

**UTILIZING THE HEAT CONTENT OF GAS-TO-LIQUIDS BY-PRODUCT
STREAMS FOR COMMERCIAL POWER GENERATION**

A Thesis

by

ADESOLA AYODEJI ADEGOKE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2006

Major Subject: Petroleum Engineering

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Approved by:

Chair of Committee: Christine Ehlig-Economides

Committee Members: Maria Barrufet

Kenneth R. Hall

Head of Department: Stephen A. Holditch

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ABSTRACT

Utilizing the Heat Content of Gas-to-Liquids By-Product Streams for Commercial Power Generation. (August 2006)

Adesola Ayodeji Adegoke, BSc., Obafemi Awolowo University, Ile-Ife, Nigeria

Chair of Advisory Committee: Dr. Christine Ehlig-Economides

The Gas-to-liquids (GTL) processes produce a large fraction of by-products whose disposal or handling ordinarily becomes a cost rather than benefit. As an alternative strategy to market stranded gas reserves, GTL provides middle distillates to an unsaturated global market and offers opportunities to generate power for commercial purposes from waste by-product streams, which normally are associated with increased expenses incurred from additional handling cost.

The key concept investigated in this work is the possibility of integrating the GTL process with power generation using conventional waste by-product steam streams. Simulation of the integrated process was conducted with the aim of identifying the critical operating conditions for successful integration of the GTL and power generation processes.

About 500 MW of electric power can be generated from 70% of the exit steam streams, with around 20 to 25% steam plant thermal efficiency. A detailed economic analysis on the LNG, stand-alone GTL, and Integrated GTL Power-Generation plants indicates that the integrated system is more profitable than the other options considered.

Justifying the technology and economics involved in the use of the by-product streams to generate power could increase the net revenue and overall profitability of GTL

projects. This technology may be transferable to GTL projects in the world, wherever a market for generated power exists.

DEDICATION

This work is dedicated to God and my wonderful parents, David and Florence Adegoke, whose unflinching support, faith and encouragement saw me through the program and helped me to achieve my goals.

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The author is indebted to Dr. Christine Ehlig-Economides for her counseling, encouragement, support, and thorough review that resulted in the completion of this research work. My special thanks go to Dr. Maria Barrufet and Dr Kenneth R. Hall for their willingness to serve on my dissertation committee, and their invaluable suggestions which, significantly contributed to the successful completion of this research work.

I am grateful to my fiancée, Fisayo, my entire family and friends for their supports and prayers. Finally, I would like to express my sincere thanks to God, the Faithful One, who gave me the assurance that saw me through this program.

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CHAPTER I

INTRODUCTION

1.1 Background

Natural gas is a clean, versatile and therefore desirable source of fuel. A strong factor that defines the mode of gas transportation or exploitation is the proximity to significant market. The volume of the global stranded gas is about 2,500 Tcf (about 250 billion BOE).¹ Industry experts have projected a greater dependence on natural gas within the energy mix as time progresses. Natural gas plays an important role in meeting the energy requirements of the world. Large volumes of stranded gas are found globally, but these require considerable capital expenditure to bring the gas to market. Natural gas can be transported to customers by pipelines, if the natural gas source is near a significant market.² Otherwise, when the market is remote, different natural gas exploitation options such as liquefied natural gas, chemical conversions into products, and gas by wire can be used to economically transport to desired markets.

The basis for the GTL conversion is the Fischer-Tropsch (FT) technology, which has been used to produce clean synthetic liquid fuels, mainly from coal, for more than half a century.² GTL describes the catalytic process that involves the chemical conversion of natural gas (primarily methane) into liquid hydrocarbons—naphtha, diesel, and waxes. A re-visited method for natural gas exploitation is the GTL technology, with most end products being useful as transportation fuels and base chemical feedstock. The base stocks produced from GTL plants have very high saturates content with no impurities

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such as nitrogen and sulphur. Isomerisation of the highly paraffinic FT liquids into GTL fuels leaves no aromatics, so that gases are practically 100% isoparaffinic, which results in high cetane ratings.

The GTL processes have around 60% thermal efficiency, with the inefficiencies distributed between the steam and tail-gas streams.³⁻⁵ The combination of the two by-product streams accounts for 40% heat losses within the GTL process; 17% of the heat loss is through the steam streams, while the remaining 23% is lost through the tail-gas stream.⁶ Agee *et al.*^{2,3,7} found that combination of the excess heat generated from the synthesis gas and FT synthesis reactions, and the tail-gas stream can provide sufficient electric power for both plant and commercial purposes. The balance between electric power and FT liquid production can be adjusted to meet market needs. They further stressed that the integration of the energy requirements within the GTL process is critical to an efficient plant design.

Several authors^{2,3,5,7} have stressed the importance of energy integration within the GTL process. This work will validate and extend these observations by performing a rigorous economic and process analysis of the use of GTL ancillary products with no commercial value for power generation, which is an often-overlooked issue that could be important to determining the most attractive natural gas option. The GTL processes, though, are not pin-point selective, but produce a large fraction of by-products whose disposal or handling ordinarily becomes a cost rather than benefit, a distinction which will be essential in this research.

The analyses in this project will present a robust, economic, process solution to natural gas exploitation, in terms of the technological and environmental factors scalable

to supply-and-demand constraints. The stand-alone GTL process has been shown not to be profitable for some gas and oil prices. Integrating the GTL process with the power-generation process will likely shift the economics in favor of the GTL process against the conventional refined crude oil, while delivering an efficient method to generate power from process wastes. Justifying the technology and economics involved in the use of by-product streams for commercial power generation could increase the net revenue and overall profitability of the GTL projects. This technology may be transferable to other GTL projects in the world, wherever a market for the generated power exists.

1.2 Objectives

The primary purpose of this research effort is to develop a process model for the conversion of the heat content of GTL by-product (primarily steam) streams to electric power for commercial purposes. The project involves a conceptual design of an integrated GTL power-generation system, which can be deployed to optimize processing of stranded natural gas.

The second objective is to evaluate the economic feasibility of the use of the heat content of GTL by-product (primarily steam) streams for commercial power generation. This involves evaluating the cost estimates and profitability of the project, which are key factors that determine successful deployment of the technology.

1.3 Problem Description

Prior studies have considered the extensive modeling of the GTL processes. The whole concept of the integrated GTL Power-generation system is based on ways to economically optimize the heat loss through the by-product streams - steam and tail-gas streams, for commercial power generation. More details of this cutting edge technology will be discussed in the literature review section.

Additionally, this work will clearly benchmark the profitability measures of the integrated GTL Power-generation plants against those of LNG and stand-alone GTL plants, and try to identify the most viable project based on these profitability measures.

Likewise, the whole integrated GTL Power-generation process will be modeled in an attempt to justify the assumptions for both the economic and process analyses, and to further strengthen the commercial nature of the power generated.

CHAPTER II

LITERATURE REVIEW

2.1 Natural Gas Options

The global proved gas reserves as at the end of 2004 is estimated to be about 6,337.4 Tcf, with a reserves-to-production ratio of 66.7.⁸ Global trade in natural gas increased by 9% in 2004 while, transportation through pipeline grew by more than 10% within the same period.⁸ Shipments of LNG increased by 5.4% whereas, the first commercial GTL plant is scheduled to commence operations in the first quarter of 2006.⁸

The global natural gas consumption increased by 3.3% in 2004 compared with an average of 2.3% over a 10-year period. With the exception of US, the gas consumption increased by 4% globally, and the largest increase were within Russia, China, and Middle East region. The world's largest gas market - US consumption did not increase because of growing gas prices and industrial restructuring.⁸ Generally, natural gas transportation via pipelines is the most cost-effective, but pipeline transportation can only serve a small portion of the global natural gas transportation needs, since pipelines have economic and geographical limits.

2.1.1 Liquefied Natural Gas

Liquefaction is a physical process which involves a phase change from gas to liquids at a cryogenic temperature (about -260°F or -161°C) and atmospheric pressure. The volume after liquefaction reduces to 1/600th of the initial gas volume, which aids transportation of the liquefied gas to desired market. LNG is transported in specially built ships to a

receiving terminal, where it is stored in heavily insulated tanks before being re-gasified from liquid to gas for industrial and domestic use. The whole supply chain for LNG includes: gas liquefaction, shipping, storage, and re-gasification.

However, while LNG accounts for 27% of all traded natural gas; the hydrocarbons used for LNG are dwarfed by the size of liquid middle distillates such as diesel and naphtha. Furthermore, LNG as traded today is strongly driven by long-term and high risk contractual agreements.

2.1.2 Gas-to-Liquids

Gas-to-liquids is a catalytic process which involves the chemical conversion of natural gas (primarily methane) into liquid hydrocarbons – naphtha, diesel, waxes. GTL is an appropriate option in natural gas exploitation, with the main end products being useful as transportation fuels and base chemical feedstock.

The base stocks produced from GTL plants have very high saturates content with no impurities such as nitrogen and sulphur. They have no aromatics due to the isomerisation of the highly paraffinic Fischer-Tropsch liquids into GTL fuels and are practically 100% iso-paraffinic, thus they have very high cetane ratings.

The GTL processes though, are not pin-point selective with a large fraction of by-products, whose disposal or handling ordinarily becomes a cost rather than benefit, a distinction which will be essential in this work.

2.1.3 Compressed Natural Gas

Compressed natural gas (CNG) is a physical process which involves a compression of gas at operating pressures (between 1,500 to 2,500 psi) and low temperatures (between -40°F and 0°F). There are two technologies for CNG transport: The Cran and Stennings technology, and the Enersea technology.⁹ Just like LNG, CNG is transported in specially built ships to a receiving terminal, where it is stored or decompressed and offloaded to the pipeline distribution system.

2.1.4 Gas-to-Hydrates

Gas hydrates are clathrates or molecular "cages" that trap gas within a water-ice lattice.¹⁰ Hydrates are generally considered as a problem which needs to be avoided during production. The gas compression ratio of about 160:1 within the lattice could allow economic transportation of gas in this form, though the water fraction is 85% by weight.¹⁰

The production of hydrates slurry basically involves the mixing of chilled water and gas. Industrial production of gas hydrates involves feeding processed gas to a hydrate production plant, where series of reactors convert it into hydrate slurry. The reactors operate in series network and each reactor stage increases the concentration of the hydrate slurry. The concentrated hydrate slurry is stored and finally offloaded to a transport vessel. The hydrate is further dissociated at the receiving terminal, and the gas can be used as desired.¹⁰ The supply chain model of gas hydrates follows closely that of LNG model.

2.2 Dynamics of Product Supply & Demand

The main objective of each of the natural gas solutions is to monetize “stranded” gas reserves by creating pathways for the natural gas to a market where it has economic value. Currently, there is much gas flaring in different regions of the world especially in the African continent. In Nigeria alone, with about 187 Tcf remaining reserves split in almost equal halves between associated and non-associated gas reserves; about 40% of the associated gas produced is flared though gas flares are scheduled to stop by 2008.

2.2.1 LNG Global Market

There is a steady increase in the global LNG market with additional liquefaction and re-gasification capacities in the different regions of the world. The additional capacities currently under construction will increase the global LNG liquefaction capacity from an estimated 6.6 Tcf (139 million metric tons) per year in 2003 to 9.4 Tcf (197 million metric tons) per year in 2007.¹¹ Most of the additional LNG liquefaction capacities will be within the Atlantic basin region.

There is also a gradual increase in the demand for LNG, which has a direct relationship with the increasing global LNG liquefaction and re-gasification capacities. In 2002 only, twelve countries shipped 5.4 Tcf of natural gas (113 million tons of LNG) to twelve LNG importing countries, an increase from less than 4 Tcf (84 million tons) shipped in 1997. LNG-importing countries have a combined annual re-gasification capacity of 15.1 Tcf (310 million tons).¹¹

Japan, South Korea and Taiwan, three LNG importing countries received 3.6 Tcf (76 million tons) in 2002, which represents about 68% of total global LNG trade, while

ten European LNG importing countries and the United States received 1.7 Tcf (37 million tons) in 2002, representing 32% of total world LNG trade. In other regions, countries like Indonesia, Mexico, Philippines and a host of others have indicated their interest in the construction of receiving terminals.¹¹

The increase in the demand for natural gas globally is mainly for distributed power generation in the deregulated power market. The environmental and security concerns for perceived explosion risks at the re-gasification facilities and for terrorist attacks on the LNG tanker are some of the key issues that may hinder LNG development.

2.2.2 GTL Global Market

Presently, the operating and announced GTL projects represent about one million bpd of new capacity, processing about 100 Bcf/D of natural gas. Only 227,500 bpd is operating; as shown in Table 2.1,¹² which represents about 25% of the projected installed capacity. There could be a bright future for GTL technology in natural gas exploitation, with nearly half of the world gas reserves stranded and over 50% of this within the harsh offshore environment.

The abundance of gas resources, increasing price of crude and environmental issues, are some key factors shifting the focus of the oil & gas industry to the development of the GTL technology globally. The additional capacities will increase the volume of GTL trade in the coming years which leads to increased transportation of the “stranded” natural gas resources as refined fuel to market. Already, the announced GTL projects include some 700,000 bpd additional capacities.

Over the years, one of the key factors in the development of the GTL technology has been the crude oil price. In most cases the price of GTL fuels is benchmarked against global crude oil prices. The chemical nature of GTL fuels makes it more economically justified to benchmark their prices with cost of refined crude oil rather than the crude oil prices. GTL is an end-product, and therefore all the costs of refining have to be fully accounted for in the determination of price.¹³

Insufficient refining capacities in countries like the US also increase the global demand for GTL fuels. Basically, GTL as a product relieves pressure on the oil supplies that are pushing up transportation costs, while the main competition from LNG ultimately comes from the power generation market which has a number of alternatives.

Table 2.1-Global GTL Capacities	
GTL Projects	Capacity (bpd)
Operational	
Sasol I (South Africa)	8,000
Sasol II/III (South Africa)	160,000
PetroSA (South Africa)	47,000
Shell (Malaysia)	12,500
Construction	
Chevron (Nigeria)	34,000
Sasol/Qatar Petroleum	34,000
Announced	
Rentech (Bolivia)	10,000
Shell (Qatar)	140,000
ConocoPhillips (Qatar)	160,000
Syntroleum/Yakutgazprom (Russia)	13,000
Sasol/Chevron (Qatar)	66,000
Sasol/Chevron (Qatar)	130,000
Syntroleum/Marathon	90,000

Table 2.1 (Continued)	
GTL Projects	Capacity (bpd)
Rentech (Indonesia)	16,000
Demonstration Plants	
BP (Alaska)	300
ConocoPhillips (Oklahoma)	400
Total (exclusive of demonstration plants)	920,500

2.2.3 Electric Power Profile – Case Study of Nigeria Local Market

In Nigeria, the current demand for power conservatively estimated as 10,000 MW far exceeds the total available generation capacity, which is about 2,500 MW, creating an imbalance in the dynamics of local demand and supply of power, as illustrated in Figure 2.1¹⁴ The installed capacity is about 5,900 MW, which is only 59% of the estimated suppressed demand for electricity.

World Bank estimates that about 60% of the total population and 90% of rural household have no access to electricity,¹⁴ leading to a very huge unexploited local market. Independent power producers (IPPs) are generating only 60 MW altogether, representing about 2% and 0.6% of the available generation capacity and local power demand respectively. As at June 2002, Nigeria Electric Power Authority (NEPA) revenue customer base was about 3.05 million: 83% of which where residential, 16% commercial and 0.4% industrial.¹³

Natural gas is the major fuel for electricity generation in Nigeria, and it accounts for close to 60% of the annual new power generation installed capacity. Hydroelectricity remains the main source of power in Nigeria, supplying over 50% of total electricity generated annually. However, concerns over the damming in the upper Niger, seasonal

rainfalls and displacement of inhabitants due to damming activities are key issues which hinder the development of the hydroelectric power generation.

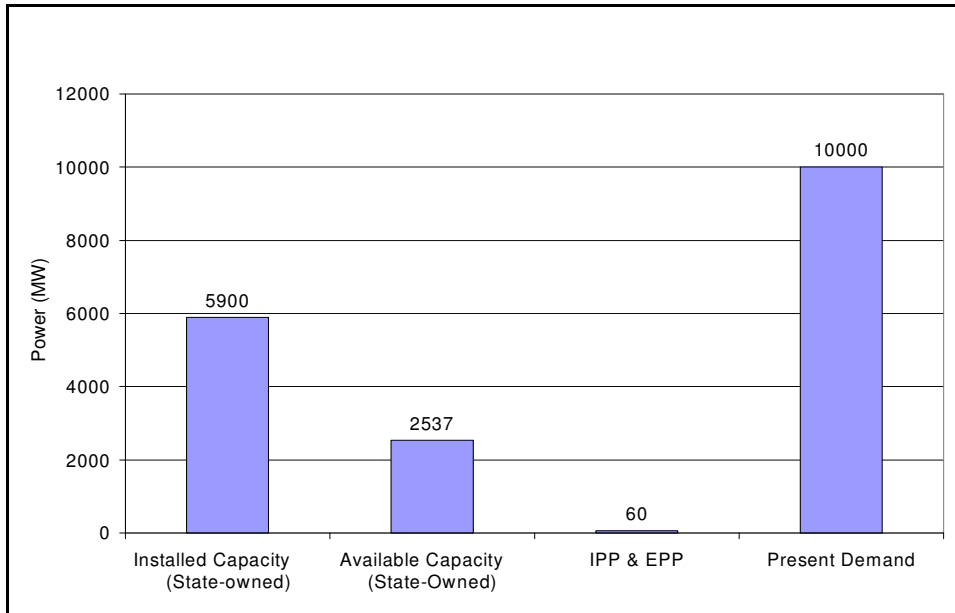


Figure 2.1-Nigerian Electric Power Capacity & Demand

Apart from countries with unsaturated local market for electric power, there is potential for countries with large gas reserves and saturated local market to export power to neighboring countries through established grid lines.

CHAPTER III

INTEGRATED GTL POWER-GENERATION PROCESS

3.1 Design Plant Processes

Integrated GTL Power-Generation process involves the combination of commercial power generation with production of GTL fuels, based on existing GTL technology, using the heat content of the steam stream and/or the tail-gas stream.

The Integrated GTL Power-Generation process was modeled using a combination Aspen Plus, for the GTL process and Steam System Assessment Tool (DOE), for the power generation. The design of the integrated GTL Power-generation process using Aspen Plus software program is described below:

1. Articulate key design principles for the integrated GTL power-generation systems.
2. Develop a process model for the integrated GTL power-generation system by use of Aspen process modeling software suites.
3. Conduct a material and energy balance over the GTL loop within the integrated system to determine the following parameters.
 - Inlet and outlet operating conditions (temperatures & pressures).
 - Quantity of liquid products in the outlet streams.
 - Quantity of steam generated in the outlet streams.
 - Quantity of tail-gas stream in the outlet stream.
4. Conduct a material and energy balance over the power-generation loop to determine the following parameters.
 - Efficiency of the thermal plants.

- Quantity and quality of inlet steam stream.
 - Inlet operating temperature and pressure of the steam.
 - Quantity of electric power supplied to the grid.
5. Conduct an overall material and energy balance over the integrated systems to determine the efficiency of the system.
 6. Analyze the output results from material and energy balances to isolate the factors that favor the integrated GTL power-generation projects.

3.2 Aspen Process Simulation

Process simulation with Aspen Plus allows prediction of the behavior of a process using basic engineering relationships such as mass and energy balances, phase and chemical equilibrium, and reaction kinetics. Simulation of actual plant behavior can be achieved given reliable thermodynamic data, realistic operating conditions, and the rigorous Aspen Plus equipment models.¹⁵

Aspen Plus allows users to interactively change specifications, such as flowsheet configuration, operating conditions, and feed compositions, to run new cases and analyze alternatives.¹⁵ Aspen Plus allows users to perform a wide range of additional tasks, which includes:

- Perform sensitivity analyses and case studies
- Generate custom graphical and tabular output
- Estimate and regress physical properties
- Fit simulation models to plant data

- Optimize plant processes

3.2.1 Material & Heat Balance Equations

The system of equations is linear; Aspen Plus solves the unknown variables directly, while using the following material and energy balance equations:¹⁵

Overall mass balance:

$$\sum_{i=1}^{NM} S_i \sigma_i F_i = 0 \quad (1)$$

Substream mass balance for j=1 to NSS:

$$\sum_{i=1}^{NM} S_i F_i f_{ij} = 0 \quad (2)$$

Component mass balance for k=1 to NC, j=1 to NSS:

$$\sum_{i=1}^{NM} S_i F_i f_{ij} Z_{ijk} = 0 \quad (3)$$

Overall energy balance

$$\sum_{i=1}^{NM} S_i \sigma_i F_i h_i + \sum_{j=1}^{NH} S_j \sigma_j H_j + \sum_{k=1}^{NW} S_k \sigma_k W_k = RHS \quad (4)$$

3.3 Steam System Assessment Tool

The Steam System Assessment Tool (SSAT) is designed by the Department of Energy, and it allows the development of approximate models of site steam system and prediction

of savings achieved from the implementation of key steam system best practices measures.¹⁶ The key features of SSAT include:

- A choice of 1, 2, or 3 pressure header models
- Simulations of major equipment items including
 - Boiler
 - Back pressure turbines
 - Condensing turbine
 - Deaerator
 - Letdowns
 - Flash vessels
 - Feedwater preheat exchangers
 - Stream traps
- Schematic representation of the site steam system
- Estimates of site environmental emissions
- Calculations of project energy and operating cost savings

3.4 GTL Process Description

There are three stages involved in the conversion of natural gas into GTL fuels - Syngas generation, Fischer-Tropsch (FT) synthesis, and Product upgrade. A detailed result of the process modeling in Aspen Plus is included in Appendix B, while the actual process map is shown in Figure A1 in Appendix A and Figure 3.1 below.

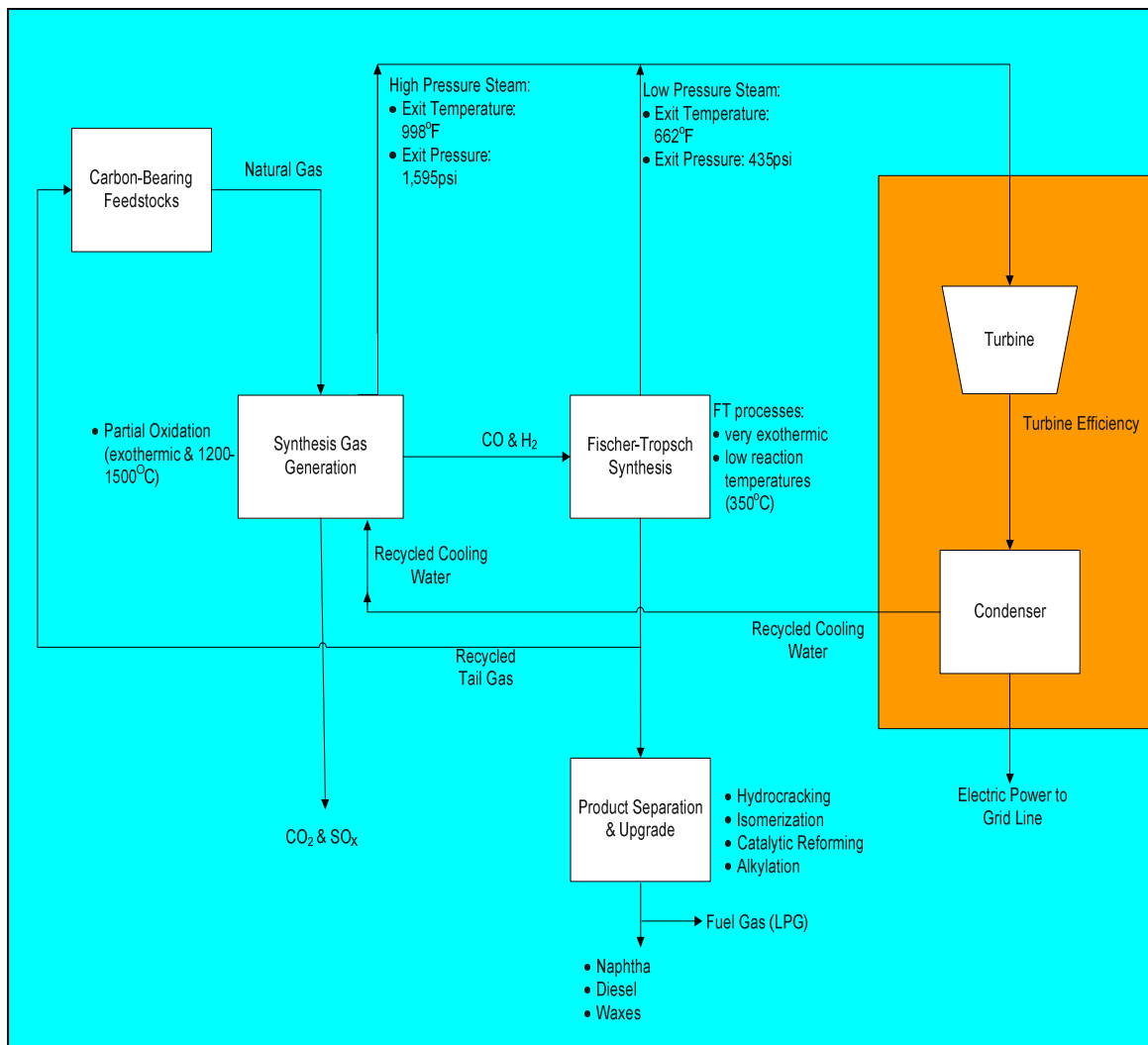


Figure 3.1-Overview of the Integrated GTL Power-Generation Process.

3.4.1 Pre-Feed Treatment

One Bscf/D of natural gas was fed into the pre-feed treatment. The impurities in the methane-rich natural gas have to be removed before being fed into the syngas generation unit. These impurities include H₂S and CO₂; while the CO₂ remained within the feed gas inlet stream into the syngas generation unit, the H₂S is removed through stream 6. A component material balance of the methane-rich natural gas inlet and outlet streams within the Pre-feed treatment unit is shown under block B1 in Appendix B “U-O-S Block

Section”, while the inlet and outlet streams are represented by streams 1, 2, & 6 in Appendix B “Stream Section”.

3.4.2 Air-Separation Unit

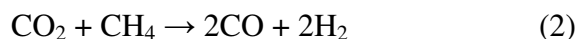
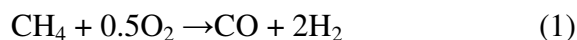
The syngas generation route that was adopted in this work is the partial oxidation process route, which involves the oxidation of methane to produce CO and H₂. The oxygen required for the partial oxidation process is obtained by compressing air at 530⁰F and 87 psi, separating into an oxygen-rich stream with about 0.5% nitrogen content. The Air-Separation unit has two components - compression and separation units represented by blocks B2 & B3 respectively, as shown in Figure A1, Appendix A. The inlet and outlet compressed air streams are represented by streams 4, 5, 7, & 8 in Figure A1, and Appendix B “Stream Section”. The oxygen-rich stream represented by stream 7 is fed into the syngas generation unit.

3.4.3 Syngas Generation

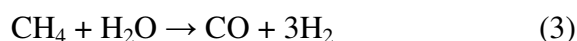
Natural gas (primarily methane) is reacted with steam and/or oxygen to produce syngas, which is a mixture of hydrogen and carbon monoxide. The natural gas (predominantly methane) can be converted to syngas through three routes:

1. Partial oxidation: an exothermic process which involves an incomplete combustion of natural gas (primarily methane). The combustion chamber operates at a very high temperature (2,192–2,732⁰F).¹⁷ A side reaction occurs in which the CO₂ component

in the inlet feed gas stream reacts with CH₄ to produce additional hydrogen molecules. The chemistry of the two reactions are presented below:



2. Steam reforming: an endothermic process which involves the reaction of the natural gas with steam in the presence of catalyst. The process conditions are at a temperature of 1,562-1,724°F and pressure of 435 psia.¹⁷ The chemistry of the reaction is:



3. Autothermal reforming: an exothermic which combines steam reforming with partial oxidation. The autothermal reforming process utilizes the heat produced from the partial oxidation process to supply the required heat for steam reforming process.

In modeling the process in Aspen Plus, the “partial oxidation” route was adopted; critical to the decision was the necessity to maintain the stoichiometric ratio of CO:H₂ at 1:2. The exothermic nature of the partial oxidation process is one of the key issues which limit its applicability. One of the key advantages of the integrated process is that the high pressure steam stream is well-suited to generate power for commercial purposes.

The key assumption in the process modeling is that the carbon conversion was about 90%, which means that 10% of the feed-gas CH₄ stream exits the whole process unreacted. The carbon conversion in the primary reaction 1, shown above was assumed to be about 80%, while the secondary reaction 2, was taken as 10%. Consequently, enough O₂ sufficient to cause 80% conversion of the feed-methane gas was supplied through stream 7 from the Air-Separation unit. The secondary reaction between the CO₂ in the

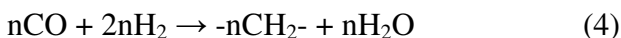
feed-gas stream and CH₄ completes the methane conversion to meet the 90% conversion for the process.

Being very exothermic, the partial oxidation process was cooled from an exit temperature of about 2,372⁰F to 572⁰F. The cooling water with an inlet condition of 60⁰F and 0.2561 psi generated about 6 MMlb/hr of steam from the syngas generation unit, with an exit temperature and pressure of 998⁰F and 1,200 psi. The Synthesis Generation unit represented by block B10 in the Appendix B “U-O-S Block Section”. The inlet and outlet streams are represented by streams 2, 7, & 9 in Appendix A, and Appendix B “Stream Section”.

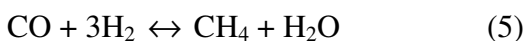
3.4.4 Fischer-Tropsch (FT) Synthesis

The synthesis gas (CO & H₂) produced is fed in the right stoichiometric combination into the FT reactor, to produce a mixture of highly paraffinic synthetic hydrocarbons. These hydrocarbons are primarily straight-chain paraffins, with the chain reaction occurring at temperature of 428-662⁰F.¹⁷

The reaction continues via chain propagation with addition of –CH₂– groups adding to the primarily paraffinic, linear hydrocarbon chains. There are three output streams from the FT reactors, the higher hydrocarbons (C₅₊) stream which is used for middle distillates production, the lower hydrocarbon (C₂-C₄) streams which can be used for Liquefied Petroleum Gas (LPG) and the by-product streams – low BTU tail gas (CO, H₂ & CH₄) & steam. This reaction is carried out in either tubular fixed-bed or slurry phase catalytic reactors. The chemistry of the reaction is represented as:



The key assumption is that the catalyzed reaction proceeds only in the forward reaction; while the reactors operate at a fairly constant temperature and pressure, hence eliminating any side reactions especially the methanation reaction (reverse steam reforming).



Based on the process model in Aspen Plus, the exit steam stream from the FT process is about 1.32 MMlb/hr at 662⁰C and 435 psia. The FT Synthesis unit represented by block B6 in the Appendix B “U-O-S Block Section”. The inlet and outlet streams are represented by streams 12 & 14 in Appendix A, and Appendix B “Stream Section”.

3.4.5 Product Upgrade

This is the last stage where the high paraffinic FT liquids are selectively isocracked into GTL fuels – diesel fuel, naphtha, and other liquid petroleum or specialty products. The addition of the hydrogen in the hydrocracking process, breaks the long-chained waxy hydrocarbons into diesel and naphtha, and stabilizes the products by removing some olefins and oxygenates in the lighter products.

The whole concept of the Integrated GTL Power-Generation process as illustrated in Figure 3.1 is based on ways to economically optimize the heat loss through the by-product streams - steam and tail-gas streams, for commercial power generation. Most of the heat losses occur during the FT processes because its reactions are highly exothermic.

Since, the GTL processes have around 60% thermal efficiency which results to about 40% heat loss within the system, the key step to a cost-effective design is to integrate the energy requirements within the GTL process.

3.5 Power Generation

The steam power plant is a large-scale heat engine in which the working fluid (water) is in steady-state flow successively through a pump, a boiler, a turbine, and a condenser in a cyclic process.¹⁸ The steam power system is based on simple ideal Rankine cycle, with the key design point being the elimination of the boiler section as illustrated in Fig. 3.1. The high-pressured (HP) and low-pressured (LP) steam streams from the syngas generation and FT process units respectively are already in the superheated steam state. Hence, the boiler section in the conventional steam power system design is practically by-passed. This design reduces the capital investment in the plant, since the boiler section requires heavier construction and more expensive materials of construction. It should also be noted that the HP and LP streams are treated separately in the power generation cycle.

The Rankine cycle works based on a cooling stage with a complete condensation of the steam, yielding saturated liquid which is normally pumped to the boiler in the conventional steam power plant represented by Figure 3.2.¹⁸ The typical Rankine cycle can be described in four steps described as follows:¹⁸

- 1->2: A constant-pressure (isobaric) heating process in a boiler.
- 2->3: Reversible, adiabatic (isentropic) expansion of vapor in a turbine to the pressure of the condenser.
- 3->4: A constant-pressure (isobaric), constant-temperature (isothermal) process in a condenser to produce saturated liquid.
- 4->5: Reversible, adiabatic (isentropic) pumping of the saturated liquid to the pressure of the boiler, producing subcooled liquid.

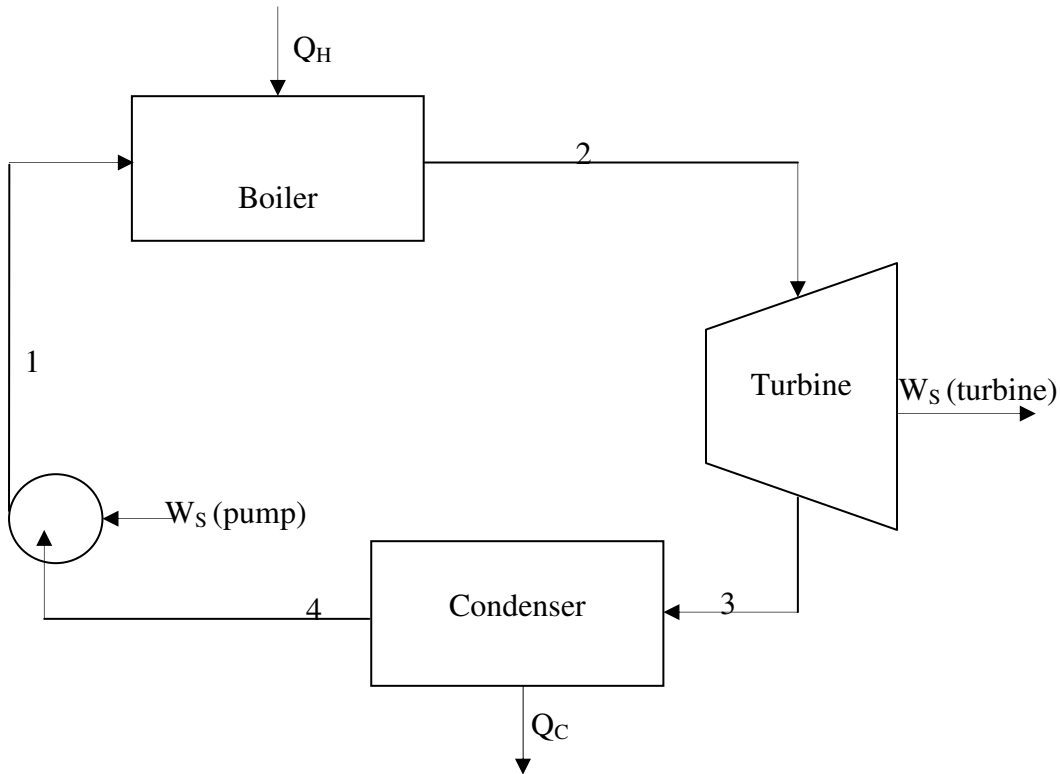


Figure 3.2-Simple Steam Power Plant

The design of the steam power plant was done using the Steam System Assisted Tool, as illustrated in Fig. 3.2. In this work, the design requirements involve the treatment and recycling of the saturated liquid as cooling water for the exothermic syngas generation and FT synthesis processes as illustrated in Fig. 3.1.

The power rating, $\dot{W}_s (net)$, from the steam power cycle can be determined using equation 5. Given the heat supplied to the boiler; the heat rejected from the condenser and the steam mass flow rate, the power rating can be calculated.

$$\dot{m}[Q(boiler) + Q(condenser)] = -\dot{W}_s (net) \quad (5)$$

The thermal efficiency of the steam power cycle, which increases with higher boiler pressure and temperatures, is calculated by the following equations

$$\eta = \frac{|W_s(\text{net})|}{Q(\text{boiler})} \quad (6)$$

$$W_s = \frac{\dot{W}_s}{\dot{m}} \quad (7)$$

$$Q(\text{boiler}) = H_2 - H_1 \quad (8)$$

H_1 is determined from the exit steam conditions of the pump, H_2 from inlet steam conditions to the turbine, and W_s from the power rating of the turbine.

The detailed results of the power rating of the steam plant with 70% of the combined steam streams from the syngas generation and FT synthesis units are shown in Table 3.1. The thermal efficiencies of the steam plant, calculated based on the operating conditions of the heating system and net work done by the shaft is about 25% and 20% for the HP and LP steam cycles respectively. Detailed calculations showing the evaluation of the thermal efficiencies for the 70% steam supply case is shown in Appendix C.

Alongside typical GTL fuel products, about 37, 75, and 522 MW of commercially available power can be generated daily for the case of 5%, 10%, and 70% steam supply respectively.

Table 3.1-Steam Power Plant Parameters (70% Steam Supply Case)		
Power Plant Parameters	HP	LP
Steam Mass Flow Rate (MMlb/hr)	4.2	0.9
Inlet Turbine Pressure (psi)	1,200	435
T1 (°F)	126.00	126.00
T1 (°K)	325.37	325.37
T2 (°F)	998.00	660.00
T2 (°K)	699.81	622.04
Ws (net-Btu/lb)	358.82	262.42
Q (heater-Btu/lb)	1,470.11	1,311.08
Thermal Efficiency	25%	20%

3.6 Integrated GTL Power-Generation Competitive Advantage

The competitive advantages of the Integrated GTL Power-Generation process are:

1. World market for middle distillates is relatively very high.
2. Premium and superior quality of GTL fuels.
3. High market demand for cleaner fuels and low cost chemical feedstock.
4. Strategic diversification for commercial power supply.
5. Monetizes waste heat to improve costs.
6. Enhances the profitability of the overall GTL project.

CHAPTER IV

ECONOMIC ANALYSES OF LNG, GTL & INTEGRATED GTL POWER- GENERATION PROCESSES

4.1 Evaluate Plant Economics

The key step to the successful implementation of the Integrated GTL Power-Generation process is to evaluate its commercial feasibility. The economic analysis is performed based on the following steps below:

1. Develop an annual cash flow for typical stand-alone GTL, LNG, and integrated GTL power-generation projects.
2. Highlight the economic and process assumptions for the variable components of the cash flow.

a) Economic Assumptions

- 1 Bcf/d feed gas volume.
- 20-year plant life.
- Capital cost amortized over 10-year period.
- Corporate tax rate taken as 30%.
- Royalties taken as 12.5%.
- Discount rate taken as 10%.
- Cost escalating at 3% per annum.
- Depreciation following a straight-line model.
- Capital expenditure (CAPEX) acquired at Year 0 while, active production starts in Year 1.
- All costs exclusive of gas-field development.

b) Process Assumptions

- GTL process has thermal efficiency of about 60%.
- Natural gas has heating value of around 1,000 Btu/ft³.
- GTL product breakdown: Diesel oil (75%), naphtha (20%), and liquefied petroleum gas (5%).
- Carbon efficiency around 90%.
- Gas-liquid product conversion ratio about 10,000 scf/bbl.
- Steam recycle ratio of 70%.

c) Cost Assumptions

- LNG CAPEX estimated as \$2 billion.
- GTL CAPEX estimated as \$28,000/bpd of plant capacity.
- Power plant CAPEX estimated as \$1,000/kW.
- Unit operation and maintenance cost for the power plant about 1 cent/kW-h.

3. Determine the following economic indicators on the basis of the after-tax cash flow for the three cases (stand-alone LNG, GTL, and Integrated GTL Power-Generation systems).

- Net present value (NPV).
- Internal rate of return (IRR).
- Profitability index (PI).
- Payback period (PBP).
- Annual operating expenditure.
- Initial capital expenditure.
- Annual revenue.

4.2 Definition of Economic Terms

The yardsticks used to measure the profitability of these projects reflect the time value of money. There are three main elements considered to determine the attractiveness of any investment: investment amount, the operating benefits, and the economic life.¹⁹

4.2.1 Net Present Value

NPV also referred to as the present value of cash surplus or present worth, is obtained by subtracting the present value of periodic cash outflows from the present value of periodic cash inflows.¹⁹ It describes a measure of capital created over and above the hurdle rate. It is used both to screen projects and rank alternative investments. To screen projects, those with NPV greater than zero, positive NPV, at hurdle rate are acceptable while, those with NPV less than zero, negative NPV are rejected. In ranking alternative investments, project with highest NPV is best project among mutually exclusive investment opportunities.

4.2.2 Internal Rate of Return

IRR measures the effective rate of return earned by an investment as though the money had been loaned at that rate. It describes the discount rate at which the NPV is exactly equivalent to zero, or the present value of cash inflows is equal to the present value of cash outflows. The IRR is used in screening projects to identify those that are to be accepted. If the IRR is greater than the hurdle rate, the project is accepted, otherwise the project is rejected.

4.2.3 Profitability Index

PI describes the dimensionless ratio of the present value of future operating cash flow for a project to the present value of total investment over its entire life. This measure describes the relative profitability of investment, the present value of benefits per present worth of every dollar invested in the project. The PI is used both in screening and ranking projects. In the screening process, projects with PIs greater than 1 are accepted while; those with PI less than 1 are rejected. As a ranking tool, projects are measured from the highest PI to the lowest. Companies generally prefer projects with the highest PI because it maximizes the corporate NPV.

4.2.4 Payback Period

Payback period is defined as the expected number of years required to recover initial project investment. It is calculated based on the time required for the cumulative discounted net cash flow to be exactly equal to zero. Generally, companies prefer investment with a shorter payback period.

4.3 Economics of LNG Plants

A typical world class LNG plant of capacity about 6.4 million tons/year which requires about 1 Bcf/day of feed gas is assumed for this study. It is estimated that the efficiency losses in the LNG value chain²⁰ are: 9% at the liquefaction stage, 1% during transportation and 2% at the re-gasification point. The gas sale price was assumed to be \$4.50/MMBtu with a natural gas heating value of 1,000 Btu/cf.

4.3.1 Capital Expenditure

The breakdown of the LNG capital expenditure¹¹ for this study is:

- Gas liquefaction cost - \$1.75 billion
- Re-gasification cost - \$0.25 billion

Typically, the liquefaction cost is the most expensive of the LNG value chain. The total investment cost required for the LNG plant is estimated as \$2 billion. The investment cost is exclusive of the capital expenditure incurred for shipping purposes either by procurement or charter of LNG ships. It is further assumed that the cost of transportation is fully accounted as part of the daily operating expenses of the plant.

4.3.2 Operation Expenditure

The operating expenditure¹¹ is broadly grouped as:

- Feed gas OPEX - \$0.50/MMBtu
- Non-feed gas OPEX - \$1.90/MMBtu
 - Liquefaction cost - \$1.00/MMBtu
 - Shipping cost - \$0.60/MMBtu
 - Re-gasification cost - \$0.30/MMBtu

The operating expenditure (including the feed gas cost) averaged over the 20 year operational plant life is around \$1.01 billion/year.

4.3.3 Revenue

The net revenue (including federal & private royalties) generated from the sale of LNG, based on an assumed unit gas price²¹ of \$4.50/MMBtu and spread over the 20 year operational plant life is about \$1.68 billion/year.

4.4 Economics of GTL Plants

A large scale GTL plant with plant capacity of 100,000bbls/day and requires 1 Bcf/day of feed gas is considered for the economic analysis in this study. The product breakdown from the GTL process strongly depends on the process operating conditions, the choice of the optimum synthesis gas route and Fischer-Tropsch reactor. The GTL product breakdown⁴ which is also used in this study is:

- Diesel Oil – 75%
- Naphtha – 20%
- LPG – 5%

4.4.1 Capital Expenditure

The capital cost currently estimated for GTL plants range from \$25,000-\$30,000/bbl.²² In this study, a capital cost of \$28,000/bbl is assumed to compensate for location effects. The breakdown of the GTL capital expenditure²³ for this study is:

- Syngas production – 30%
- FT Synthesis – 15%
- Product work-up – 10%
- Utilities – 15%
- Offsites – 20%

Based on the unit capital cost, the total investment cost required for the GTL plant is estimated at \$2.8 billion/year.

4.4.2 Operation Expenditure

The operating expenditure, with an assumed natural gas heating value of 1,000 Btu/cf is broadly grouped as:

- Feed gas OPEX
 - Free associated gas - \$0/MMBtu
 - Non-associated gas - \$0.5/MMBtu
- Non-feed gas OPEX - \$6.00/bbl of product

The operating expenditure (including the feed gas cost) averaged over the 20-year operational plant life is around \$533 million/year.

4.4.3 Revenue

The product pricing for GTL fuels is highly dependent on the proximity to the target market, and it differs for different locations. The average GTL products price based on the product breakdown is:

- Diesel Oil – \$30/bbl
- Naphtha – \$25/bbl
- LPG²¹ – 7cents/litre (equivalent to \$12/bbl)

The net revenue (including royalties) generated from the sale of the GTL fuels & LPG, spread over the 20-year operational plant life is about \$1.18 billion/year.

4.5 Economics of Integrated GTL Power-Generation Plants

It has already been established that GTL processes have around 60% thermal efficiency.

The basis for the Integrated GTL Power-Generation concept in this study is the utilization

of the 17% heat loss through the by-product steam stream. The three case scenarios studied were when 5%²⁴, 10%, and 70% of the by-product steam stream is supplied to the power generating unit. Alongside typical GTL fuel products, about 37, 75, and 522 MW of commercially available power can be generated daily for the case of 5%, 10%, and 70% steam supply respectively.

4.5.1 Capital Expenditure

Apart from the unit capital cost of the GTL plant, an additional capital cost²⁵ of about \$1000/kW is incurred on the power plant. The investment cost for the power plant is about \$6 million, \$12 million, and \$85 million for the case of 5%, 10%, and 70% steam supply respectively. Hence, the total investment cost for the Integrated GTL Power-Generation plant is around \$3.11 billion, \$3.13 billion and \$3.46 billion for the three cases studied respectively.

4.5.2 Operation Expenditure

The unit operation & maintenance cost for the power plant is about 1 cent/kW-h,²⁶ which means an additional operating expenditure of \$4 million/year and \$9 million/year, and \$60 million/year for the case of 5%, 10% and 70% steam supply respectively, averaged over the 20-year operational plant life. The total operating expenditure (including the GTL plant operating expenses) averaged over the 20-year operational plant life is around \$530 million/year, \$540 million, and \$590 million/year for the case of 5%, 10%, and 70% steam supply respectively.

4.5.3 Revenue

The product pricing for power produced is also highly dependent on both the demand and proximity to local market. The average electric tariff²⁷ varies based on the service provider, the electric tariff is about 6.50 and 15.90 cents/kW-h for government funded and privately provided power respectively. The additional revenue (including royalties) from the sale of the electricity is about \$43 million/year, \$87 million/year, and \$606 million/year, which gives a net revenue of about \$1.23 billion, \$1.27 billion, and \$1.72 billion over the 20-year operational plant life, for the case of 5%, 10%, and 70% steam supply respectively.

4.6 Capital Budgeting: LNG, GTL & Integrated GTL Power Systems

The result of the economic analysis is presented in Table 4.1. The net present value (NPV), which refers to the revenue (discounted), generated by the investment, is highest for the Integrated GTL Power-Generation plants with 70% steam supply. The NPV is about \$2.32 billion for the case of 70% steam supply, while for the associated gas case the NPV increases to \$3.91 billion. The NPV for the LNG project is about \$2.51 billion and \$1.46 billion for the associated and non-associated gas cases, higher than the integrated GTL projects with 5% and 10% steam supply and stand-alone GTL project, but significantly lower than the integrated GTL Power-Generation project with 70% steam supply.

Table 4.1-Cash Flow Analysis Results										
Factors	LNG		GTL		GTL-Power (5% Steam Supply)		GTL-Power (10% Steam Supply)		GTL-Power (70% Steam Supply)	
Gas Price (\$/MMBtu)	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5
NPV (\$billion)	2.51	1.46	2.06	1.01	2.21	1.18	2.35	1.31	3.91	2.32
Internal Rate Return (%)	28	22	20	15	22	18	24	19	32	30
Profitability Index	1.88	1.51	1.73	1.36	1.79	1.42	1.84	1.47	2.40	2.02
Payback Period (years)	1.50	3.00	3.00	8.50	2.50	6.50	2.50	6.50	1.50	3.00
Operating Cost (\$ billion/yr)	0.84	1.01	0.29	0.53	0.29	0.53	0.30	0.54	0.35	0.59
Capital Cost (\$ billion)	2.00		2.80		3.11		3.13		3.46	
Revenue (\$ billion/year)	1.68		1.18		1.23		1.27		1.72	
Power Generation (MW)	-		-		37		75		522	

The internal rate of return (IRR) which is a measure of profitability and the marginal efficiency of the capital investment have the maximum value for the Integrated GTL Power-Generation project with 70% steam supply. The IRR is about 30% and 32% for the non-associated gas and associated gas respectively. This is a significant improvement compared with both the 5% and 10% steam supply cases. The IRR for the LNG project is about 28% and 22% for the associated and non-associated gas respectively, which is significantly lower than the Integrated GTL Power-Generation projects, and is not profitable at typical hurdle rates of 30%.

The profitability index (PI), which is a measure of the amount of present value benefits is generated for each dollar invested is highest for the Integrated GTL Power-Generation project with 70% steam supply, with a PI of about 2.40 and 2.02 for associated and non-associated gas cases respectively. This means for each \$1 invested, the integrated GTL project with 70% steam supply delivers \$2.4 and \$2.0 for the associated and non-associated gas cases respectively. The LNG project on the other hand delivers \$1.88 and \$1.50 for every dollar invested, for the associated and non-associated gas cases respectively.

The payback period or breakeven point, which describes the expected number of years required for recovering the initial investment, is practically the same for the Integrated GTL Power-Generation and LNG project at about 1.5 and 3 years for the associated and non-associated gas cases respectively. The other projects including the stand-alone GTL plants take a longer period to breakeven, which translates to a longer waiting period for investment to yield profits.

The economic analysis shows a trend that justifies the choice of the Integrated GTL Power-Generation project with 70% steam supply compared to the LNG or stand-alone GTL projects. Overall, the profitability indices measured above clearly favors the Integrated GTL project with 70% steam supply as being more economically viable.

CHAPTER V

SENSITIVITY ANALYSES-ECONOMIC & STEAM SUPPLY

5.1 Price Sensitivity

Variations in natural gas and crude oil prices have significant impact on the economics of LNG & GTL plants. Price changes can make hitherto uneconomical projects very profitable. Hence, sensitivity analyses for variations in crude oil price and electric tariff were fully considered and discussed in details in this chapter.

5.1.1 LNG Price Sensitivities

Based on the economic assumptions, a gas sale price of \$3.5/MMBtu is not profitable, the NPV is negative and the profitability index is below 1, as illustrated in Table 5.1. The IRR before the project can break even should be greater than 8%.

A gas price shift of \$1/MMBtu to \$4.5/MMBtu increases the profitability of the plant significantly with the payback period reducing to only three years. The profitability index is between the range 1.51 to 4.62, for a gas price of \$4.5 to \$10/MMBtu.

The profitability measures presented in Table 5.1 show the significant impact of gas price shifts. The IRR can be as high as 60%, for a gas price of \$10/MMBtu, based on the current economic assumptions. Therefore, gas prices must not be as small as \$3.5/MMBtu if LNG projects are to be profitable.

Table 5.1-LNG Price Sensitivities					
Factors	LNG				
Gas Price (\$/MMBtu)	3.5	4.5	6.5	8.5	10
NPV (\$billion)	(0.14)	1.46	4.67	7.89	10.30
Internal Rate Return (%)	8.82	21.65	39.03	52.80	61.64
Profitability Index	0.95	1.51	2.64	3.77	4.62
Payback Period (years)	20+	3.00	0.80	0.80	0.30
Revenue (\$billion/year)	1.31	1.68	2.42	3.17	3.73

5.1.2 GTL Price Sensitivities

With a crude oil price of \$30/bbl, the IRR is about 15% and NPV of \$1.01 billion. The payback period decreases from about 8 years to just 6 months with increasing crude oil prices, as shown in Table 5.2. The IRR can be as high as 40%, for a crude oil price of \$70/bbl, based on the current economic assumptions.

Table 5.2-GTL Price Sensitivities					
Factors	GTL				
Crude Oil Price (\$/bbl)	30	40	50	60	70
NPV (\$billion)	1.01	3.73	5.49	7.20	8.91
Internal Rate Return (%)	15.00	27.25	33.12	38.32	43.25
Profitability Index	1.36	2.33	2.96	3.57	4.18
Payback Period (years)	8.50	1.30	0.80	0.60	0.50
Revenue (\$billion/year)	1.18	1.81	2.22	2.62	3.02

5.1.3 Integrated GTL Power-Generation Price Sensitivities

The NPV varies from \$2.8 to \$8.1 billion, \$2.9 to \$8.5 billion and \$3.4 to \$11.0 billion for the Integrated GTL Power-Generation projects with 5%, 10%, and 70% steam supply respectively, as shown in Tables 5.3, 5.4, and 5.5.

Table 5.3-Integrated GTL Price Sensitivities (5% Steam Supply)												
Factors	Integrated GTL (5% Steam Supply)											
Oil Price (\$/bbl)	40			50			60			70		
Electric Tariff	5	10	15.9	5	10	15.9	5	10	15.9	5	10	15.9
NPV (\$billion)	2.81	2.89	2.98	4.52	4.60	4.69	6.23	6.31	6.40	7.94	8.02	8.11
IRR (%)	25.8	26.1	26.3	34.6	34.8	35.0	37.8	37.9	38.1	46.0	43.7	46.3
Profitability Index	2.00	2.03	2.07	2.61	2.64	2.68	3.22	3.25	3.29	3.83	3.86	3.90
Revenue (\$billion/yr)	1.61	1.63	1.65	2.00	2.02	2.05	2.40	2.42	2.44	2.80	2.82	2.84

Table 5.4-Integrated GTL Price Sensitivities (10% Steam Supply)												
Factors	Integrated GTL (10% Steam Supply)											
Oil Price (\$/bbl)	40			50			60			70		
Electric Tariff	5	10	15.9	5	10	15.9	5	10	15.9	5	10	15.9
NPV (\$billion)	2.85	3.02	3.21	4.56	4.73	4.92	6.27	6.44	6.63	7.98	8.15	8.34
IRR (%)	25.9	26.4	26.9	34.6	35.0	35.4	37.8	38.1	38.3	46.0	46.3	46.5
Profitability Index	2.02	2.08	2.15	2.63	2.69	2.76	3.24	3.30	3.37	3.85	3.91	3.98
Revenue (\$billion/yr)	1.63	1.66	1.71	2.02	2.06	2.11	2.42	2.46	2.50	2.82	2.85	2.90

Table 5.5-Integrated GTL Price Sensitivities (70% Steam Supply)												
Factors	Integrated GTL (70% Steam Supply)											
Oil Price (\$/bbl)	40			50			60			70		
Electric Tariff	5	10	15.9	5	10	15.9	5	10	15.9	5	10	15.9
NPV (\$billion)	3.43	4.57	5.92	5.14	6.28	7.63	6.85	7.99	9.34	8.56	9.70	11.0
IRR (%)	31.0	34.0	36.6	35.2	37.2	39.1	38.0	45.3	47.0	46.0	47.4	48.8
Profitability Index	2.23	2.63	3.11	2.84	3.24	3.73	3.45	3.85	4.34	4.06	4.46	4.95
Revenue (\$billion/yr)	1.85	2.12	2.43	2.25	2.52	2.83	2.42	2.91	3.23	3.04	3.31	3.62

Figures 5.1 and 5.2 show that at crude oil prices between \$40 and \$70 and natural gas prices between \$4/MMBtu and \$10/MMBtu, the IRR, NPV and PI are obviously greater than the LNG and stand-alone GTL projects.

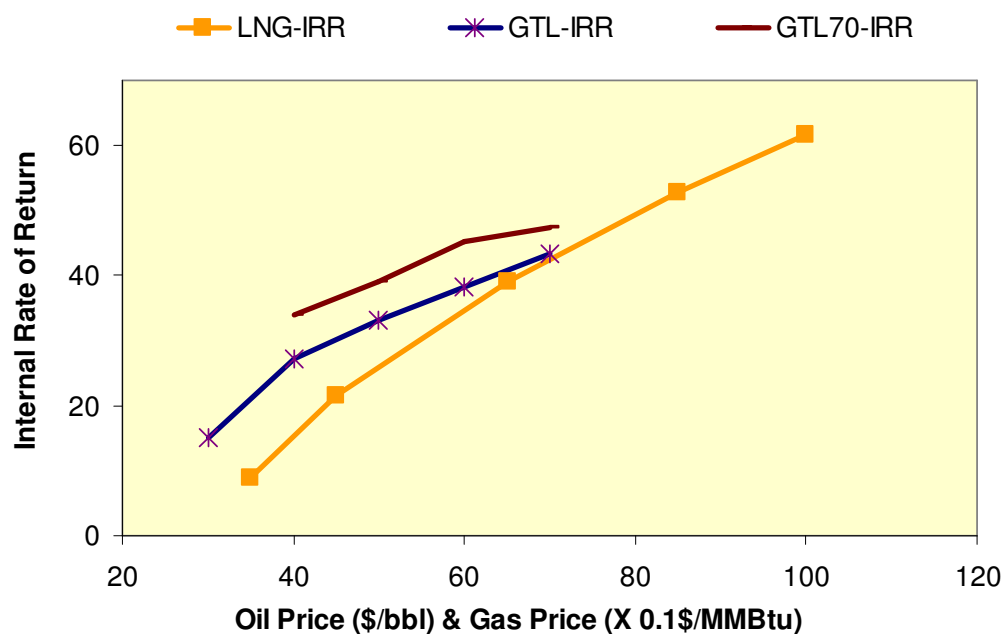


Figure 5.1-Internal Rate of Return for LNG, GTL, and Integrated GTL Power-Generation Projects.

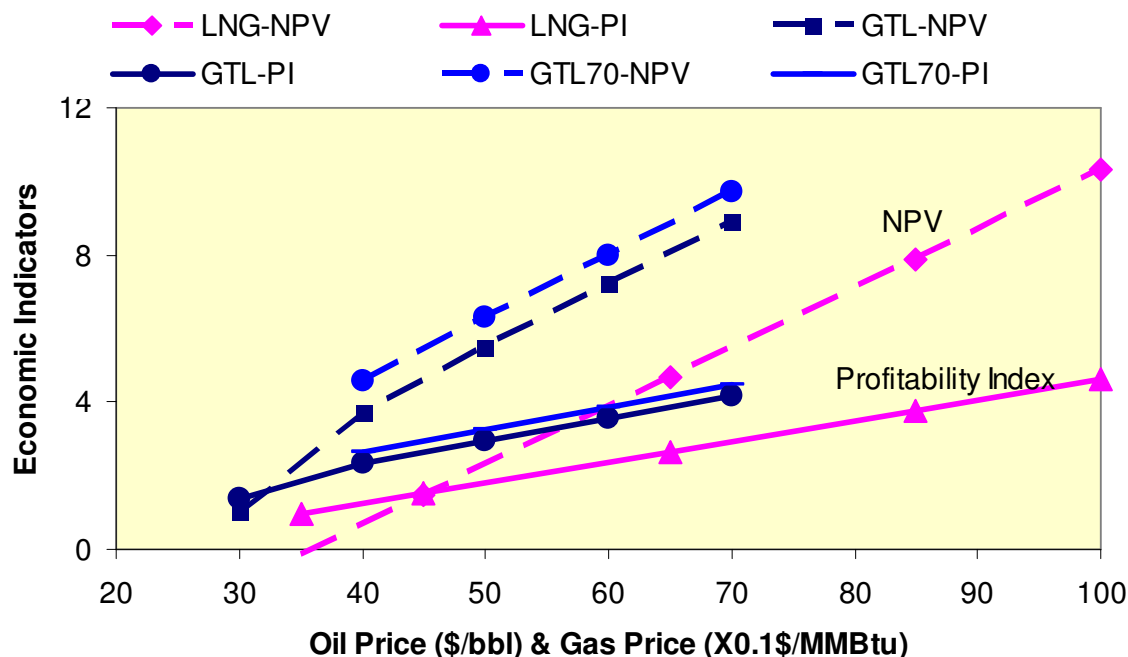


Figure 5.2-NPV and PI for LNG, GTL, and Integrated GTL Power-Generation Projects.

The payback period in the three steam supply cases reduces significantly compared to the stand-alone GTL project. The payback period varies from 6 months to 18 months for the different options of Integrated GTL Power-Generation projects compared to the stand-alone GTL plants which vary from 6 months to 9 years, with the same crude oil prices.

The profitability indices of the Integrated GTL Power-Generation projects is higher compared with the stand-alone GTL plants for the same crude oil prices, showing that the integrated projects are more profitable than the stand-alone GTL plants at any crude oil prices. The IRR of the integrated plant with 70% steam supply is between 30 and 50%, therefore, the projects will breakeven at discount rates as high as 30%, with crude oil prices varying from \$40 to \$70.

It can be readily observed that at crude oil prices of about \$50/bbl and gas prices of about \$6-6.5/MMBtu, both the LNG and GTL projects have very close or even equal economic returns.²⁸ With the same gas and crude oil prices, Integrated GTL Power-Generation option with 70% steam supply offers greater economic returns compared to both the stand-alone GTL and LNG projects. In terms of PIs, the Integrated GTL Power-Generation project with 70% steam supply varies from 2.23 to 4.95 as compared to 0.95 and 4.62 for both GTL and LNG projects.

CHAPTER VI

CONCLUSIONS & RECOMMENDATIONS

6.1 Conclusions

GTL plants produce a range of high quality, superior, sulfur-free fuel and chemical feedstock products different from the conventional crude oil refinery. The integration of power generation with GTL fuels creates a strategic diversification for commercial power supply, monetizes waste heat to improve cost, and improves the overall profitability of GTL plants.

The estimates of profitability measures make the Integrated GTL Power-Generation project with 70% steam supply the most profitable of the different options considered. Considering the current gas and crude oil prices, the Integrated GTL Power-Generation project with 70% steam supply can deliver more benefits on each dollar invested compared with the stand-alone GTL & LNG projects. The internal rate of return is greater than 30% for each of the projects with the current gas and crude oil prices, which means the projects will breakeven at a discount rate of 30%.

The estimates of the Integrated GTL Power-Generation plants show that the value-added is unquantifiable in terms of the economics. The key constraint to integrated systems is the availability of market for the generated power.

6.2 Recommendations for Future Work

- 1 The effects of feed gas compositional variance and carbon conversion efficiencies on the quantity and quality of steam generated from the Syngas generation and FT

synthesis units should be considered. The key constraint in the power generation cycle is the quantity and quality of steam supplied into the turbines.

- 2** A deterministic economic approach was used to analyze cash flow for the different projects. Since, the key issue in GTL projects is economics, a probabilistic approach can be used which gives more information on downside risk.
- 3** Other methods to improve the thermal efficiencies of the steam plants should be considered, since the steam plant power rating is a direct function of the thermal efficiencies.

NOMENCLATURE

DOE	= Department of Energy
S_i	= +1 for inlet streams, -1 for outlet streams
σ_I	= Stream scale factor
F_i	= Mass flow of stream i, lb
f_{ij}	= Mass fraction of substream j in stream i
Z_{ijk}	= Mass fraction of component k in substream j of stream i
NM	= Number of combined inlet and outlet material streams
NH	= Number of combined inlet and outlet heat streams
NW	= Number of combined inlet and outlet work streams
NSS	= Number of substreams within material streams
NC	= Number of components specified on the Components Specifications or Components Comp-Group forms
h_i	= Mass enthalpy of stream I, Btu/lb
H_j	= Heat flow of heat stream j, Btu/lb
W_k	= Work flow of work stream k, Btu/lb
RHS	= Right-hand side of the energy balance equation
Ws (net)	= Net work of cycle, Btu/lb
Ws (pump)	= Work done by pump shaft, Btu/lb

W_s (turbine) = Work done by turbine shaft, Btu/lb

Q (boiler)/ Q_H = Heat supplied to boiler, Btu/lb

Q_C = Heat rejected from the condenser, Btu/lb

$\dot{W}_s(\text{net})$ = Net cycle work rate or Power rating, Btu/hr or Watts

\dot{m} = Steam mass flow rate, lb/hr

P_1 = Turbine steam inlet pressure, psi

P_2 = Pump steam exit pressure, psi

T_1 = Turbine steam inlet temperature, psi

T_2 = Pump steam exit temperature, psi

H_2 = Enthalpy of superheated steam into turbine, Btu/lb

H_1 = Enthalpy of saturated liquid exiting pump, Btu/lb

η = Thermal efficiency of cycle, %

Subscript

i, j, k = Stream notations

Units

Tcf = Trillion cubic feet (10^{12} cubic feet)

BOE = Barrel of Oil Equivalent

Bcf = Billion cubic feet (10^9 cubic feet)

bpd = barrel per day

Bcf/D = billion cubic feet per day

MW = Megawatts (10^6 Watts)

Btu = British thermal units

kW-h = kilowatts hour

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APPENDIX A: ASPEN PROCESS MAP

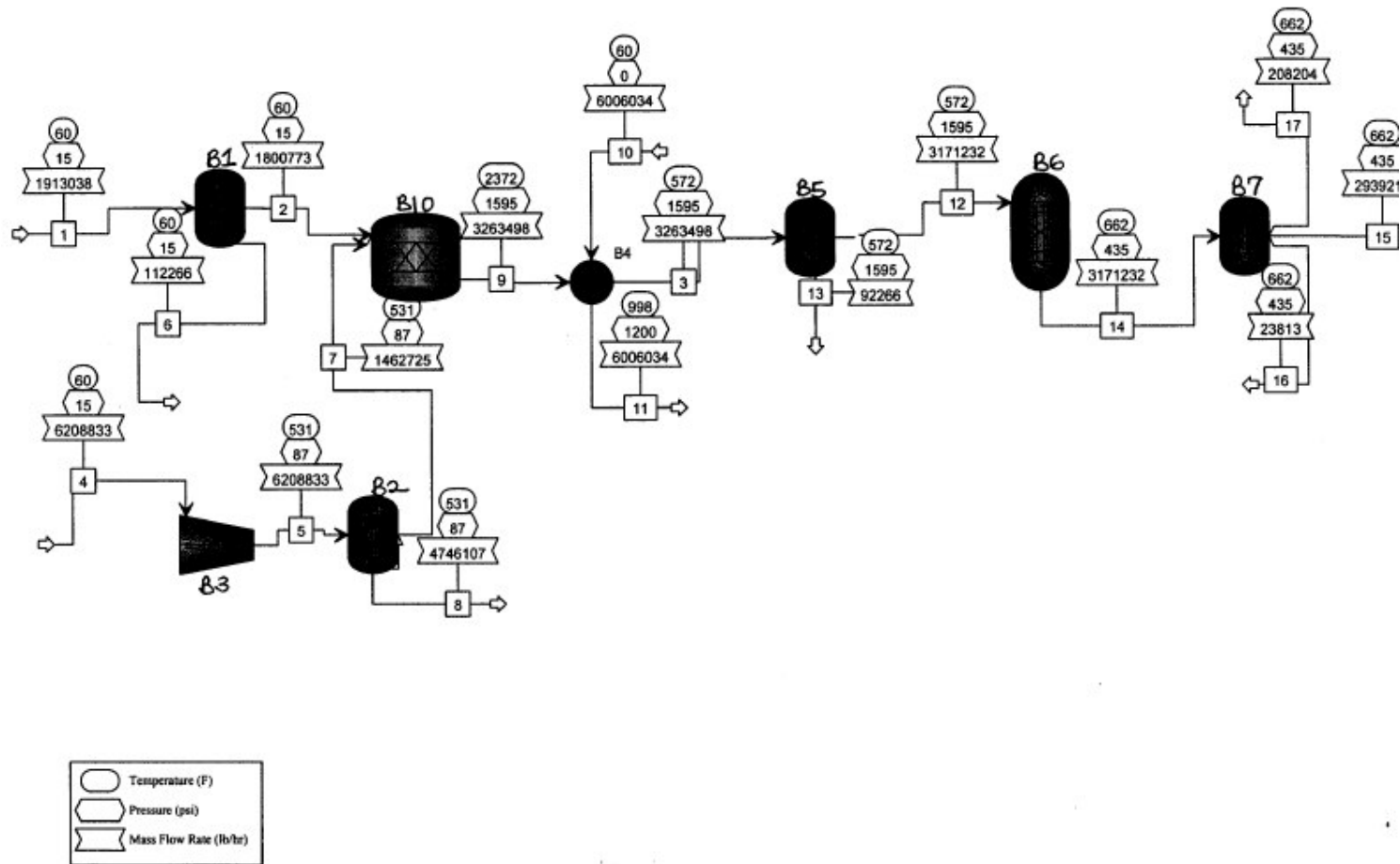


Figure A1-Overview of GTL Process Designed with Aspen Plus.

APPENDIX B: ASPEN REPORT

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ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
RUN CONTROL SECTION

RUN CONTROL INFORMATION

THIS COPY OF ASPEN PLUS LICENSED TO TEXAS A&M UNIV

TYPE OF RUN: NEW

INPUT FILE NAME: _2920nnh.inm

OUTPUT PROBLEM DATA FILE NAME: _2920nnh
 LOCATED IN:

PDF SIZE USED FOR INPUT TRANSLATION:

NUMBER OF FILE RECORDS (PSIZE) = 0
 NUMBER OF IN-CORE RECORDS = 256
 PSIZE NEEDED FOR SIMULATION = 256

CALLING PROGRAM NAME: apmain
 LOCATED IN: C:\PROGRA~1\ASPENT~1\ASPENP~1.1\Engine\xeq

SIMULATION REQUESTED FOR ENTIRE FLOWSHEET

DESCRIPTION

GAS PROCESSING WITH ENGLISH UNITS: F, PSI, LB/HR, MMSCFD,
 MMBTU/HR, MMCUFT/HR. PROPERTY METHOD: PENG-ROB FLOW BASIS FOR
 INPUT: MOLE STREAM REPORT COMPOSITION: MOLE FLOW

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
FLWSHEET SECTION

FLWSHEET CONNECTIVITY BY STREAMS

STREAM	SOURCE	DEST	STREAM	SOURCE	DEST
4	----	B3	1	----	B1
10	----	B4	5	B3	B2
9	B10	B4	2	B1	B10
6	B1	----	7	B2	B10
8	B2	----	3	B4	B5
11	B4	----	12	B5	B6
13	B5	----	14	B6	B7
15	B7	----	16	B7	----
17	B7	----			

FLWSHEET CONNECTIVITY BY BLOCKS

BLOCK	INLETS	OUTLETS
B3	4	5
B10	2 7	9
B1	1	2 6
B2	5	7 8
B4	9 10	3 11
B5	3	12 13
B6	12	14
B7	14	15 16 17

COMPUTATIONAL SEQUENCE

SEQUENCE USED WAS:

B1 B3 B2 B10 *B4 B5 *B6 B7

OVERALL FLWSHEET BALANCE

*** MASS AND ENERGY BALANCE ***				
	IN	OUT	GENERATION	RELATIVE DIFF.
CONVENTIONAL COMPONENTS				
(MMSCFD)				
CH4	940.000	90.9160	-849.084	-0.604717E-16
CO2	30.0000	0.000000E+00	-30.0000	0.000000E+00

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
FLWSHEET SECTION

MASS AND ENERGY BALANCE (CONTINUED)

CONVENTIONAL COMPONENTS

(MMSCFD)

H2S	30.0000	30.0000	0.000000E+00	0.000000E+00
N2	1548.40	1548.40	0.000000E+00	0.000000E+00
O2	411.600	2.05800	-409.542	0.884726E-16
NO	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
CO	0.000000E+00	30.0000	30.0000	0.000000E+00
H2	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
NAPHTHA	0.000000E+00	21.0511	21.0511	0.000000E+00
LPG	0.000000E+00	5.26558	5.26558	0.000000E+00
N-EICOSA	0.000000E+00	78.9445	78.9445	0.000000E+00
H2O	3036.30	3141.56	105.256	0.723761E-16
O2S	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00

TOTAL BALANCE

MOLE (MMSCFD)	5996.30	4948.19	-1048.11	0.000000E+00
MASS (LB/HR)	0.141279E+08	0.141279E+08		0.131842E-15
ENTHALPY (MMBTU/HR)	-45288.3	-37959.2		-0.161831

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
PHYSICAL PROPERTIES SECTION

COMPONENTS

ID	TYPE	FORMULA	NAME OR ALIAS	REPORT NAME
CH4	C	CH4	CH4	CH4
CO2	C	CO2	CO2	CO2
H2S	C	H2S	H2S	H2S
N2	C	N2	N2	N2
O2	C	O2	O2	O2
NO	C	NO	NO	NO
CO	C	CO	CO	CO
H2	C	H2	H2	H2
NAPHTHA	C	C10H8	C10H8	NAPHTHA
LPG	C	C4H10-1	C4H10-1	LPG
N-EICOSA	C	C20H42	C20H42	N-EICOSA
H2O	C	H2O	H2O	H2O
O2S	C	O2S	O2S	O2S

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
U-O-S BLOCK SECTION

BLOCK: B1 MODEL: SEP

 INLET STREAM: 1
 OUTLET STREAMS: 2 6
 PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

***** MASS AND ENERGY BALANCE *****

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE (MMSCFD)	1000.00	1000.00	0.113687E-15
MASS (LB/HR)	0.191304E+07	0.191304E+07	-0.243415E-15
ENTHALPY (MMBTU/HR)	-3909.98	-3909.99	0.285806E-05

***** INPUT DATA *****

FLASH SPECS FOR STREAM 2

TWO PHASE TP FLASH

PRESSURE DROP	PSI	0.0	
MAXIMUM NO. ITERATIONS		30	
CONVERGENCE TOLERANCE		0.00010000	

FLASH SPECS FOR STREAM 6

TWO PHASE TP FLASH

PRESSURE DROP	PSI	0.0	
MAXIMUM NO. ITERATIONS		30	
CONVERGENCE TOLERANCE		0.00010000	

FRACTION OF FEED

SUBSTREAM= MIXED

STREAM= 2	CPT= CH4	FRACTION=	1.00000
	CO2		1.00000

***** RESULTS *****

HEAT DUTY	MMBTU/HR	-0.31380E-01
-----------	----------	--------------

COMPONENT = CH4

STREAM	SUBSTREAM	SPLIT FRACTION
2	MIXED	1.00000

ASPEN PLUS PLAT: WIN32 VER: 12.1
INTEGRATED GTL-POWER GENERATION PROCESS
U-O-S BLOCK SECTION

RESULTS (CONTINUED)

COMPONENT = CO2

STREAM	SUBSTREAM	SPLIT FRACTION
2	MIXED	1.00000

COMPONENT = H2S

STREAM	SUBSTREAM	SPLIT FRACTION
	6	MIXED 1.00000

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
U-O-S BLOCK SECTION

BLOCK: B10 MODEL: RSTOIC

 INLET STREAMS: 2 7
 OUTLET STREAM: 9
 PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

***** MASS AND ENERGY BALANCE *****

	IN	OUT	GENERATION	RELATIVE DIFF.
TOTAL BALANCE				
MOLE (MMSCFD)	1387.28	2675.91	1288.63	0.849706E-16
MASS (LB/HR)	0.326350E+07	0.326350E+07		0.285376E-15
ENTHALPY (MMBTU/HR)	-3729.64	320.281		-1.08587

***** INPUT DATA *****

STOICHIOMETRY MATRIX:

REACTION # 1:
 SUBSTREAM MIXED :
 CH4 -1.00 O2 -0.500 CO 1.00 H2 2.00

REACTION # 2:
 SUBSTREAM MIXED :
 CH4 -1.00 CO2 -1.00 CO 2.00 H2 2.00

REACTION CONVERSION SPECS: NUMBER= 2

REACTION # 1:
 SUBSTREAM:MIXED KEY COMP:O2 CONV FRAC: 1.000
 REACTION # 2:
 SUBSTREAM:MIXED KEY COMP:CO2 CONV FRAC: 1.000

ONE PHASE TP FLASH SPECIFIED PHASE IS VAPOR

SPECIFIED TEMPERATURE F	2,372.00
SPECIFIED PRESSURE PSI	1,595.42
MAXIMUM NO. ITERATIONS	30
CONVERGENCE TOLERANCE	0.00010000
SIMULTANEOUS REACTIONS	
GENERATE COMBUSTION REACTIONS FOR FEED SPECIES	NO

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
U-O-S BLOCK SECTION

***** RESULTS *****

OUTLET TEMPERATURE	F	2372.0
OUTLET PRESSURE	PSI	1595.4
HEAT DUTY	MMBTU/HR	4049.9

HEAT OF REACTIONS:

REACTION NUMBER	REFERENCE COMPONENT	HEAT OF REACTION BTU/LBMOL
1	CH4	-15475.00
2	CH4	0.10620E+06

REACTION EXTENTS:

REACTION NUMBER	REACTION EXTENT MMSCFD
1	819.08
2	30.000

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
U-O-S BLOCK SECTION

BLOCK: B2 MODEL: SEP

 INLET STREAM: 5
 OUTLET STREAMS: 7 8
 PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

***** MASS AND ENERGY BALANCE *****

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE (MMSCFD)	1960.00	1960.00	-0.232014E-15
MASS (LB/HR)	0.620883E+07	0.620883E+07	0.000000E+00
ENTHALPY (MMBTU/HR)	689.638	689.637	0.138528E-05

***** INPUT DATA *****

FLASH SPECS FOR STREAM 7

TWO PHASE TP FLASH

PRESSURE DROP	PSI	0.0
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.00010000

FLASH SPECS FOR STREAM 8

TWO PHASE TP FLASH

PRESSURE DROP	PSI	0.0
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.00010000

FRACTION OF FEED

SUBSTREAM= MIXED

STREAM= 7	CPT= N2	FRACTION=	0.0050000
	O2		0.99500

***** RESULTS *****

HEAT DUTY	MMBTU/HR	0.42218E-02
-----------	----------	-------------

COMPONENT = N2

STREAM	SUBSTREAM	SPLIT FRACTION
7	MIXED	0.0050000
8	MIXED	0.99500

ASPEN PLUS PLAT: WIN32 VER: 12.1
INTEGRATED GTL-POWER GENERATION PROCESS
U-O-S BLOCK SECTION

RESULTS (CONTINUED)

COMPONENT = O2

STREAM	SUBSTREAM	SPLIT FRACTION
7	MIXED	0.99500
8	MIXED	0.0050000

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
U-O-S BLOCK SECTION

BLOCK: B3 MODEL: COMPR

INLET STREAM: 4
 OUTLET STREAM: 5
 PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

***** MASS AND ENERGY BALANCE *****

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE (MMSCFD)	1960.00	1960.00	0.000000E+00
MASS (LB/HR)	0.620883E+07	0.620883E+07	0.000000E+00
ENTHALPY (MMBTU/HR)	-26.2813	689.638	-1.03811

***** INPUT DATA *****

ISENTROPIC CENTRIFUGAL COMPRESSOR

OUTLET PRESSURE PSI	87.0226
ISENTROPIC EFFICIENCY	0.72000
MECHANICAL EFFICIENCY	1.00000

***** RESULTS *****

INDICATED HORSEPOWER REQUIREMENT HP	281,367.00
BRAKE HORSEPOWER REQUIREMENT HP	281,367.00
NET WORK REQUIRED HP	281,367.00
POWER LOSSES HP	0.00
ISENTROPIC HORSEPOWER REQUIREMENT HP	202,584.00
CALCULATED OUTLET TEMP F	530.731
ISENTROPIC TEMPERATURE F	401.081
EFFICIENCY (POLYTR/ISENTR) USED	0.72000
OUTLET VAPOR FRACTION	1.00000
IDEAL HEAD DEVELOPED, FT	64,604.10
ACTUAL HEAD DEVELOPED, FT	89,728.00
MECHANICAL EFFICIENCY USED	1.00000
INLET HEAT CAPACITY RATIO	1.39761
INLET VOLUMETRIC FLOW RATE , MMCUFT/H	81.8847
OUTLET VOLUMETRIC FLOW RATE, MMCUFT/H	26.3440
INLET COMPRESSIBILITY FACTOR	0.99953
OUTLET COMPRESSIBILITY FACTOR	1.00228
AV. ISENT. VOL. EXPONENT	1.39794

ASPEN PLUS PLAT: WIN32 VER: 12.1
INTEGRATED GTL-POWER GENERATION PROCESS
U-O-S BLOCK SECTION

RESULTS (CONTINUED)

AV. ISENT. TEMP EXPONENT	1.39512
AV. ACTUAL VOL. EXPONENT	1.57109
AV. ACTUAL TEMP EXPONENT	1.56730

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
U-O-S BLOCK SECTION

BLOCK: B4 MODEL: HEATX

HOT SIDE:

 INLET STREAM: 9
 OUTLET STREAM: 3
 PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE
 COLD SIDE:

INLET STREAM: 10
 OUTLET STREAM: 11
 PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

***** MASS AND ENERGY BALANCE *****

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE (MMSCFD)	5712.21	5712.21	0.000000E+00
MASS (LB/HR)	0.926953E+07	0.926953E+07	0.000000E+00
ENTHALPY (MMBTU/HR)	-41029.1	-41029.1	0.177336E-15

***** INPUT DATA *****

FLASH SPECS FOR HOT SIDE:

ONE PHASE FLASH SPECIFIED PHASE IS VAPOR

MAXIMUM NO. ITERATIONS	30
CONVERGENCE TOLERANCE	0.00010000

FLASH SPECS FOR COLD SIDE:

TWO PHASE FLASH

MAXIMUM NO. ITERATIONS	30
CONVERGENCE TOLERANCE	0.00010000

FLOW DIRECTION AND SPECIFICATION:

COUNTERCURRENT HEAT EXCHANGER

SPECIFIED HOT OUTLET TEMP

SPECIFIED VALUE	F	572.0000
-----------------	---	----------

LMTD CORRECTION FACTOR	1.00000
------------------------	---------

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
U-O-S BLOCK SECTION

INPUT DATA (CONTINUED)

PRESSURE SPECIFICATION:

HOT SIDE OUTLET PRESSURE	PSI	1595.4151
COLD SIDE PRESSURE DROP	PSI	0.0000

HEAT TRANSFER COEFFICIENT SPECIFICATION:

HOT LIQUID	COLD LIQUID	BTU/HR-SQFT-R	149.6937
HOT 2-PHASE	COLD LIQUID	BTU/HR-SQFT-R	149.6937
HOT VAPOR	COLD LIQUID	BTU/HR-SQFT-R	149.6937
HOT LIQUID	COLD 2-PHASE	BTU/HR-SQFT-R	149.6937
HOT 2-PHASE	COLD 2-PHASE	BTU/HR-SQFT-R	149.6937
HOT VAPOR	COLD 2-PHASE	BTU/HR-SQFT-R	149.6937
HOT LIQUID	COLD VAPOR	BTU/HR-SQFT-R	149.6937
HOT 2-PHASE	COLD VAPOR	BTU/HR-SQFT-R	149.6937
HOT VAPOR	COLD VAPOR	BTU/HR-SQFT-R	149.6937

***** OVERALL RESULTS *****

STREAMS:

9	----->	HOT	----->	3
T= 2.3720D+03				T= 5.7200D+02
P= 1.5954D+03				P= 1.5954D+03
V= 1.0000D+00				V= 1.0000D+00
11	<-----	COLD	<-----	10
T= 9.9800D+02				T= 6.0000D+01
P= 1.2000D+03				P= 2.5610D-01
V= 1.0000D+00				V= 0.0000D+00

DUTY AND AREA:

CALCULATED HEAT DUTY	MMBTU/HR	4176.1779
CALCULATED (REQUIRED) AREA	SQFT	23492.7645
ACTUAL EXCHANGER AREA	SQFT	23492.7645
PER CENT OVER-DESIGN		0.0000

HEAT TRANSFER COEFFICIENT:

AVERAGE COEFFICIENT (DIRTY)	BTU/HR-SQFT-R	149.6937
UA (DIRTY)	BTU/HR-R	3516717.8117

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
U-O-S BLOCK SECTION

OVERALL RESULTS (CONTINUED)

LOG-MEAN TEMPERATURE DIFFERENCE:

LMTD CORRECTION FACTOR		1.0000
LMTD (CORRECTED)	F	1187.5215
NUMBER OF SHELLS IN SERIES		1

PRESSURE DROP:

HOTSIDE, TOTAL	PSI	0.0000
COLD SIDE, TOTAL	PSI	0.0000

PRESSURE DROP PARAMETER:

HOT SIDE:		0.00000E+00
COLD SIDE:		0.00000E+00

***** ZONE RESULTS *****

TEMPERATURE LEAVING EACH ZONE:

HOT			
9	VAP	VAP	3
2372.0	590.5	572.0	572.0
11	BOIL	LIQ	10
66.2	66.2	60.0	60.0
COLD			

ZONE HEAT TRANSFER AND AREA:

ZONE	HEAT DUTY MMBTU/HR	AREA SQFT	DTLM F	AVERAGE U BTU/HR-SQFT-R	UA BTU/HR-R
1	4136.161	22976.8583	1202.5507	149.6937	3439489.9202
2	40.017	515.9062	518.1649	149.6937	77227.8915

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
U-O-S BLOCK SECTION

BLOCK: B5 MODEL: SEP

 INLET STREAM: 3
 OUTLET STREAMS: 12 13
 PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

***** MASS AND ENERGY BALANCE *****

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE (MMSCFD)	2675.91	2675.91	0.000000E+00
MASS (LB/HR)	0.326350E+07	0.326350E+07	-0.142688E-15
ENTHALPY (MMBTU/HR)	-3855.90	-3856.00	0.271277E-04

***** INPUT DATA *****

FLASH SPECS FOR STREAM 12

TWO PHASE TP FLASH

PRESSURE DROP PSI 0.0

MAXIMUM NO. ITERATIONS 30

CONVERGENCE TOLERANCE 0.00010000

FLASH SPECS FOR STREAM 13

TWO PHASE TP FLASH

PRESSURE DROP PSI 0.0

MAXIMUM NO. ITERATIONS 30

CONVERGENCE TOLERANCE 0.00010000

FRACTION OF FEED

SUBSTREAM= MIXED

STREAM= 12	CPT= CH4	FRACTION=	1.00000
	N2		1.00000
	CO		0.96587
	H2		1.00000

***** RESULTS *****

HEAT DUTY MMBTU/HR -0.10460

COMPONENT = CH4

STREAM	SUBSTREAM	SPLIT FRACTION
12	MIXED	1.00000

ASPEN PLUS PLAT: WIN32 VER: 12.1
INTEGRATED GTL-POWER GENERATION PROCESS
U-O-S BLOCK SECTION

RESULTS (CONTINUED)

COMPONENT = N2

STREAM	SUBSTREAM	SPLIT FRACTION
12	MIXED	1.00000

COMPONENT = CO

STREAM	SUBSTREAM	SPLIT FRACTION
12	MIXED	0.96587
13	MIXED	0.034126

COMPONENT = H2

STREAM	SUBSTREAM	SPLIT FRACTION
12	MIXED	1.00000

*** MASS AND ENERGY BALANCE ***

*** INPUT DATA ***

MOLE-YIELD

INERTS: N2 CH4

*** RESULTS ***

OUTLET TEMPERATURE	F	662.00
OUTLET PRESSURE	PSI	435.11
HEAT DUTY	MMBTU/HR	321.76
VAPOR FRACTION		1.0000

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
U-O-S BLOCK SECTION

INPUT DATA (CONTINUED)

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
CH4	0.29406	0.57664E-01	0.40077	6.9501
N2	0.25041E-01	0.37894E-02	0.34634E-01	9.1398
NAPHTHA	0.68088E-01	0.10353	0.52087E-01	0.50309
LPG	0.17031E-01	0.74922E-02	0.21337E-01	2.8479
N-EICOSA	0.25534	0.68156	0.62945E-01	0.92353E-01
H2O	0.34044	0.14596	0.42823	2.9338

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
U-O-S BLOCK SECTION

BLOCK: B7 MODEL: SEP

 INLET STREAM: 14
 OUTLET STREAMS: 15 16 17
 PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

***** MASS AND ENERGY BALANCE *****

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE (MMSCFD)	309.175	309.175	0.000000E+00
MASS (LB/HR)	0.317123E+07	0.317123E+07	0.000000E+00
ENTHALPY (MMBTU/HR)	-2324.47	-1150.13	-0.505207

***** INPUT DATA *****

FLASH SPECS FOR STREAM 17
 TWO PHASE TP FLASH
 PRESSURE DROP PSI 0.0
 MAXIMUM NO. ITERATIONS 30
 CONVERGENCE TOLERANCE 0.00010000

FRACTION OF FEED

SUBSTREAM= MIXED

STREAM= 15	CPT= CH4	FRACTION=	1.00000
	CO		0.0
	H2		0.0
	NAPHTHA		1.00000
	LPG		1.00000
	N-EICOSA		1.00000
STREAM= 16	CPT= N2	FRACTION=	1.00000
	CO		1.00000
	H2		1.00000

***** RESULTS *****

HEAT DUTY MMBTU/HR 0.37334E+38

COMPONENT = CH4

STREAM	SUBSTREAM	SPLIT FRACTION
15	MIXED	1.00000

COMPONENT = N2

STREAM	SUBSTREAM	SPLIT FRACTION
16	MIXED	1.00000

ASPEN PLUS PLAT: WIN32 VER: 12.1
INTEGRATED GTL-POWER GENERATION PROCESS
U-O-S BLOCK SECTION

RESULTS (CONTINUED)

COMPONENT = NAPHTHA

STREAM	SUBSTREAM	SPLIT FRACTION
15	MIXED	1.00000

COMPONENT = LPG

STREAM	SUBSTREAM	SPLIT FRACTION
15	MIXED	1.00000

COMPONENT = N-EICOSA

STREAM	SUBSTREAM	SPLIT FRACTION
15	MIXED	1.00000

COMPONENT = H2O

STREAM	SUBSTREAM	SPLIT FRACTION
17	MIXED	1.00000

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
STREAM SECTION

1 10 11 12 13

STREAM ID	1	10	11	12	13
FROM :	----	----	B4	B5	B5
TO :	B1	B4	----	B6	----

SUBSTREAM: MIXED

PHASE:	VAPOR	LIQUID	VAPOR	VAPOR	VAPOR
COMPONENTS: MMSCFD					
CH4	940.0000	0.0	0.0	90.9160	0.0
CO2	30.0000	0.0	0.0	0.0	0.0
H2S	30.0000	0.0	0.0	0.0	0.0
N2	0.0	0.0	0.0	7.7420	0.0
O2	0.0	0.0	0.0	0.0	0.0
NO	0.0	0.0	0.0	0.0	0.0
CO	0.0	0.0	0.0	849.0840	30.0000
H2	0.0	0.0	0.0	1698.1680	0.0
NAPHTHA	0.0	0.0	0.0	0.0	0.0
LPG	0.0	0.0	0.0	0.0	0.0
N-EICOSA	0.0	0.0	0.0	0.0	0.0
H2O	0.0	3036.3000	3036.3000	0.0	0.0
O2S	0.0	0.0	0.0	0.0	0.0

COMPONENTS: MOLE FRAC

CH4	0.9400	0.0	0.0	3.4361-02	0.0
CO2	3.0000-02	0.0	0.0	0.0	0.0
H2S	3.0000-02	0.0	0.0	0.0	0.0
N2	0.0	0.0	0.0	2.9260-03	0.0
O2	0.0	0.0	0.0	0.0	0.0
NO	0.0	0.0	0.0	0.0	0.0
CO	0.0	0.0	0.0	0.3209	1.0000
H2	0.0	0.0	0.0	0.6418	0.0
NAPHTHA	0.0	0.0	0.0	0.0	0.0
LPG	0.0	0.0	0.0	0.0	0.0
N-EICOSA	0.0	0.0	0.0	0.0	0.0
H2O	0.0	1.0000	1.0000	0.0	0.0
O2S	0.0	0.0	0.0	0.0	0.0

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
STREAM SECTION

1 10 11 12 13

COMPONENTS: STD MMCUFT/H

CH4	8.8547-02	0.0	0.0	8.5642-03	0.0
CO2	2.8260-03	0.0	0.0	0.0	0.0
H2S	2.8260-03	0.0	0.0	0.0	0.0
N2	0.0	0.0	0.0	7.2929-04	0.0
O2	0.0	0.0	0.0	0.0	0.0
NO	0.0	0.0	0.0	0.0	0.0
CO	0.0	0.0	0.0	7.9983-02	2.8260-03
H2	0.0	0.0	0.0	0.1600	0.0
NAPHTHA	0.0	0.0	0.0	0.0	0.0
LPG	0.0	0.0	0.0	0.0	0.0
N-EICOSA	0.0	0.0	0.0	0.0	0.0
H2O	0.0	9.6393-02	9.6393-02	0.0	0.0
O2S	0.0	0.0	0.0	0.0	0.0
TOTAL MMCUFT/HR	9.4199-02	9.6393-02	9.6393-02	0.2492	2.8260-03

COMPONENTS: STD VOL FRAC

CH4	0.9400	0.0	0.0	3.4361-02	0.0
CO2	3.0000-02	0.0	0.0	0.0	0.0
H2S	3.0000-02	0.0	0.0	0.0	0.0
N2	0.0	0.0	0.0	2.9260-03	0.0
O2	0.0	0.0	0.0	0.0	0.0
NO	0.0	0.0	0.0	0.0	0.0
CO	0.0	0.0	0.0	0.3209	1.0000
H2	0.0	0.0	0.0	0.6418	0.0
NAPHTHA	0.0	0.0	0.0	0.0	0.0
LPG	0.0	0.0	0.0	0.0	0.0
N-EICOSA	0.0	0.0	0.0	0.0	0.0
H2O	0.0	1.0000	1.0000	0.0	0.0
O2S	0.0	0.0	0.0	0.0	0.0
TOTAL MMCUFT/HR	9.4199-02	9.6393-02	9.6393-02	0.2492	2.8260-03

TOTAL FLOW:

MMSCFD	1000.0000	3036.3000	3036.3000	2645.9100	30.0000
LB/HR	1.9130+06	6.0060+06	6.0060+06	3.1712+06	9.2266+04
MMCUFT/HR	41.7097	9.5960-02	96.2074	2.0943	2.3869-02

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
STREAM SECTION

1 10 11 12 13

STREAM ID		1	10	11	12	13
STATE VARIABLES:						
TEMP	F	60.0000	60.0000	998.0000	572.0000	572.0000
PRES	PSI	14.6500	0.2561	1200.0000	1595.4151	1595.4151
VFRAC		1.0000	0.0	1.0000	1.0000	1.0000
LFRAC		0.0	1.0000	0.0	0.0	0.0
SFRAC		0.0	0.0	0.0	0.0	0.0
ENTHALPY:						
BTU/LBMOL		-3.5609+04	-1.2404+05	0.0	-1.2773+04	-4.4033+04
BTU/LB		-2043.7869	-6885.0784	0.0	-1170.1944	-1572.0083
MMBTU/HR		-3909.8426	-4.1352+04	0.0	-3710.9579	-145.0433
ENTROPY:						
BTU/LBMOL-R		-17.5106	-40.7288	0.0	3.0426	16.5284
BTU/LB-R		-1.0050	-2.2608	0.0	0.2787	0.5901
DENSITY:						
LBMOL/CUFT		2.6325-03	3.4742	0.0	0.1387	0.1380
LB/CUFT		4.5866-02	62.5887	0.0	1.5143	3.8656
AVG MW		17.4229	18.0153	18.0153	10.9157	28.0104

MIXED SUBSTREAM PROPERTIES:

***** ALL PHASES *****

TCMX	F	-100.6377	705.1640	705.1640	-332.0978	-220.4140
PCMX	PSI	698.1301	3198.8073	3198.8073	309.4400	507.4870
VCMX	CUFT/LBMOL	1.5772	0.8962	0.8962	1.2032	1.5121

***** VAPOR PHASE *****

ZMX		0.9979	0.0	0.9362	1.0388	1.0442
VMX	CUFT/MIN	6.9516+05	0.0	6.7808+04	3.4904+04	397.8115
MOLEFLMX	MMSCFD	1000.0000	0.0	3036.3000	2645.9100	30.0000
CPCVMX		1.3110	0.0	1.3815	1.3822	1.4033
HMX	BTU/LB	-2043.7869	0.0	-5373.1145	-1170.1944	-1572.0083
CPMX	BTU/LB-R	0.4861	0.0	0.5750	0.6726	0.2681
KMX	BTU-FT/HR-SQ	1.8229-02	0.0	4.1325-02	0.1003	2.4558-02
RHOMX	LB/CUFT	4.5866-02	0.0	1.4762	1.5143	3.8656
MUMX	CP	1.1158-02	0.0	3.0616-02	2.4230-02	2.9447-02

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
STREAM SECTION

1 10 11 12 13

***** LIQUID PHASE *****

STREAM ID		1	10	11	12	13
HMX	BTU/LB	0.0	-6885.0784	0.0	0.0	0.0
CPMX	BTU/LB-R	0.0	1.0816	0.0	0.0	0.0
KMX	BTU-FT/HR-SQ	0.0	0.3423	0.0	0.0	0.0
RHOMX	LB/CUFT	0.0	62.5887	0.0	0.0	0.0
MUMX	CP	0.0	1.1344	0.0	0.0	0.0
SIGMAMX	DYNE/CM	0.0	37.1500	0.0	0.0	0.0

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
STREAM SECTION

14 15 16 17 2

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STREAM ID          14          15          16          17          2
FROM :            B6          B7          B7          B7          B1
TO   :            B7          ----          ----          ----          B10
SUBSTREAM: MIXED
PHASE:            MIXED      MIXED      VAPOR      VAPOR      VAPOR
COMPONENTS: MMSCFD
  CH4              90.9160    90.9160    0.0         0.0         940.0000
  CO2               0.0        0.0        0.0         0.0         30.0000
  H2S               0.0        0.0        0.0         0.0         0.0
  N2                7.7420    0.0        7.7420      0.0         0.0
  O2                0.0        0.0        0.0         0.0         0.0
  NO                0.0        0.0        0.0         0.0         0.0
  CO                0.0        0.0        0.0         0.0         0.0
  H2                0.0        0.0        0.0         0.0         0.0
  NAPHTHA          21.0511    21.0511    0.0         0.0         0.0
  LPG              5.2656     5.2656    0.0         0.0         0.0
  N-EICOSA         78.9445    78.9445    0.0         0.0         0.0
  H2O             105.2555    0.0        0.0        105.2555    0.0
  O2S              0.0        0.0        0.0         0.0         0.0
COMPONENTS: MOLE FRAC
  CH4              0.2941    0.4634    0.0         0.0         0.9691
  CO2               0.0        0.0        0.0         0.0         3.0928-02
  H2S               0.0        0.0        0.0         0.0         0.0
  N2                2.5041-02    0.0        1.0000      0.0         0.0
  O2                0.0        0.0        0.0         0.0         0.0
  NO                0.0        0.0        0.0         0.0         0.0
  CO                0.0        0.0        0.0         0.0         0.0
  H2                0.0        0.0        0.0         0.0         0.0
  NAPHTHA          6.8088-02    0.1073    0.0         0.0         0.0
  LPG              1.7031-02    2.6841-02  0.0         0.0         0.0
  N-EICOSA         0.2553    0.4024    0.0         0.0         0.0
  H2O              0.3404    0.0        0.0         1.0000      0.0
  O2S              0.0        0.0        0.0         0.0         0.0

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ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
STREAM SECTION

14 15 16 17 2

 COMPONENTS: STD MMCUFT/H

CH4	8.5642-03	8.5642-03	0.0	0.0	8.8547-02
CO2	0.0	0.0	0.0	0.0	2.8260-03
H2S	0.0	0.0	0.0	0.0	0.0
N2	7.2929-04	0.0	7.2929-04	0.0	0.0
O2	0.0	0.0	0.0	0.0	0.0
NO	0.0	0.0	0.0	0.0	0.0
CO	0.0	0.0	0.0	0.0	0.0
H2	0.0	0.0	0.0	0.0	0.0
NAPHTHA	4.0308-03	4.0308-03	0.0	0.0	0.0
LPG	9.2347-04	9.2347-04	0.0	0.0	0.0
N-EICOSA	4.9627-02	4.9627-02	0.0	0.0	0.0
H2O	3.3415-03	0.0	0.0	3.3415-03	0.0
O2S	0.0	0.0	0.0	0.0	0.0
TOTAL MMCUFT/HR	6.7216-02	6.3145-02	7.2929-04	3.3415-03	9.1373-02

COMPONENTS: STD VOL FRAC

CH4	0.1274	0.1356	0.0	0.0	0.9691
CO2	0.0	0.0	0.0	0.0	3.0928-02
H2S	0.0	0.0	0.0	0.0	0.0
N2	1.0850-02	0.0	1.0000	0.0	0.0
O2	0.0	0.0	0.0	0.0	0.0
NO	0.0	0.0	0.0	0.0	0.0
CO	0.0	0.0	0.0	0.0	0.0
H2	0.0	0.0	0.0	0.0	0.0
NAPHTHA	5.9968-02	6.3834-02	0.0	0.0	0.0
LPG	1.3739-02	1.4625-02	0.0	0.0	0.0
N-EICOSA	0.7383	0.7859	0.0	0.0	0.0
H2O	4.9713-02	0.0	0.0	1.0000	0.0
O2S	0.0	0.0	0.0	0.0	0.0
TOTAL MMCUFT/HR	6.7216-02	6.3145-02	7.2929-04	3.3415-03	9.1373-02

TOTAL FLOW:

MMSCFD	309.1747	196.1771	7.7420	105.2555	970.0000
LB/HR	3.1712+06	2.9392+06	2.3813+04	2.0820+05	1.8008+06
MMCUFT/HR	0.6784	47.0817	0.3815	0.3005	40.4632

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
STREAM SECTION

14 15 16 17 2

STATE VARIABLES:

TEMP	F	662.0000	662.0000	662.0000	662.0000	60.0000
PRES	PSI	435.1132	435.1132	435.1132	435.1132	14.6500
VFRAC		0.6890	0.0	0.0	1.0000	1.0000
LFRAC		0.3110	0.0	0.0	0.0	0.0
SFRAC		0.0	0.0	0.0	0.0	0.0
ENTHALPY:						
BTU/LBMOL		-6.8473+04	0.0	0.0	-9.9518+04	-3.6431+04
BTU/LB		-732.9862	0.0	0.0	-5524.0686	-2154.6920
MMBTU/HR		-2324.4693	0.0	0.0	-1150.1305	-3880.1104
ENTROPY:						
BTU/LBMOL-R		-104.9178	0.0	0.0	-11.4778	-18.6368
BTU/LB-R		-1.1231	0.0	0.0	-0.6371	-1.1023
DENSITY:						
LBMOL/CUFT		5.0037-02	0.0	0.0	3.8460-02	2.6322-03
LB/CUFT		4.6742	0.0	0.0	0.6929	4.4504-02
AVG MW		93.4162	136.4523	28.0135	18.0153	16.9077

MIXED SUBSTREAM PROPERTIES:

***** ALL PHASES *****

TCMX	F	501.1783	420.6877	-232.5100	705.1640	-110.3281
PCMX	PSI	1389.8291	454.6401	493.1283	3198.8073	679.5168
VCMX	CUFT/LBMOL	6.1043	9.0831	1.4290	0.8962	1.5771

***** VAPOR PHASE *****

ZMX		0.9424	0.9759	0.9921	0.9399	0.9980
VMX	CUFT/MIN	1.0163+04	4695.7008	190.4770	5008.2744	6.7439+05
MOLEFLMX	MMSCFD	213.0184	95.0406	7.7420	105.2555	970.0000
CPCVMX		1.1193	1.0965	1.4525	1.3779	1.3104
HMX	BTU/LB	-1364.6833	-564.4715	1.0082-05	-5524.0686	-2154.6920
CPMX	BTU/LB-R	0.6488	0.6975	0.2611	0.5252	0.5014
KMX	BTU-FT/HR-SQ	3.0426-02	3.7514-02	1.5016-02	2.8374-02	1.8630-02
RHOMX	LB/CUFT	1.5656	1.5082	2.0837	0.6929	4.4504-02
MUMX	CP	2.0223-02	1.7997-02	1.8521-02	2.2638-02	1.1082-02

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 INTEGRATED GTL-POWER GENERATION PROCESS
STREAM SECTION

14 15 16 17 2

***** LIQUID PHASE *****

STREAM ID		14	15	16	17	2
HMX	BTU/LB	-460.9189	-380.4439	0.0	0.0	0.0
CPMX	BTU/LB-R	0.7911	0.7799	0.0	0.0	0.0
KMX	BTU-FT/HR-SQ	4.6389-02	4.6300-02	0.0	0.0	0.0
RHOMX	LB/CUFT	32.2757	31.6715	0.0	0.0	0.0
MUMX	CP	0.1073	8.3595-02	0.0	0.0	0.0
SIGMAMX	DYNE/CM	6.5206	6.4581	0.0	0.0	0.0

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INTEGRATED GTL-POWER GENERATION PROCESS
STREAM SECTION

3 4 5 6 7

STREAM ID	3	4	5	6	7
FROM :	B4	----	B3	B1	B2
TO :	B5	B3	B2	----	B10

SUBSTREAM: MIXED

PHASE:	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR
COMPONENTS: MMSCFD					

CH4	90.9160	0.0	0.0	0.0	0.0
CO2	0.0	0.0	0.0	0.0	0.0
H2S	0.0	0.0	0.0	30.0000	0.0
N2	7.7420	1548.4000	1548.4000	0.0	7.7420
O2	0.0	411.6000	411.6000	0.0	409.5420
NO	0.0	0.0	0.0	0.0	0.0
CO	879.0840	0.0	0.0	0.0	0.0
H2	1698.1680	0.0	0.0	0.0	0.0
NAPHTHA	0.0	0.0	0.0	0.0	0.0
LPG	0.0	0.0	0.0	0.0	0.0
N-EICOSA	0.0	0.0	0.0	0.0	0.0
H2O	0.0	0.0	0.0	0.0	0.0
O2S	0.0	0.0	0.0	0.0	0.0

COMPONENTS: MOLE FRAC

CH4	3.3976-02	0.0	0.0	0.0	0.0
CO2	0.0	0.0	0.0	0.0	0.0
H2S	0.0	0.0	0.0	1.0000	0.0
N2	2.8932-03	0.7900	0.7900	0.0	1.8553-02
O2	0.0	0.2100	0.2100	0.0	0.9814
NO	0.0	0.0	0.0	0.0	0.0
CO	0.3285	0.0	0.0	0.0	0.0
H2	0.6346	0.0	0.0	0.0	0.0
NAPHTHA	0.0	0.0	0.0	0.0	0.0
LPG	0.0	0.0	0.0	0.0	0.0
N-EICOSA	0.0	0.0	0.0	0.0	0.0
H2O	0.0	0.0	0.0	0.0	0.0
O2S	0.0	0.0	0.0	0.0	0.0

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 INTEGRATED GTL-POWER GENERATION PROCESS
STREAM SECTION

3 4 5 6 7

COMPONENTS: STD MMCUFT/H

CH4	8.5642-03	0.0	0.0	0.0	0.0
CO2	0.0	0.0	0.0	0.0	0.0
H2S	0.0	0.0	0.0	2.8260-03	0.0
N2	7.2929-04	0.1459	0.1459	0.0	7.2929-04
O2	0.0	3.8772-02	3.8772-02	0.0	3.8578-02
NO	0.0	0.0	0.0	0.0	0.0
CO	8.2809-02	0.0	0.0	0.0	0.0
H2	0.1600	0.0	0.0	0.0	0.0
NAPHTHA	0.0	0.0	0.0	0.0	0.0
LPG	0.0	0.0	0.0	0.0	0.0
N-EICOSA	0.0	0.0	0.0	0.0	0.0
H2O	0.0	0.0	0.0	0.0	0.0
O2S	0.0	0.0	0.0	0.0	0.0
TOTAL MMCUFT/HR	0.2521	0.1846	0.1846	2.8260-03	3.9308-02

COMPONENTS: STD VOL FRAC

CH4	3.3976-02	0.0	0.0	0.0	0.0
CO2	0.0	0.0	0.0	0.0	0.0
H2S	0.0	0.0	0.0	1.0000	0.0
N2	2.8932-03	0.7900	0.7900	0.0	1.8553-02
O2	0.0	0.2100	0.2100	0.0	0.9814
NO	0.0	0.0	0.0	0.0	0.0
CO	0.3285	0.0	0.0	0.0	0.0
H2	0.6346	0.0	0.0	0.0	0.0
NAPHTHA	0.0	0.0	0.0	0.0	0.0
LPG	0.0	0.0	0.0	0.0	0.0
N-EICOSA	0.0	0.0	0.0	0.0	0.0
H2O	0.0	0.0	0.0	0.0	0.0
O2S	0.0	0.0	0.0	0.0	0.0
TOTAL MMCUFT/HR	0.2521	0.1846	0.1846	2.8260-03	3.9308-02

TOTAL FLOW:

MMSCFD	2675.9100	1960.0000	1960.0000	30.0000	417.2840
LB/HR	3.2635+06	6.2088+06	6.2088+06	1.1227+05	1.4627+06
MMCUFT/HR	2.1182	81.8846	26.3440	1.2431	5.6040

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
STREAM SECTION

3 4 5 6 7

STATE VARIABLES:

TEMP	F	572.0000	60.0000	530.7305	60.0000	530.7305
PRES	PSI	1595.4151	14.6500	87.0226	14.6500	87.0226
VFRAC		1.0000	1.0000	1.0000	1.0000	1.0000
LFRAC		0.0	0.0	0.0	0.0	0.0
SFRAC		0.0	0.0	0.0	0.0	0.0
ENTHALPY:						
BTU/LBMOL		-1.3124+04	-122.1204	3204.5184	-9035.7027	3284.0912
BTU/LB		-1181.5225	-4.2329	111.0736	-265.1175	102.8694
MMBTU/HR		-3855.8966	-26.2813	689.6376	-29.7636	150.4697
ENTROPY:						
BTU/LBMOL-R		3.2191	0.7964	1.8043	9.9694	1.0679
BTU/LB-R		0.2898	2.7606-02	6.2540-02	0.2925	3.3450-02
DENSITY:						
LBMOL/CUFT		0.1387	2.6282-03	8.1691-03	2.6499-03	8.1759-03
LB/CUFT		1.5407	7.5824-02	0.2357	9.0313-02	0.2610
AVG MW		11.1073	28.8504	28.8504	34.0819	31.9249

MIXED SUBSTREAM PROPERTIES:

***** ALL PHASES *****

TCMX	F	-330.8457	-221.7824	-221.7824	212.6840	-182.3738
PCMX	PSI	311.6603	543.1707	543.1707	1299.9602	727.0041
VCMX	CUFT/LBMOL	1.2067	1.3758	1.3758	1.5778	1.1805

***** VAPOR PHASE *****

ZMX		1.0389	0.9995	1.0023	0.9914	1.0015
VMX	CUFT/MIN	3.5304+04	1.3647+06	4.3907+05	2.0718+04	9.3400+04
MOLEFLMX	MMSCFD	2675.9100	1960.0000	1960.0000	30.0000	417.2840
CPCVMX		1.3823	1.4016	1.3818	1.3330	1.3600
HMX	BTU/LB	-1181.5225	-4.2329	111.0736	-265.1175	102.8694
CPMX	BTU/LB-R	0.6611	0.2419	0.2507	0.2422	0.2369
KMX	BTU-FT/HR-SQ	9.9161-02	1.4846-02	2.4809-02	7.9765-03	2.6287-02
RHOMX	LB/CUFT	1.5407	7.5824-02	0.2357	9.0313-02	0.2610
MUMX	CP	2.4351-02	1.7845-02	2.8603-02	1.2283-02	3.2381-02

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
STREAM SECTION

3 4 5 6 7

***** LIQUID PHASE *****

STREAM ID		3	4	5	6	7
HMX	BTU/LB	0.0	0.0	0.0	0.0	0.0
CPMX	BTU/LB-R	0.0	0.0	0.0	0.0	0.0
KMX	BTU-FT/HR-SQ	0.0	0.0	0.0	0.0	0.0
RHOMX	LB/CUFT	0.0	0.0	0.0	0.0	0.0
MUMX	CP	0.0	0.0	0.0	0.0	0.0
SIGMAMX	DYNE/CM	0.0	0.0	0.0	0.0	0.0

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
STREAM SECTION

8 9

STREAM ID	8	9
FROM :	B2	B10
TO :	----	B4

SUBSTREAM: MIXED

PHASE:	VAPOR	VAPOR
COMPONENTS: MMSCFD		
CH4	0.0	90.9160
CO2	0.0	0.0
H2S	0.0	0.0
N2	1540.6580	7.7420
O2	2.0580	0.0
NO	0.0	0.0
CO	0.0	879.0840
H2	0.0	1698.1680
NAPHTHA	0.0	0.0
LPG	0.0	0.0
N-EICOSA	0.0	0.0
H2O	0.0	0.0
O2S	0.0	0.0

COMPONENTS: MOLE FRAC		
CH4	0.0	3.3976-02
CO2	0.0	0.0
H2S	0.0	0.0
N2	0.9987	2.8932-03
O2	1.3340-03	0.0
NO	0.0	0.0
CO	0.0	0.3285
H2	0.0	0.6346
NAPHTHA	0.0	0.0
LPG	0.0	0.0
N-EICOSA	0.0	0.0
H2O	0.0	0.0
O2S	0.0	0.0

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
STREAM SECTION

8 9

 COMPONENTS: STD MMCUFT/H

CH4	0.0	8.5642-03
CO2	0.0	0.0
H2S	0.0	0.0
N2	0.1451	7.2929-04
O2	1.9386-04	0.0
NO	0.0	0.0
CO	0.0	8.2809-02
H2	0.0	0.1600
NAPHTHA	0.0	0.0
LPG	0.0	0.0
N-EICOSA	0.0	0.0
H2O	0.0	0.0
O2S	0.0	0.0
TOTAL MMCUFT/HR	0.1453	0.2521

COMPONENTS: STD VOL FRAC

CH4	0.0	3.3976-02
CO2	0.0	0.0
H2S	0.0	0.0
N2	0.9987	2.8932-03
O2	1.3340-03	0.0
NO	0.0	0.0
CO	0.0	0.3285
H2	0.0	0.6346
NAPHTHA	0.0	0.0
LPG	0.0	0.0
N-EICOSA	0.0	0.0
H2O	0.0	0.0
O2S	0.0	0.0
TOTAL MMCUFT/HR	0.1453	0.2521

TOTAL FLOW:

MMSCFD	1542.7160	2675.9100
LB/HR	4.7461+06	3.2635+06
MMCUFT/HR	20.7400	5.6947

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
STREAM SECTION

8 9

STATE VARIABLES:

TEMP	F	530.7305	2372.0000
PRES	PSI	87.0226	1595.4151
VFRAC		1.0000	1.0000
LFRAC		0.0	0.0
SFRAC		0.0	0.0
ENTHALPY:			
BTU/LBMOL		3182.9894	1090.0791
BTU/LB		113.6019	98.1405
MMBTU/HR		539.1670	320.2813
ENTROPY:			
BTU/LBMOL-R		0.7766	11.0878
BTU/LB-R		2.7716-02	0.9982
DENSITY:			
LBMOL/CUFT		8.1673-03	5.1595-02
LB/CUFT		0.2288	0.5731
AVG MW		28.0188	11.1073

MIXED SUBSTREAM PROPERTIES:

***** ALL PHASES *****

TCMX	F	-232.4418	-330.8457
PCMX	PSI	493.4462	311.6603
VCMX	CUFT/LBMOL	1.4287	1.2067

***** VAPOR PHASE *****

ZMX		1.0025	1.0176
VMX	CUFT/MIN	3.4567+05	9.4911+04
MOLEFLMX	MMSCFD	1542.7160	2675.9100
CPCVMX		1.3882	1.3081
HMX	BTU/LB	113.6019	98.1405
CPMX	BTU/LB-R	0.2549	0.7629
KMX	BTU-FT/HR-SQ	2.4451-02	0.2150
RHOMX	LB/CUFT	0.2288	0.5731
MUMX	CP	2.7641-02	4.6547-02

ASPEN PLUS PLAT: WIN32 VER: 12.1
 INTEGRATED GTL-POWER GENERATION PROCESS
STREAM SECTION

8 9

***** LIQUID PHASE *****

STREAM ID		8	9
HMX	BTU/LB	0.0	0.0
CPMX	BTU/LB-R	0.0	0.0
KMX	BTU-FT/HR-SQ	0.0	0.0
RHOMX	LB/CUFT	0.0	0.0
MUMX	CP	0.0	0.0
SIGMAMX	DYNE/CM	0.0	0.0

APPENDIX C: THERMAL EFFICIENCIES CALCULATIONS

1) High-Pressure (HP) Steam Performance

Steam Inlet Conditions (Turbine)

$$P_1 = 1200\text{psi}$$

$$T_1 = 998^\circ\text{F}$$

Steam Outlet Conditions (Pump)

$$P_2 = 0.2561\text{psia}$$

$$T_2 = 60^\circ\text{F}$$

From Steam tables, at the conditions specified for the turbine and pump, the enthalpies are given as:

$$H_1 = 1498.20\text{Btu/lb}$$

$$H_2 = 28.09\text{ Btu/lb}$$

Steam mass flow rate

$$\dot{m} = 4204.2\text{Klb} / \text{hr}$$

Power rating

$$\dot{W}_s = 442.141\text{MW}$$

$$1\text{MW} = 3.412\text{Btu} / \text{hr}$$

$$\dot{W}_s = (442.141 * 10^6 * 3.412)\text{Btu} / \text{hr}$$

$$\dot{W}_s = (1,508.59 * 10^6)\text{Btu} / \text{hr}$$

Net work done by the shaft:

$$W_s = \frac{\dot{W}_s}{\dot{m}}$$

$$W_s = \frac{1,508.59 * 10^6}{4204.2 * 10^3}$$

$$W_s(\text{net}) = 358.82 \text{ Btu} / \text{lb}$$

Heat transferred through the boiler (heating system) section:

$$Q(\text{boiler}) = H_2 - H_1$$

$$Q(\text{boiler}) = 1498.20 - 28.09$$

$$Q(\text{boiler}) = 1470.11 \text{ Btu} / \text{lb}$$

Hence, the thermal efficiency of the steam plant:

$$\eta = \frac{|W_s(\text{net})|}{Q(\text{boiler})}$$

$$\eta = \frac{|358.82|}{1470.11}$$

$$\eta = 0.244$$

$$\eta = 24.4\%$$

2) Low-Pressure (LP) Steam Performance

Steam Inlet Conditions (Turbine)

$$P_1 = 435 \text{ psi}$$

$$T_1 = 660^\circ \text{F}$$

Steam Outlet Conditions (Pump)

$$P_2 = 0.2561 \text{ psia}$$

$$T_2 = 60^\circ \text{F}$$

From Steam tables, at the conditions specified for the turbine and pump, the enthalpies are given as:

$$H_1 = 1339.17 \text{ Btu/lb}$$

$$H_2 = 28.09 \text{ Btu/lb}$$

Steam mass flow rate

$$\dot{m} = 923.5 \text{ Klb/hr}$$

Power rating

$$\dot{W}_s = 71.03 \text{ MW}$$

$$1 \text{ MW} = 3.412 \text{ Btu/hr}$$

$$\dot{W}_s = (71.03 * 10^6 * 3.412) \text{ Btu/hr}$$

$$\dot{W}_s = (242.35 * 10^6) \text{ Btu/hr}$$

Net work done by the shaft

$$W_s = \frac{\dot{W}_s}{\dot{m}}$$

$$W_s = \frac{242.35 * 10^6}{923.5 * 10^3}$$

$$W_s(\text{net}) = 262.42 \text{ Btu/lb}$$

Heat transferred through the boiler (heating system) section:

$$Q(\text{boiler}) = H_2 - H_1$$

$$Q(\text{boiler}) = 1339.17 - 28.09$$

$$Q(\text{boiler}) = 1311.08 \text{ Btu/lb}$$

Hence, the thermal efficiency of the steam plant:

$$\eta = \frac{|W_s(\text{net})|}{Q(\text{boiler})}$$

$$\eta = \frac{|262.42|}{1311.08}$$

$$\eta = 0.200$$

$$\eta = 20.0\%$$

VITA

NAME: Adegoke Adesola Ayodeji

PERMANENT ADDRESS: No 8, Akobo Baptist Road One
Ibadan, Oyo State
Nigeria

EMAIL: adesola.adegoke@gmail.com

EDUCATION: BSc, Chemical Engineering
Obafemi Awolowo University, Ile-Ife, Nigeria
August 2002

MS, Petroleum Engineering
Texas A&M University, College Station, TX
August 2006