0.0000
Cost Based on Flow	(Cost/s)	0.0000	0.0000	0.0000	0.0000	0.0000
Act. Gas Flow	(ACT_m3/h)	3.424e+004	---	---	3.423e+004	---
Avg. Liq. Density	(kgmole/m3)	21.45	55.31	9.317	19.79	55.30
Specific Heat	(kJ/kgmole-C)	98.51	78.73	234.0	48.81	78.76
Std. Gas Flow	(STD_m3/h)	6.820e+005	8.725e+004	1.323e+005	2.359e+005	4.011e+005
Std. Ideal Liq. Mass Density	(kg/m3)	804.7	997.8	891.0	609.9	997.8
Act. Liq. Flow	(m3/s)	0.2467	1.928e-002	0.1773	3.480e-006	8.873e-002
Z Factor		---	---	---	---	---
Watson K		10.59	11.44	11.65	10.44	11.13
User Property		---	---	---	---	---
Partial Pressure of H2S	(bar)	0.0000	0.0000	0.0000	0.0000	0.0000
Cp/(Cp - R)		1.092	1.118	1.037	1.205	1.118
Cp/Cv		1.034	1.172	1.136	1.231	1.172
Heat of Vap.	(Btu/SCF)	106.6	52.90	213.2	28.59	57.03
Kinematic Viscosity	(cSt)	---	0.3380	9.391	---	0.3350
Liq. Mass Density (Std. Cond)	(kg/m3)	796.5	1016	926.6	1.309	1016
Liq. Vol. Flow (Std. Cond)	(m3/h)	1358	65.56	577.3	2.348e+005	301.3
Liquid Fraction		0.6541	1.000	1.000	6.288e-006	1.000
Molar Volume	(m3/kgmole)	1.218	1.881e-002	0.1141	3.431	1.883e-002
Mass Heat of Vap.	(kJ/kg)	2508	2588	1968	818.9	2790
Phase Fraction [Molar Basis]		0.3459	0.0000	0.0000	1.0000	0.0000
Surface Tension	(dyne/cm)	---	---	---	---	---
Thermal Conductivity	(W/m-K)	---	0.6725	0.1331	3.020e-002	0.6729
Viscosity	(cP)	---	0.3241	7.872	1.641e-002	0.3210
Cv (Semi-Ideal)	(kJ/kgmole-C)	90.20	70.42	225.7	40.50	70.45
Mass Cv (Semi-Ideal)	(kJ/kg-C)	2.405	3.904	2.360	1.314	3.905
Cv	(kJ/kgmole-C)	95.29	67.20	205.9	39.66	67.22
Mass Cv	(kJ/kg-C)	2.541	3.725	2.153	1.287	3.726
Cv (Ent. Method)	(kJ/kgmole-C)	---	65.09	---	---	65.08
Mass Cv (Ent. Method)	(kJ/kg-C)	---	3.608	---	---	3.608

* Specified by user.

3 Phase Separator: Production Separator (continued)

PROPERTIES

Name		100-0003	100-0052R	100-0010	100-0005	100-0015
Cp/Cv (Ent. Method)		---	1.210	---	---	1.210
Reid VP at 37.8 C	(bar)	149.2	6.266	1.086	---	15.82
True VP at 37.8 C	(bar)	567.2	2.217	6.595	---	5.559
Liq. Vol. Flow - Sum(Std. Cond)	(m3/h)	2.357e+005	65.61	599.1	2.348e+005	301.7
Viscosity Index		-7.654	-18.94	15.99	-18.19	-19.25
HHV Molar Basis (Std)	(Btu/SCF)	---	---	---	---	---
HHV Mass Basis (Std)	(kJ/kg)	---	---	---	---	---
CO2 Loading		---	---	---	---	---
CO2 Apparent Mole Conc.	(kgmole/m3)	---	1.006e-004	3.695e-004	---	1.380e-004
CO2 Apparent Wt. Conc.	(kgmol/kg)	---	1.049e-007	4.408e-007	---	1.440e-007
Phase Fraction [Act. Vol. Basis]		0.9747	0.0000	0.0000	1.000	0.0000
Mass Exergy	(kJ/kg)	64.80	25.41	15.23	180.9	26.04

DYNAMICS

Vessel Parameters: Initialize from Product

Vessel Volume	(m3)	---	Level Calculator		Horizontal cylinder
Vessel Diameter	(m)	---	Fraction Calculator		Use levels and nozzles
Vessel Length	(m)	---	Feed Delta P	(psi)	0.0000
Liquid Level Percent	(%)	50.00	Vessel Pressure	(bar)	8.598

Holdup: Vessel Levels

Phase	Level (m)	Percent (%)	Volume (m3)
Vapour	---	---	0.0000
Liquid	---	---	0.0000
Aqueous	---	---	0.0000

Holdup: Details

Phase	Accumulation (MMSCFD)	Moles (kgmole)	Volume (m3)
Vapour	0.0000	0.0000 *	0.0000
Liquid	0.0000	0.0000 *	0.0000
Aqueous	0.0000	0.0000 *	0.0000
Total	**0.0000**	**0.0000**	**0.0000**

NOTES

Carry Over Calculation - Feed Fraction Basis

	Carry Over as Fraction of Feed
Light liquid in gas	0.0000
Heavy liquid in gas	0.0000
Gas in light liquid	0.0000
Heavy liquid in light liquid	0.1800 *
Gas in heavy liquid	0.0000
Light liquid in heavy liquid	0.0010 *
Carry Over to Zero Flow Streams: No	

Carry Over Calculation - Results Summary

	Feed Fraction	Product Fraction	Product Flow (MMSCFD)	Mass Per Volume (kg/m3)
Light liquid in gas	0.0000	0.0000	0.0000	0.0000

* Specified by user.

CHEVRON USA Burlington, MA USA	Case Name:	PHD.HSC
	Unit Set:	NewUser
	Date/Time:	Mon Apr 06 10:33:51 2015

3 Phase Separator: Production Separator (continued)

	Feed Fraction	Product Fraction	Product Flow (MMSCFD)	Mass Per Volume (kg/m3)
Heavy liquid in gas	0.0000	0.0000	0.0000	0.0000
Gas in light liquid	0.0000	0.0000	0.0000	0.0000
Heavy liquid in light liquid	0.1800	0.6657	74.76	105.1
Gas in heavy liquid	0.0000	0.0000	0.0000	0.0000
Light liquid in heavy liquid	0.0010	0.0001	3.758e-002	1.466
Total liquid in gas	0.0000	0.0000	0.0000	0.0000

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Export Oil Pumps Printouts

aspentech	CHEVRON USA Burlington, MA USA	Case Name: PHD.HSC Unit Set: NewUser Date/Time: Mon Apr 06 10:43:12 2015

Pump: Export Oil Pumps

CONNECTIONS

Inlet Stream

Stream Name	From Unit Operation	
100-0071	Mixer	MIX-112

Outlet Stream

Stream Name	To Unit Operation	
100-0072	Tee	TEE-102

Energy Stream

Stream Name	From Unit Operation
Q-P102	

PARAMETERS

Adiabatic Efficiency (%):	75.00 *	Delta P:	4145 psi	Duty:	6532 kW

CURVES

Delta P:	4145 psi	Duty:	6532 kW		
Coefficient A:	0.0000 *	Coefficient B:	0.0000 *	Coefficient C:	0.0000 *
Parameter Preferences	Units for Delta P: ft	Flow Basis	ActVolFlow	Units for Flow:	barrel/day

User Variables

RATING

Head Offset:	0.0000 m	Efficiency Offset:	0.0000

Characteristic Curves

Speed:		
Flow	Head	Efficiency (%)

NPSH

NPSH Required	---	NPSH Available	434.2 m	Enable NPSH Curves:	No

NPSH Curves		

Nozzle Paramaters

Base Elevation Relative to Ground Level 0.0000 m *

		100-0071	100-0072	
Diameter	(m)	5.000e-002	5.000e-002	
Elevation (Base)	(m)	0.0000	0.0000	
Elevation (Ground)	(m)	0.0000	0.0000	

Inertia

Rotational inertia (kg-m2)	0.5000	Radius of gyration (m)	0.1000	Mass (kg)	50.00	Friction loss factor (kg-m2/s)	5.000e-002

Start Up

Design Flow Typical Operating Capacity 10.00 m3/h

CONDITIONS

Name		100-0071	100-0072	Q-P102	
Vapour		0.0000	0.0000	---	
Temperature	(C)	42.8979	43.3890	---	
Pressure	(bar)	4.8263	290.5931	---	
Molar Flow	(MMSCFD)	41.8242	41.8242	---	

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* Specified by user.

aspentech	CHEVRON USA USA	Case Name:	PHD.HSC
		Unit Set:	NewUser
		Date/Time:	Mon Apr 06 10:43:12 2015

Pump: Export Oil Pumps (continued)

CONDITIONS

Mass Flow	(kg/h)	529938.8636	529938.8636	---	
Std Ideal Liq Vol Flow	(m3/h)	602.2258	602.2258	---	
Molar Enthalpy	(Btu/SCF)	-612.3	-599.5	---	
Molar Entropy	(kJ/kgmole-C)	590.4	587.3	---	
Heat Flow	(kJ/h)	-1.1259e+09	-1.1023e+09	2.3516e+07	

PROPERTIES

Name		100-0071	100-0072			
Molecular Weight		254.4	254.4			
Molar Density	(kgmole/m3)	3.375	3.470			
Mass Density	(kg/m3)	858.6	882.8			
Act. Volume Flow	(m3/h)	617.2	600.3			
Mass Enthalpy	(kJ/kg)	-2125	-2080			
Mass Entropy	(kJ/kg-C)	2.321	2.308			
Heat Capacity	(kJ/kgmole-C)	505.9	502.2			
Mass Heat Capacity	(kJ/kg-C)	1.989	1.974			
LHV Molar Basis (Std)	(Btu/SCF)	---	---			
LHV Mass Basis (Std)	(kJ/kg)	---	---			
Phase Fraction [Vol. Basis]		0.0000	0.0000			
Phase Fraction [Mass Basis]		0.0000	0.0000			
Partial Pressure of CO2	(bar)	0.0000	0.0000			
Cost Based on Flow	(Cost/s)	0.0000	0.0000			
Act. Gas Flow	(ACT_m3/h)	---	---			
Avg. Liq. Density	(kgmole/m3)	3.459	3.459			
Specific Heat	(kJ/kgmole-C)	505.9	502.2			
Std. Gas Flow	(STD_m3/h)	4.925e+004	4.925e+004			
Std. Ideal Liq. Mass Density	(kg/m3)	880.0	880.0			
Act. Liq. Flow	(m3/s)	0.1714	0.1667			
Z Factor		---	---			
Watson K		11.67	11.67			
User Property		---	---			
Partial Pressure of H2S	(bar)	0.0000	0.0000			
Cp/(Cp - R)		1.017	1.017			
Cp/Cv		1.139	1.156			
Heat of Vap.	(Btu/SCF)	511.6	---			
Kinematic Viscosity	(cSt)	12.61	12.78			
Liq. Mass Density (Std. Cond)	(kg/m3)	878.6	878.6			
Liq. Vol. Flow (Std. Cond)	(m3/h)	603.2	603.2			
Liquid Fraction		1.000	1.000			
Molar Volume	(m3/kgmole)	0.2963	0.2882			
Mass Heat of Vap.	(kJ/kg)	1775	-128.8			
Phase Fraction [Molar Basis]		0.0000	0.0000			
Surface Tension	(dyne/cm)	---	---			
Thermal Conductivity	(W/m-K)	0.1182	0.1180			
Viscosity	(cP)	10.83	11.28			
Cv (Semi-Ideal)	(kJ/kgmole-C)	497.6	493.9			
Mass Cv (Semi-Ideal)	(kJ/kg-C)	1.956	1.942			
Cv	(kJ/kgmole-C)	444.1	434.6			
Mass Cv	(kJ/kg-C)	1.746	1.708			
Cv (Ent. Method)	(kJ/kgmole-C)	---	---			
Mass Cv (Ent. Method)	(kJ/kg-C)	---	---			
Cp/Cv (Ent. Method)		---	---			
Reid VP at 37.8 C	(bar)	0.3533	0.3533			
True VP at 37.8 C	(bar)	0.9133	0.9133			

* Specified by user.

aspentech	CHEVRON USA Burlington, MA USA	Case Name:	PHD.HSC
		Unit Set:	NewUser
		Date/Time:	Mon Apr 06 10:43:12 2015

Pump: Export Oil Pumps (continued)

PROPERTIES

Name	100-0071	100-0072			
Liq. Vol. Flow - Sum(Std. Cond) (m3/h)	603.1	603.1			
Viscosity Index	24.80	24.87			
HHV Molar Basis (Std) (Btu/SCF)	---	---			
HHV Mass Basis (Std) (kJ/kg)	---	---			
CO2 Loading	---	---			
CO2 Apparent Mole Conc. (kgmole/m3)	1.235e-004	1.270e-004			
CO2 Apparent Wt. Conc. (kgmol/kg)	1.439e-007	1.439e-007			
Phase Fraction [Act. Vol. Basis]	0.0000	0.0000			
Mass Exergy (kJ/kg)	1.663	49.67			

PERFORMANCE

Results

Total Head	---	Velocity Head	-21.02 m *
Total Fluid Head	---	Delta P excluding Static Head Results	---
Pressure Head	3394 m *		

DYNAMICS

Dynamic Specifications

Head (m)	---	Not Active	Power (kJ/h)	2.352e+007	Not Active
Fluid Head (kJ/kg)	---	Not Active	Capacity (m3/h)	602.2	
Adiabatic Efficiency (rpm)	---	Not Active	Use Characteristic Curves		Not Active
Polytropic Efficiency (%)	75.00 *	Active	Pump is Acting as a Turbine		Not Active
Pressure Increase (psi)	4145	Active			

Holdup Details

Phase	Accumulation (MMSCFD)	Moles (kgmole)	Volume (m3)
Vapour	0.0000	0.0000 *	0.0000
Liquid	0.0000	0.0000 *	0.0000
Aqueous	0.0000	0.0000 *	0.0000
Total	**0.0000**	**0.0000**	**0.0000**

NOTES

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Gas Dehydration Tower Printouts

aspentech	CHEVRON USA Burlington, MA USA	Case Name:	PHD.HSC
		Unit Set:	NewUser
		Date/Time:	Mon Apr 06 10:51:03 2015

Component Splitter: Gas Dehydration

CONNECTIONS

Inlet Stream

STREAM NAME	FROM UNIT OPERATION	
400-0050	Separator	Dehy. inlet Drum

Outlet Stream

STREAM NAME	TO UNIT OPERATION	
from Dehy	Valve:	VLV-113
500-0550		

Energy Stream

STREAM NAME	FROM UNIT OPERATION

PARAMETERS

Stream Specifications

Overhead Pressure:	76.12 bar	Overhead Vapour Fraction:	1.0000
Bottoms Pressure:	76.12 bar	Bottoms Vapour Fraction:	0.0000

SPLITS

Component Fraction To Overhead

Component	Split Basis	Split Type	from Dehy		
Nitrogen	Molar	FeedFrac. to Products	1.000 *		
CO2	Molar	FeedFrac. to Products	1.000 *		
H2S	Molar	FeedFrac. to Products	1.000 *		
Methane	Molar	FeedFrac. to Products	1.000 *		
Ethane	Molar	FeedFrac. to Products	1.000 *		
Propane	Molar	FeedFrac. to Products	1.000 *		
i-Butane	Molar	FeedFrac. to Products	1.000 *		
n-Butane	Molar	FeedFrac. to Products	1.000 *		
i-Pentane	Molar	FeedFrac. to Products	1.000 *		
n-Pentane	Molar	FeedFrac. to Products	1.000 *		
n-Hexane	Molar	FeedFrac. to Products	1.000 *		
C7s*	Molar	FeedFrac. to Products	0.0000 *		
C8s*	Molar	FeedFrac. to Products	0.0000 *		
C9s*	Molar	FeedFrac. to Products	0.0000 *		
C10s*	Molar	FeedFrac. to Products	0.0000 *		
C11s*	Molar	FeedFrac. to Products	0.0000 *		
C12s*	Molar	FeedFrac. to Products	0.0000 *		
C13s*	Molar	FeedFrac. to Products	0.0000 *		
C14s*	Molar	FeedFrac. to Products	0.0000 *		
C15s*	Molar	FeedFrac. to Products	0.0000 *		
C16s*	Molar	FeedFrac. to Products	0.0000 *		
C17s*	Molar	FeedFrac. to Products	0.0000 *		
C18s*	Molar	FeedFrac. to Products	0.0000 *		
C19s*	Molar	FeedFrac. to Products	0.0000 *		
C20s*	Molar	FeedFrac. to Products	0.0000 *		
C21s*	Molar	FeedFrac. to Products	0.0000 *		
C22s*	Molar	FeedFrac. to Products	0.0000 *		
C23s*	Molar	FeedFrac. to Products	0.0000 *		
C24s*	Molar	FeedFrac. to Products	0.0000 *		
C25s*	Molar	FeedFrac. to Products	0.0000 *		

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Component Splitter: Gas Dehydration (continued)

SPLITS

Component	Split Basis	Split Type	from Dehy		
C26s*	Molar	FeedFrac. to Products	0.0000 *		
C27s*	Molar	FeedFrac. to Products	0.0000 *		
C28s*	Molar	FeedFrac. to Products	0.0000 *		
C29s*	Molar	FeedFrac. to Products	0.0000 *		
C30L+*	Molar	FeedFrac. to Products	0.0000 *		
C30H+*	Molar	FeedFrac. to Products	0.0000 *		
H2O	Molar	FeedFrac. to Products	1.000e-002 *		
Argon	Molar	FeedFrac. to Products	1.000 *		
Oxygen	Molar	FeedFrac. to Products	1.000 *		

User Variables

NOZZLE PARAMETERS

Base Elevation Relative to Ground Level 0.0000 m *

		400-0050	500-0550	from Dehy
Diameter	(m)	5.000e-002	5.000e-002	5.000e-002
Elevation (Base)	(m)	0.0000	0.0000	0.0000
Elevation (Ground)	(m)	0.0000	0.0000	0.0000

CONDITIONS

Name		400-0050	from Dehy	500-0550	
Vapour		1.0000	1.0000	0.0000	
Temperature	(C)	46.0951	48.3367	48.3360	
Pressure	(bar)	76.1181	76.1181	76.1181	
Molar Flow	(MMSCFD)	175.3013	174.7714	0.5299	
Mass Flow	(kg/h)	249527.6765	248741.4386	786.2379	
Std Ideal Liq Vol Flow	(m3/h)	425.1859	424.2390	0.9469	
Molar Enthalpy	(Btu/SCF)	-41.03	-40.22	-308.9	
Molar Entropy	(kJ/kgmole-C)	133.0	133.1	82.54	
Heat Flow	(kJ/h)	-3.1621e+08	-3.0901e+08	-7.1959e+06	

PROPERTIES

Name		400-0050	from Dehy	500-0550		
Molecular Weight		28.58	28.58	29.79		
Molar Density	(kgmole/m3)	3.178	3.140	27.33		
Mass Density	(kg/m3)	90.84	89.72	814.2		
Act. Volume Flow	(m3/h)	2747	2772	0.9657		
Mass Enthalpy	(kJ/kg)	-1267	-1242	-9152		
Mass Entropy	(kJ/kg-C)	4.653	4.657	2.771		
Heat Capacity	(kJ/kgmole-C)	48.14	47.92	98.14		
Mass Heat Capacity	(kJ/kg-C)	1.685	1.677	3.294		
LHV Molar Basis (Std)	(Btu/SCF)	---	604.9	---		
LHV Mass Basis (Std)	(kJ/kg)	---	1.868e+004	---		
Phase Fraction [Vol. Basis]		1.000	1.000	0.0000		
Phase Fraction [Mass Basis]		1.000	1.000	0.0000		
Partial Pressure of CO2	(bar)	0.1449	0.1454	0.0000		
Cost Based on Flow	(Cost/s)	0.0000	0.0000	0.0000		
Act. Gas Flow	(ACT_m3/h)	2747	2772	---		
Avg. Liq. Density	(kgmole/m3)	20.54	20.52	27.87		
Specific Heat	(kJ/kgmole-C)	48.14	47.92	98.14		
Std. Gas Flow	(STD_m3/h)	2.064e+005	2.058e+005	624.1		
Std. Ideal Liq. Mass Density	(kg/m3)	586.9	586.3	830.4		
Act. Liq. Flow	(m3/s)	4.732e-006	---	2.682e-004		

* Specified by user.

Component Splitter: Gas Dehydration (continued)

PROPERTIES

Name		400-0050	from Dehy	500-0550
Z Factor		---	0.9070	---
Watson K		10.18	10.18	12.34
User Property		---	---	---
Partial Pressure of H2S	(bar)	0.0000	0.0000	0.0000
Cp/(Cp - R)		1.209	1.210	1.093
Cp/Cv		1.470	1.460	1.140
Heat of Vap.	(Btu/SCF)	14.00	13.96	30.95
Kinematic Viscosity	(cSt)	---	0.2020	1.784
Liq. Mass Density (Std. Cond)	(kg/m3)	1.212	1.212	889.2
Liq. Vol. Flow (Std. Cond)	(m3/h)	2.059e+005	2.053e+005	0.8842
Liquid Fraction		1.975e-005	0.0000	1.000
Molar Volume	(m3/kgmole)	0.3146	0.3185	3.659e-002
Mass Heat of Vap.	(kJ/kg)	432.5	431.3	917.1
Phase Fraction [Molar Basis]		1.0000	1.0000	0.0000
Surface Tension	(dyne/cm)	---	---	---
Thermal Conductivity	(W/m-K)	3.301e-002	3.314e-002	0.2392
Viscosity	(cP)	1.805e-002	1.812e-002	1.453
Cv (Semi-Ideal)	(kJ/kgmole-C)	39.83	39.61	89.82
Mass Cv (Semi-Ideal)	(kJ/kg-C)	1.394	1.386	3.015
Cv	(kJ/kgmole-C)	32.76	32.82	86.06
Mass Cv	(kJ/kg-C)	1.146	1.149	2.889
Cv (Ent. Method)	(kJ/kgmole-C)	---	---	---
Mass Cv (Ent. Method)	(kJ/kg-C)	---	---	---
Cp/Cv (Ent. Method)		---	---	---
Reid VP at 37.8 C	(bar)	---	---	0.1389
True VP at 37.8 C	(bar)	---	---	0.2037
Liq. Vol. Flow - Sum(Std. Cond)	(m3/h)	2.059e+005	2.053e+005	0.9397
Viscosity Index		---	---	-3.569
HHV Molar Basis (Std)	(Btu/SCF)	---	657.4	---
HHV Mass Basis (Std)	(kJ/kg)	---	2.031e+004	---
CO2 Loading		---	---	---
CO2 Apparent Mole Conc.	(kgmole/m3)	---	---	0.0000
CO2 Apparent Wt. Conc.	(kgmol/kg)	---	---	0.0000
Phase Fraction [Act. Vol. Basis]		1.000	1.000	0.0000
Mass Exergy	(kJ/kg)	362.9	363.4	12.92

DYNAMICS

Pressure Specification

Attached Streams	Pressure	Active
400-0050	76.12 bar	No
from Dehy	76.12 bar	No
500-0550	76.12 bar	No

Comp. Splitter Vessel Volume: 0.0000 m3 *

IGC 3rd Stage Compressor Printouts

aspentech	CHEVRON USA Burlington, MA USA	Case Name:	PHD.HSC
		Unit Set:	NewUser
		Date/Time:	Mon Apr 06 10:55:10 2015

Compressor: IGC 3rd stage Compressor

DESIGN

Connections

Inlet Stream

STREAM NAME	FROM UNIT OPERATION	
900-0040	Separator	IGC 3rd Stage Suction Drum

Outlet Stream

STREAM NAME	TO UNIT OPERATION	
Injection Wells	Heater	IGC 3rd stage cooler

Energy Stream

STREAM NAME	FROM UNIT OPERATION
Q-K95	

Parameters

Speed:	---	Duty:	1.9459e+04 kW
Adiabatic Eff.:	75.00	PolyTropic Eff.:	76.65
Adiabatic Head:	1.516e+004 m	Polytropic Head:	1.549e+004 m
Adiabatic Fluid Head:	148.7 kJ/kg	Polytropic Fluid Head:	151.9 kJ/kg

Polytropic Exp.	5.523	Isentropic Exp.	4.346	Poly Head Factor	0.9977

User Variables

RATING

Curves

Compressor Speed: ---	Efficiency:	Adiabatic	Curves Enabled: Yes
Head Offset:	0.0000 m	Efficiency Offset:	0.0000

Speed:

Flow	Head	Efficiency (%)

Flow Limits

Surge Curve: Inactive

Speed	Flow	Speed	Flow	Speed	Flow

Stone Wall Curve: Inactive

Speed	Flow	Speed	Flow	Speed	Flow

Surge Flow Rate	---	Field Flow Rate	765.2 ACT_m3/h	Stone Wall Flow	---	Compressor Volume	0.0000 m3

Nozzle Paramaters

Base Elevation Relative to Ground Level 0.0000 m *

		900-0040	Injection Wells	
Diameter	(m)	5.000e-002	5.000e-002	
Elevation (Base)	(m)	0.0000	0.0000	
Elevation (Ground)	(m)	0.0000	0.0000	

Inertia

Rotational inertia (kg-m2)	6.000	Radius of gyration (m)	0.2000
Mass (kg)	150.0	Friction loss factor (rad/min) (kg-m2/s)	6.000e-003

WORKSHEET

Conditions

Name	900-0040	Injection Wells	Q-K95

Aspen Technology Inc. Aspen HYSYS Version 8.2 (28.0.1.8215) Page 1 of 3

Licensed to: CHEVRON USA * Specified by user.

Compressor: IGC 3rd stage Compressor (continued)

Conditions

Vapour		1.0000	1.0000	---	
Temperature	(C)	37.7778	120.5698	---	
Pressure	(bar)	620.5283	1383.4125 *	---	
Molar Flow	(MMSCFD)	249.7714	249.7714	---	
Mass Flow	(kg/h)	353385.2074	353385.2074	---	
Std Ideal Liq Vol Flow	(m3/h)	554.0098	554.0098	---	
Molar Enthalpy	(Btu/SCF)	-30.18	-23.80	---	
Molar Entropy	(kJ/kgmole-C)	141.9	145.6	---	
Heat Flow	(kJ/h)	-3.3133e+08	-2.6128e+08	7.0052e+07	

Properties

Name		900-0040	Injection Wells			
Molecular Weight		28.41	28.41			
Molar Density	(kgmole/m3)	16.26	18.80			
Mass Density	(kg/m3)	461.8	533.9			
Act. Volume Flow	(m3/h)	765.2	661.8			
Mass Enthalpy	(kJ/kg)	-937.6	-739.4			
Mass Entropy	(kJ/kg-C)	4.995	5.126			
Heat Capacity	(kJ/kgmole-C)	49.51	47.80			
Mass Heat Capacity	(kJ/kg-C)	1.743	1.683			
LHV Molar Basis (Std)	(Btu/SCF)	423.2	423.2			
LHV Mass Basis (Std)	(kJ/kg)	1.315e+004	1.315e+004			
Phase Fraction [Vol. Basis]		1.000	1.000			
Phase Fraction [Mass Basis]		1.000	1.000			
Partial Pressure of CO2	(bar)	0.8292	1.849			
Cost Based on Flow	(Cost/s)	0.0000	0.0000			
Act. Gas Flow	(ACT_m3/h)	765.2	661.8			
Avg. Liq. Density	(kgmole/m3)	22.46	22.46			
Specific Heat	(kJ/kgmole-C)	49.51	47.80			
Std. Gas Flow	(STD_m3/h)	2.941e+005	2.941e+005			
Std. Ideal Liq. Mass Density	(kg/m3)	637.9	637.9			
Act. Liq. Flow	(m3/s)	---	---			
Z Factor		---	2.248			
Watson K		9.044	9.044			
User Property		---	---			
Partial Pressure of H2S	(bar)	0.0000	0.0000			
Cp/(Cp - R)		1.202	1.211			
Cp/Cv		1.613	1.446			
Heat of Vap.	(Btu/SCF)	---	7.068			
Kinematic Viscosity	(cSt)	9.980e-002	0.1078			
Liq. Mass Density (Std. Cond)	(kg/m3)	60.55	60.55			
Liq. Vol. Flow (Std. Cond)	(m3/h)	5836	5836			
Liquid Fraction		0.0000	0.0000			
Molar Volume	(m3/kgmole)	6.151e-002	5.320e-002			
Mass Heat of Vap.	(kJ/kg)	-1154	219.6			
Phase Fraction [Molar Basis]		1.0000	1.0000			
Surface Tension	(dyne/cm)	---	---			
Thermal Conductivity	(W/m-K)	7.805e-002	0.1003			
Viscosity	(cP)	4.609e-002	5.755e-002			
Cv (Semi-Ideal)	(kJ/kgmole-C)	41.20	39.49			
Mass Cv (Semi-Ideal)	(kJ/kg-C)	1.450	1.390			
Cv	(kJ/kgmole-C)	30.70	33.05			
Mass Cv	(kJ/kg-C)	1.081	1.164			
Cv (Ent. Method)	(kJ/kgmole-C)	30.71	31.77			

* Specified by user.

CHEVRON USA
Burlington, MA
USA

Case Name:	PHD.HSC
Unit Set:	NewUser
Date/Time:	Mon Apr 06 10:55:10 2015

Compressor: IGC 3rd stage Compressor (continued)

Properties

Name		900-0040	Injection Wells			
Mass Cv (Ent. Method)	(kJ/kg-C)	1.081	1.118			
Cp/Cv (Ent. Method)		1.613	1.505			
Reid VP at 37.8 C	(bar)	---	---			
True VP at 37.8 C	(bar)	9.934	9.934			
Liq. Vol. Flow - Sum(Std. Cond)	(m3/h)	5836	5836			
Viscosity Index		---	---			
HHV Molar Basis (Std)	(Btu/SCF)	460.0	460.0			
HHV Mass Basis (Std)	(kJ/kg)	1.429e+004	1.429e+004			
CO2 Loading		---	---			
CO2 Apparent Mole Conc	(kgmole/m3)	---	---			
CO2 Apparent Wt. Conc.	(kgmol/kg)	---	---			
Phase Fraction [Act. Vol. Basis]		1.000	1.000			
Mass Exergy	(kJ/kg)	560.6	719.9			

PERFORMANCE

Results

Adiabatic Head	(m)	1.516e+004	Power Consumed	(kW)	1.946e+004
Polytropic Head	(m)	1.549e+004	Polytropic Head Factor		0.9977
Adiabatic Fluid Head	(kJ/kg)	148.7	Polytropic Exponent		5.523
Polytropic Fluid Head	(kJ/kg)	151.9	Isentropic Exponent		4.346
Adiabatic Efficiency		75	Speed	(rpm)	---
Polytropic Efficiency		77			---

Power/Torque

Total Rotor Power	(kW)	1.946e+004	Total Rotor Torque	(N-m)	---
Transient Rotor Power	(kW)	0.0000	Transient Rotor Torque	(N-m)	---
Friction Power Loss	(kW)	0.0000	Friction Torque Loss	(N-m)	---
Fluid Power	(kW)	1.946e+004	Fluid Torque	(N-m)	---

DYNAMICS

Dynamic Specifications

Duty	(kJ/h)	7.005e+007	Active	Head	(m)	1.549e+004	Not Active
Adiabatic Efficiency		75	Not Active	Fluid Head	(kJ/kg)	151.9	Not Active
Polytropic Efficiency		77	Active	Capacity	(ACT_m3/h)	765.2	Not Active
Pressure Increase	(psi)	1.106e+004	Not Active	Speed	(rpm)	---	Not Active
		---		Use Characteristic Curves			No

Holdup Details

Phase	Accumulation (MMSCFD)	Moles (kgmole)	Volume (m3)
Vapour	0.0000	0.0000 *	0.0000
Liquid	0.0000	0.0000 *	0.0000
Aqueous	0.0000	0.0000 *	0.0000
Total	**0.0000**	**0.0000**	**0.0000**

NOTES

* Specified by user.

IGC 2nd Stage Discharge Cooler Heat Exchanger Printouts

aspentech	CHEVRON USA Burlington, MA USA	Case Name: PHD.HSC Unit Set: NewUser Date/Time: Mon Apr 06 13:20:34 2015

Heat Exchanger: IGC 2nd Stage Discharge Cooler

CONNECTIONS

Tube Side				Shell Side			
Inlet		Outlet		Inlet		Outlet	
Name	900-0030	Name	900-0035	Name	CW in 11	Name	CW out 11
From Op.	2nd Stage Compressor	To Op.	rd Stage Suction Drum	From Op.		To Op.	
Op. Type	Compressor	Op. Type	Separator	Op. Type		Op. Type	
Temp	144.09 C	Temp	37.78 C *	Temp	32.22 C *	Temp	40.56 C *

PARAMETERS

Heat Exchanger Model:	Simple Weighted				
Tube Side DeltaP:	5.000 psi *	Shell Side DeltaP:	5.000 psi *	UA:	1.954e+006 kJ/C-h
Heat Leak/Loss:	None	Tolerance:	1.0000e-04		

Individual Heat Curve Details

Pass Name	900-0030-900-0035	CW_in_11-CW_out_11		
Intervals	5 *	5 *		
Dew/Bubble Pt.	Enabled	Enabled		
Step Type	Equal Enthalpy	Equal Enthalpy		
Pressure Profile	Const dPdH	Const dPdH		

Tube Side Data		Shell Side Data	
Heat Transfer Coeff	---	Heat Transfer Coeff	---
Tube Pressure Drop	5.00 psi *	Shell Pressure Drop	5.00 psi *
Fouling	0.00000 C-h-m2/kJ	Fouling	0.00000 C-h-m2/kJ
Tube Length	6.00 m	Shell Passes	1
Tube O.D.	20.00 mm	Shell Series	1
Tube Thickness	2.0000 mm	Shell Parallel	1
Tube Pitch	50.0000 mm	Baffle Type	Single
Orientation	Horizontal	Baffle Cut(%Area)	20.00
Passes Per Shell	2	Baffle Orientation	Horizontal
Tubes Per Shell	160 *	Spacing	800.0000 mm
Layout Angle	Triangular (30 degrees)	Diameter	739.0488 mm
TEMA Type	A E L	Area	60.32 m2

SPECS

	Spec Value	Curr Value	Rel Error	Active	Estimate
E-100 Heat Balance	0.0000 kJ/h	-2.184e-002 kJ/h	-3.338e-010	On	Off
E-100 UA	---	1.954e+006 kJ/C-h	---	On	Off

Detailed Specifications

E-100 Heat Balance		
Type: Duty	Pass: Error	Spec Value: 0.0000 kJ/h
E-100 UA		
Type: UA	Pass: Overall	Spec Value: ---

User Variables

RATING

Sizing

Overall Data

Configuration					
# of Shells in Series	1	Tube Passes per Shell	2	Elevation (Base)	0.0000 m
# of Shells in Parallel	1	Exchanger Orientation	Horizontal	First Tube Pass Flow Direction	Counter

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aspentech	CHEVRON USA USA	Case Name:	PHD.HSC
		Unit Set:	NewUser
		Date/Time:	Mon Apr 06 13:20:34 2015

Heat Exchanger: IGC 2nd Stage Discharge Cooler (continued)

TEMA Type:	A	E	L

Calculated Information

Shell HT Coeff	---	Tube HT Coeff	---
Overall U	3.239e+004 kJ/h-m2-C	Overall UA	1.954e+006 kJ/C-h
Shell DP	5.000 psi *	Tube DP	5.000 psi *
Shell Vol per Shell	2.272 m3	Tube Vol per Shell	0.1930 m3
HT Area per Shell	60.32 m2		

Shell Data

Shell and Tube Bundle

Shell Diameter (mm)	739.0	Tube Pitch (mm)	50.00	Shell Fouling (C-h-m2/kJ)	0.0000
# of Tubes per Shell	160 *	Tube Layout Angle		Triangular (30 degrees)	

Shell Baffles

Shell Baffle Type	Single	Shell Baffle Orientation	Horizontal
Baffle Cut (%Area)	20.00	Baffle Spacing	800.0 mm

Tube Data

Dimensions

OD (mm)	20.00	ID (mm)	16.00	Tube Thickness (mm)	2.000	Tube Length (m)	6.000

Tube Properties

Tube Fouling (C-h-m2/kJ)	0.0000	Thermal Cond. (W/m-K)	45.00	Wall Cp (kJ/kg-C)	---	Wall Density (kg/m3)	---

Nozzle Parameters

Base Elevation Relative to Ground Level 0.0000 m

		900-0030	CW_in_11	900-0035
Diameter	(m)	5.000e-002	5.000e-002	5.000e-002
Elevation (Base)	(m)	0.0000	0.0000	0.0000
Elevation (Ground)	(m)	0.0000	0.0000	0.0000
Elevation (% of Height)	(%)	0.00	0.00	0.00
		CW_out_11		
Diameter	(m)	5.000e-002		
Elevation (Base)	(m)	0.0000		
Elevation (Ground)	(m)	0.0000		
Elevation (% of Height)	(%)	0.00		

CONDITIONS

Name		900-0030	CW_in_11	900-0035	CW_out_11
Vapour		1.0000	0.0000	1.0000	0.0000
Temperature	(C)	144.0920	32.2222 *	37.7778 *	40.5556 *
Pressure	(bar)	620.8731 *	4.4606 *	620.5283	4.1159
Molar Flow	(MMSCFD)	249.7714	2030.1648	249.7714	2030.1648
Mass Flow	(kg/h)	353385.2074	1821625.4277	353385.2074	1821625.4277
Std Ideal Liq Vol Flow	(m3/h)	554.0098	1825.3015	554.0098	1825.3015
Molar Enthalpy	(Btu/SCF)	-24.22	-323.6	-30.18	-322.9
Molar Entropy	(kJ/kgmole-C)	156.4	55.56	141.9	57.65
Heat Flow	(kJ/h)	-2.6590e+08	-2.8884e+10	-3.3133e+08	-2.8819e+10

PROPERTIES

Name		900-0030	CW_in_11	900-0035	CW_out_11	
Molecular Weight		28.41	18.02	28.41	18.02	
Molar Density	(kgmole/m3)	12.68	55.62	16.26	55.27	
Mass Density	(kg/m3)	360.1	1002	461.8	995.6	
Act. Volume Flow	(m3/h)	981.2	1818	765.2	1830	
Mass Enthalpy	(kJ/kg)	-752.4	-1.586e+004	-937.6	-1.582e+004	
Mass Entropy	(kJ/kg-C)	5.507	3.084	4.995	3.200	

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* Specified by user.

aspentech	CHEVRON USA Burlington, MA USA	Case Name: PHD.HSC Unit Set: NewUser Date/Time: Mon Apr 06 13:20:34 2015

Heat Exchanger: IGC 2nd Stage Discharge Cooler (continued)

PROPERTIES

Name		900-0030	CW_in_11	900-0035	CW_out_11	
Heat Capacity	(kJ/kgmole-C)	49.44	77.70	49.51	77.75	
Mass Heat Capacity	(kJ/kg-C)	1.741	4.313	1.743	4.316	
LHV Molar Basis (Std)	(Btu/SCF)	423.2	0.0000	423.2	0.0000	
LHV Mass Basis (Std)	(kJ/kg)	1.315e+004	---	1.315e+004	---	
Phase Fraction [Vol. Basis]		1.000	0.0000	1.000	0.0000	
Phase Fraction [Mass Basis]		1.000	0.0000	1.000	0.0000	
Partial Pressure of CO2	(bar)	0.8297	0.0000	0.8292	0.0000	
Cost Based on Flow	(Cost/s)	0.0000	0.0000	0.0000	0.0000	
Act. Gas Flow	(ACT_m3/h)	981.2	---	765.2	---	
Avg. Liq. Density	(kgmole/m3)	22.46	55.40	22.46	55.40	
Specific Heat	(kJ/kgmole-C)	49.44	77.70	49.51	77.75	
Std. Gas Flow	(STD_m3/h)	2.941e+005	2.391e+006	2.941e+005	2.391e+006	
Std. Ideal Liq. Mass Density	(kg/m3)	637.9	998.0	637.9	998.0	
Act. Liq. Flow	(m3/s)	---	0.5050	---	0.5082	
Z Factor		1.412	3.159e-003	1.476	2.855e-003	
Watson K		9.044	---	9.044	---	
User Property		---	---	---	---	
Partial Pressure of H2S	(bar)	0.0000	0.0000	0.0000	0.0000	
Cp/(Cp - R)		1.202	1.120	1.202	1.120	
Cp/Cv		1.488	1.151	1.613	1.156	
Heat of Vap.	(Btu/SCF)	---	43.74	---	43.92	
Kinematic Viscosity	(cSt)	0.1051	0.7591	9.980e-002	0.6474	
Liq. Mass Density (Std. Cond)	(kg/m3)	60.55	1015	60.55	1015	
Liq. Vol. Flow (Std. Cond)	(m3/h)	5836	1795	5836	1795	
Liquid Fraction		0.0000	1.000	0.0000	1.000	
Molar Volume	(m3/kgmole)	7.888e-002	1.798e-002	6.151e-002	1.809e-002	
Mass Heat of Vap.	(kJ/kg)	-1154	2143	-1154	2152	
Phase Fraction [Molar Basis]		1.0000	0.0000	1.0000	0.0000	
Surface Tension	(dyne/cm)	---	70.85	---	69.40	
Thermal Conductivity	(W/m-K)	6.961e-002	0.6213	7.805e-002	0.6322	
Viscosity	(cP)	3.784e-002	0.7606	4.609e-002	0.6446	
Cv (Semi-Ideal)	(kJ/kgmole-C)	41.13	69.39	41.20	69.43	
Mass Cv (Semi-Ideal)	(kJ/kg-C)	1.448	3.852	1.450	3.854	
Cv	(kJ/kgmole-C)	33.23	67.49	30.70	67.26	
Mass Cv	(kJ/kg-C)	1.170	3.746	1.081	3.734	
Cv (Ent. Method)	(kJ/kgmole-C)	36.31	---	30.71	---	
Mass Cv (Ent. Method)	(kJ/kg-C)	1.278	---	1.081	---	
Cp/Cv (Ent. Method)		1.362	---	1.613	---	
Reid VP at 37.8 C	(bar)	---	6.467e-002	---	6.467e-002	
True VP at 37.8 C	(bar)	9.934	6.467e-002	9.934	6.467e-002	
Liq. Vol. Flow - Sum(Std. Cond)	(m3/h)	5836	1795	5836	1795	
Viscosity Index		---	-0.8230	---	-3.485	
HHV Molar Basis (Std)	(Btu/SCF)	460.0	46.46	460.0	46.46	
HHV Mass Basis (Std)	(kJ/kg)	1.429e+004	2276	1.429e+004	2276	
CO2 Loading		---	---	---	---	
CO2 Apparent Mole Conc.	(kgmole/m3)	---	0.0000	---	0.0000	
CO2 Apparent Wt. Conc.	(kgmol/kg)	---	0.0000	---	0.0000	
Phase Fraction [Act. Vol. Basis]		1.000	0.0000	1.000	0.0000	
Mass Exergy	(kJ/kg)	593.1	0.7773	560.6	2.057	

DETAILS

Heat Exchanger: IGC 2nd Stage Discharge Cooler (continued)

Overall/Detailed Performance

Duty:	6.543e+07 kJ/h	UA Curv. Error:	8.44e+02 kJ/C-h
Heat Leak:	0.000e-01 kJ/h	Hot Pinch Temp:	37.78 C
Heat Loss:	0.000e-01 kJ/h	Cold Pinch Temp:	32.22 C
UA:	1.954e+06 kJ/C-h	Ft Factor:	---
Min. Approach:	5.556 C	Uncorrected Lmtd:	---
Lmtd:	33.49 C		

TABLES

Shell Side - Overall Phase

Temperature (C)	Pressure (bar)	Heat Flow (kJ/h)	Enthalpy (Btu/SCF)
32.22	4.46	0.00	-323.64
33.89	4.39	13086574.93	-323.50
35.56	4.32	26174177.09	-323.35
37.22	4.25	39261707.72	-323.20
38.89	4.18	52348850.66	-323.06
40.56	4.12	65432874.63	-322.91

UA (kJ/C-h)	Molar Vap Frac	Mass Vap Frac	Heat of Vap. (Btu/SCF)
0.00	0.0000	0.0000	---
1008226.07	0.0000	0.0000	---
1393273.92	0.0000	0.0000	---
1635974.24	0.0000	0.0000	---
1813576.63	0.0000	0.0000	---
1953678.60	0.0000	0.0000	---

Shell Side - Vapour Phase

Mass Flow (kg/h)	Molecular Wt	Density (kg/m3)	Mass Sp Heat (kJ/kg-C)	Viscosity (cP)	Thermal Cond (W/m-K)
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---

Std Gas Flow (STD_m3/h)	Z Factor	Pseudo Pc (bar)	Pseudo Tc (C)	Pseudo Zc	Pseudo Omega
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---

Shell Side - Light Liquid Phase

Mass Flow (kg/h)	Density (kg/m3)	Mass Sp Heat (kJ/kg-C)	Viscosity (cP)	Thermal Cond (W/m-K)	Surface Tens (dyne/cm)
---	---	---	---	---	70.85
---	---	---	---	---	70.56
---	---	---	---	---	70.27
---	---	---	---	---	69.98
---	---	---	---	---	69.69
---	---	---	---	---	69.40

CHEVRON USA
Burlington, MA
USA

Case Name:	PHD.HSC
Unit Set:	NewUser
Date/Time:	Mon Apr 06 13:20:34 2015

Heat Exchanger: IGC 2nd Stage Discharge Cooler (continued)

Shell Side - Light Liquid Phase

Molecular Wt	Sp Gravity	Pseudo Pc (bar)	Pseudo Tc (C)	Pseudo Zc	Pseudo Omega
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---

Shell Side - Heavy Liquid Phase

Mass Flow (kg/h)	Density (kg/m3)	Mass Sp Heat (kJ/kg-C)	Viscosity (cP)	Thermal Cond (W/m-K)	Surface Tens (dyne/cm)
1821625.43	1001.99	4.31	0.76	0.62	70.85
1821625.43	1000.72	4.31	0.73	0.62	70.56
1821625.43	999.45	4.31	0.71	0.63	70.27
1821625.43	998.18	4.31	0.69	0.63	69.98
1821625.43	996.91	4.31	0.67	0.63	69.69
1821625.43	995.63	4.32	0.64	0.63	69.40
Molecular Wt	**Sp Gravity**	**Pseudo Pc (bar)**	**Pseudo Tc (C)**	**Pseudo Zc**	**Pseudo Omega**
18.02	1.00	221.20	374.15	0.26	0.34
18.02	1.00	221.20	374.15	0.26	0.34
18.02	1.00	221.20	374.15	0.26	0.34
18.02	1.00	221.20	374.15	0.26	0.34
18.02	1.00	221.20	374.15	0.26	0.34
18.02	1.00	221.20	374.15	0.26	0.34

Shell Side - Mixed Liquid

Mass Flow (kg/h)	Density (kg/m3)	Mass Sp Heat (kJ/kg-C)	Viscosity (cP)	Thermal Cond (W/m-K)	Surface Tens (dyne/cm)
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
Molecular Wt	**Sp Gravity**	**Pseudo Pc (bar)**	**Pseudo Tc (C)**	**Pseudo Zc**	**Pseudo Omega**
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---

Tube Side - Overall Phase

Temperature (C)	Pressure (bar)	Heat Flow (kJ/h)	Enthalpy (Btu/SCF)
37.78	620.53	0.00	-30.18
59.00	620.60	13073809.00	-28.98
80.26	620.67	26165076.89	-27.79
101.53	620.74	39258506.57	-26.60
122.81	620.80	52346299.72	-25.41
144.09	620.87	65432874.66	-24.22

 * Specified by user.

CHEVRON USA
Burlington, MA
USA

Case Name:	PHD.HSC
Unit Set:	NewUser
Date/Time:	Mon Apr 06 13:20:34 2015

Heat Exchanger: IGC 2nd Stage Discharge Cooler (continued)

Tube Side - Overall Phase

UA (kJ/C-h)	Molar Vap Frac	Mass Vap Frac	Heat of Vap. (Btu/SCF)
0.00	1.0000	1.0000	---
1007717.92	1.0000	1.0000	---
1393070.38	1.0000	1.0000	---
1635924.46	1.0000	1.0000	---
1813546.23	1.0000	1.0000	---
1953678.60	1.0000	1.0000	---

Tube Side - Vapour Phase

Mass Flow (kg/h)	Molecular Wt	Density (kg/m3)	Mass Sp Heat (kJ/kg-C)	Viscosity (cP)	Thermal Cond (W/m-K)
353385.21	28.41	461.81	1.74	0.05	0.08
353385.21	28.41	437.99	1.74	0.04	0.08
353385.21	28.41	415.94	1.74	0.04	0.07
353385.21	28.41	395.67	1.74	0.04	0.07
353385.21	28.41	377.11	1.74	0.04	0.07
353385.21	28.41	360.14	1.74	0.04	0.07

Std Gas Flow (STD_m3/h)	Z Factor	Pseudo Pc (bar)	Pseudo Tc (C)	Pseudo Zc	Pseudo Omega
294145.90	1.48	36.88	-107.82	0.29	0.05
294145.90	1.46	36.88	-107.82	0.29	0.05
294145.90	1.44	36.88	-107.82	0.29	0.05
294145.90	1.43	36.88	-107.82	0.29	0.05
294145.90	1.42	36.88	-107.82	0.29	0.05
294145.90	1.41	36.88	-107.82	0.29	0.05

Tube Side - Light Liquid Phase

Mass Flow (kg/h)	Density (kg/m3)	Mass Sp Heat (kJ/kg-C)	Viscosity (cP)	Thermal Cond (W/m-K)	Surface Tens (dyne/cm)
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---

Molecular Wt	Sp Gravity	Pseudo Pc (bar)	Pseudo Tc (C)	Pseudo Zc	Pseudo Omega
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---

Tube Side - Heavy Liquid Phase

Mass Flow (kg/h)	Density (kg/m3)	Mass Sp Heat (kJ/kg-C)	Viscosity (cP)	Thermal Cond (W/m-K)	Surface Tens (dyne/cm)
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---

* Specified by user.

Heat Exchanger: IGC 2nd Stage Discharge Cooler (continued)

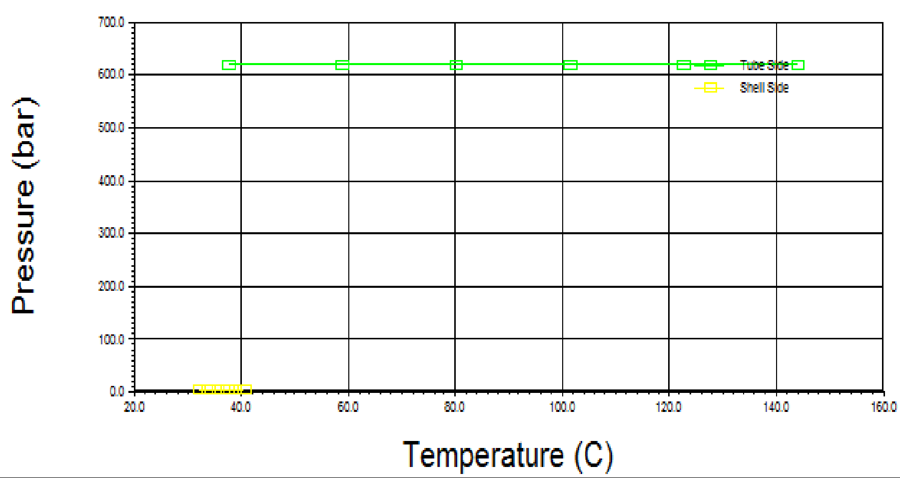
Tube Side - Heavy Liquid Phase

Molecular Wt	Sp Gravity	Pseudo Pc (bar)	Pseudo Tc (C)	Pseudo Zc	Pseudo Omega
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---

Tube Side - Mixed Liquid

Mass Flow (kg/h)	Density (kg/m3)	Mass Sp Heat (kJ/kg-C)	Viscosity (cP)	Thermal Cond (W/m-K)	Surface Tens (dyne/cm)
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---

Molecular Wt	Sp Gravity	Pseudo Pc (bar)	Pseudo Tc (C)	Pseudo Zc	Pseudo Omega
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---
---	---	---	---	---	---



DYNAMICS

Basic Model

aspentech	CHEVRON USA Burlington, MA	Case Name:	PHD.HSC
		Unit Set:	NewUser
		Date/Time:	Mon Apr 06 13:20:34 2015

Heat Exchanger: IGC 2nd Stage Discharge Cooler (continued)

Basic Model

Model Parameters

Tube Volume	(m3)	0.1000	Shell UA	(kg/h)	---
Shell Volume	(m3)	0.1000	Tube UA	(kg/h)	---
Elevation	(m)	0.0000	Minimum Flow Scale Factor		0.0000 *
Overall UA	(kJ/C-h)	1.954e+006			

Summary

Shell Duty: ---	Tube Duty: ---

Pressure Flow Specifications

Shell Side Specification

Delta P	(psi)	5.000 *	Active	k	kg/hr/sqrt(kPa-kg/m3)	---	Not Active

Tube Side Specifications

Delta P	(psi)	5.000 *	Active	k	kg/hr/sqrt(kPa-kg/m3)	---	Not Active

Holdup

Shell Holdup

Phase	Accumulation (MMSCFD)	Moles (kgmole)	Volume (m3)
Vapour	0.0000	0.0000 *	0.0000
Liquid	0.0000	0.0000 *	0.0000
Aqueous	0.0000	0.0000 *	0.0000
Total	**0.0000**	**0.0000**	**0.0000**

Tube Holdup

Phase	Accumulation (MMSCFD)	Moles (kgmole)	Volume (m3)
Vapour	0.0000	0.0000 *	0.0000
Liquid	0.0000	0.0000 *	0.0000
Aqueous	0.0000	0.0000 *	0.0000
Total	**0.0000**	**0.0000**	**0.0000**

NOTES

HTFS

Exchanger Design and Rating

* Specified by user.

Heat and Material Balance Printouts (Sample Streams Only)

Name	to Facility	from reservoir	0	Feed From Well
Vapour Fraction	0.3883	0.3291	0.3102	0.2979
Temperature [C]	117.5	18.11	43.33	42.11
Pressure [bar]	12.39	1.014	12.05	12.05
Molar Flow [MMSCFD]	552.9	552.9	552.9	579.1
Mass Flow [kg/h]	1.022e+006	1.022e+006	1.022e+006	1.082e+006
Liquid Volume Flow [m3/h]	1261	1261	1261	1344
Heat Flow [kJ/h]	-5.856e+009	-6.184e+009	-6.133e+009	-6.456e+009

Name	Q-K100	Q-P101	Q-P102	Q-P100
Heat Flow [kJ/h]	9.927e+004	5.873e+005	2.352e+007	3.287e+008
Name	Q-K101	Q-K102	Q-K103	Q-K104
Heat Flow [kJ/h]	1.588e+005	4.260e+007	4.041e+007	5.290e+007
Name	Q-107	Q-100	Q-101	Q-102
Heat Flow [kJ/h]	1006	1.725e+005	4.214e+007	3.848e+004
Name	Q-108	Q-109	Q-110	Q-111
Heat Flow [kJ/h]	76.79	2.588e+005	2042	690.5
Name	ROS_ PumpQ	Q-K903	Q-K95	Q-WH
Heat Flow [kJ/h]	3.878e+004	6.043e+007	7.005e+007	-6.691e+005

Appendix C. Samples of Binary interaction Parameters

Mushrif has provided one of the methods to determine the EOS binary interaction parameters using K- and L points in his 2004 paper (Mushrif, 2004). Sample of binary interaction parameters for the PR and SRK EOS is shown on table below.

		H_2S	CO_2	CH_4	C_2H_6	C_3H_8
CO_2	PR	0.0974	0.0000			
	SRK	0.0989	0.0000			
CH_4	PR	0.0840	0.0919	0.0000		
	SRK	0.0849	0.0933	0.0000		
C_2H_6	PR	0.0833	0.1322	-0.0020	0.0000	
	SRK	0.0852	0.1363	-0.0078	0.0000	
C_3H_8	PR	0.0878	0.1241	0.0330	-0.0067	0.0000
	SRK	0.0855	0.1289	0.0289	-0.0100	0.0000

Hamad-Allah has also provided binary interaction parameters as below in their 2010 paper (Hamad-Allah et al., 2010).

Comp -onent	C_2	C_3	$i\text{-}C_4$	$n\text{-}C_4$	$i\text{-}C_5$	$n\text{-}C_5$	C_6	C_7	C_8	C_9	C_{10}	N_2	CO_2	H_2S
C_1	0.005	0.01	0.035	0.025	0.050	0.030	0.030	0.035	0.040	0.040	0.045	0.025	0.105	0.070
C_2		0.005	0.0	0.010	0.010	0.010	0.020	0.020	0.020	0.020	0.020	0.010	0.130	0.085
C_3			0.0	0/0	0.015	0.002	0.010	0.005	0.005	0.005	0.005	0.090	0.125	0.090
$i\text{-}C_4$				0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.095	0.115	0.075
$n\text{-}C_4$					0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.095	0.115	0.075
$i\text{-}C_5$						0.0	0.0	0.0	0.0	0.0	0.0	0.100	0.115	0.070
$n\text{-}C_5$							0.0	0.0	0.0	0.005	0.0	0.100	0.115	0.070
C_6								0.0	0.0	0.0	0.0	0.110	0.115	0.070
C_7									0.0	0.0	0.0	0.115	0.115	0.060
C_8										0.0	0.0	0.120	0.115	0.060
C_9											0.0	0.120	0.115	0.060
C_{10}												0.125	0.115	0.055
N_2													0.0	0.130
CO_2														0.135