DESIGN AND ECONOMICS OF A FISCHER-TROPSCH PLANT FOR CONVERTING NATURAL GAS TO LIQUID TRANSPORTATION FUELS

Gerald N. Choi, Sheldon J. Kramer and Samuel S. Tam
(Bechtel Corporation, San Francisco, CA)
Joseph M. Fox III (Consultant)

Keywords: Fischer-Tropsch, natural gas liquefaction, economics

ABSTRACT

There is considerable interest in the development of an economic process for the conversion of natural gas to liquid transportation fuels. Such a process will allow the commercialization of many remote natural gas fields which are not now viable. Under DOE sponsorship, a conceptual plant design, cost and economics were developed for a grass-roots plant using Fischer-Tropsch technology to produce about 45,000 bbls/day of liquid transportation fuels from 410 MMSCF/day of natural gas. The natural gas is converted to synthesis gas via a combination of non-catalytic partial oxidation and steam reforming. This synthesis gas is then converted to liquid hydrocarbons in a two-stage, Fischer-Tropsch slurry-bed reactor system. The Fischer-Tropsch wax and liquid hydrocarbons are upgraded to high quality naphtha and diesel blending stocks by conventional petroleum refinery processes. Economics are dependent on both plant and natural gas costs. At a location where construction costs are equivalent to the US Gulf coast and natural gas costs are low, this plant can be competitive at today's crude oil prices.

INTRODUCTION

Bechtel, along with Amoco as the main subcontractor, has developed a Baseline design (and a computer process simulation model) for indirect coal liquefaction using advanced Fischer-Tropsch (F-T) technology under DOE Contact No. DE-AC22-91PC90027. In 1995, the original study was extended to add four additional tasks; one of which was to develop a case in which natural gas, instead of coal, is used as the feedstock to produce high-quality, liquid transportation fuels. This paper describes the results of this task. It discusses the design of this plant and the economics of liquefying natural gas using F-T technology to produce liquid transportation fuels.

OVERALL PLANT CONFIGURATION

Figure 1 is a simplified block flow diagram showing the overall process configuration of the conceptual design for the natural gas-based F-T liquefaction plant. This design uses proven commercial technology for syngas generation, non-catalytic partial oxidation in combination with steam reforming. A cobalt-based catalyst in slurry-bed reactors is used for the F-T synthesis. The plant is located at a hypothetical southern Illinois mine-mouth location to be consistent with the previous coal based F-T liquefaction study. It produces about 43,200 BPD of high quality gasoline and diesel blending stocks from about 410 MMSCF/day of natural gas. In developing this natural gas case, where applicable, individual plant designs and cost estimates were prorated directly from the coal-based Baseline design.[1]

The overall natural gas-based F-T plant consists of three main processing areas; synthesis gas preparation, F-T synthesis, and product upgrading. In addition, there are eighteen ancillary offsite plants which are similar to those which were developed for the Baseline design with minor modifications as required for this natural gas case.

Synthesis Gas Preparation Area (Area 100)

This area consists of three major plants; air separation, partial oxidation, and steam reforming (sulfur is removed from the natural gas before syngas generation). Most of the syngas is generated by partial oxidation using 99.5% pure oxygen which produces a syngas with a molar H_2/CO ratio of 1.8/1. The steam reforming plant, produces a syngas with a H_2/CO ratio of 5.9/1. This is a relatively small plant. It is used only to supplement the syngas production by the partial oxidation plant by increasing the H_2/CO ratio of the total syngas going to the Fischer-Tropsch synthesis area to a H_2/CO ratio of about 1.9/1.

Fischer-Tropsch Synthesis Loop (Area 200)

This area consists of five plants; F-T synthesis, CO_2 removal, recycle gas compression and dehydration, hydrocarbon recovery, and hydrogen recovery. Hydrogen is recovered from the unconverted syngas. After satisfying the downstream hydroprocessing needs, the excess hydrogen is recycled back to the F-T reactors. The remaining unconverted syngas is used for fuel.

A cobalt-based catalyst was selected for F-T synthesis because it has negligible activity for the water-gas shift reaction compared to an iron-based catalyst, and thus, it requires a syngas with a molar H_2/CO ratio near the stoichiometric value of 2.0/1. Since methane, the principal component in natural gas, has a molar H_2/C ratio of 2.0/1, syngas produced from it has a similar H_2/CO ratio. Also, for iron-based catalyst with a high water-gas shift activity, CO_2 is the primary byproduct from the Fischer-Tropsch synthesis. With cobalt-based catalyst, water is the primary byproduct.

A total of 24 slurry-bed reactors process the syngas from Area 100. These reactors are arranged in eight trains with each train having two first-stage slurry-bed reactors feeding a single second-stage slurry-bed reactor. The unconverted syngas leaving the first-stage reactors is cooled and flashed to condense and remove liquids before being reheated and fed to the second-stage reactors. The CO conversion in each of the parallel first-stage reactors is about 56%, and in the second-stage reactors, the CO conversion is about 59%. This gives an overall CO conversion per pass of about 82%. The first-stage F-T slurry-bed reactors operate at about 428 °F and 335 psig, and the second-stage reactors operate at 428 °F and 290 psig. Excess heat is removed by the generation of 150 psig steam from tubes within the reactors.

Slurry-bed reactor sizing is based on an improved version of the kinetic reactor model which originally was developed by Viking Systems, International.[2] The primary modification to this model was the insertion of the kinetic parameters developed by Satterfield et al for cobalt-based catalyst.[3]

Product Upgrading and Refining Area (Area 300)
This area consists of eight processing plants. Fischer-Tropsch synthesis produces a wide spectrum of hydrocarbon products, similar to crude oil except that naphthenes and aromatics are absent. Upgrading is required to produce high-quality transportation fuels. For consistency with the coal-based Baseline design, Area 300 uses the same conventional petroleum processing technologies to upgrade and refine the F-T products to high quality liquid transportation fuels. This area consists of a wax hydrocracker, distillate hydrotreater, naphtha hydrotreater, catalytic reformer, C5/C6 isomerization unit, C4 isomerization unit, C3/C4/C5 alkylation unit, and a saturated gas plant. Area 300 is designed to produce maximum amounts of high-octane gasoline and high-cetane diesel blending stocks.

PLANT SUMMARY

The conceptual plant consumes about 410 MMSCF/day of natural gas and produces about 45,000 BPD of liquid products. The primary liquid products are C3 LPG, a C5-350 °F fully upgraded gasoline blending stock, and a 350-850 °F distillate. The gasoline product has a clear (R+M)/2 octane of about 88 and is basically a mixture of C3/C4/C5 alkylate, C5/C6 isomerate and catalytic reformate. The distillate product also is high quality and has a high cetane number, on the order of 70. Both products are essentially free of sulfur, nitrogen and oxygen containing compounds.

The plant uses all of the byproduct steam and fuel gas to generate electric power. In addition to supplying its entire power requirement, about 25 MW of excess electric power is sold. The only materials delivered to the plant are natural gas, raw water, catalysts, chemicals and some normal butane which is used as a feed for C4 isomerization and, subsequently, alkylation.

Following the philosophy of the previous indirect coal liquefaction study, the overall plant is designed to comply with all applicable environmental, safety and health regulations. Air cooling is maximized, wherever possible, in order to minimize cooling water requirements. A brief summary of the major feed and product streams entering and leaving this natural gas liquefaction plant is shown in Table 1.

Capital Cost Estimate
Total capital cost for this natural gas F-T plant is about 1.84 billion dollars. This is a mid-1993 cost, consistent with the coal-based F-T study. The estimated plant cost is about 40% less than that for the corresponding coal-based design. A different syngas preparation area and a smaller CO_2 removal plant account for most of the cost reduction. A brief summary of the estimated capital cost breakdown is given in Table 2.

ECONOMIC SENSITIVITY STUDIES

A discounted-cash-flow analysis on the production cost of the F-T products for a 15% internal rate of return on investment was carried out to examine the economics of the natural gas F-T design using similar financial assumptions to those employed for the coal-based F-T study.[4] Inflation projections are based on the 1996 Energy Information Administration forecast.[5] Results are expressed in terms of a crude oil equivalent price (COE) which is defined as the current hypothetical break-even crude oil price where the F-T liquefaction products are competitive with products from crude oil at a typical PADD II refinery.

The primary liquefaction products are gasoline and diesel blending stocks. Their relative values to the crude oil price were determined using a PIMS linear programming model of a typical PADD II refinery using current crude oil prices, processing costs and margins. The methodology of and results from this study are documented in a 1994 ACS paper.[6] For the Baseline coal case, the F-T gasoline blending stock had a value of 10.07 $/bbl more than crude oil, and the F-T diesel blending stock had a value that was 7.19 $/bbl more than crude oil. These same margins are used for this natural gas F-T study since the properties of these F-T gasoline and diesel blending stocks are essentially the same as those from the coal-based Baseline design.

Figure 2 shows the results of the natural gas F-T economic calculations at the southern Illinois siteas a function of the natural gas price using the economic parameters given in Table 3. With natural gas priced at 2.0 $/MMBtu, the calculated COE price is 30.7 $/bbl in current dollars. The economics are strongly dependent on the natural gas price. If natural gas is available at 0.5 \$/MMBtu, the COE drops to only 19.1 \$/bbl.

Figure 2 also shows the effects of increased capital cost (by 25 and 50%) and decreased capital cost (by 10, 25 and 50%). The former are included to show the effect of higher construction costs at remote sites. The latter are included to show the potential improvement in the economies via advanced technologies and/or location at sites where construction costs are lower. Emerging technologies for synthesis gas generation include combined autothermal reforming and ceramic membranes oxidation. These offer a potentially significant reduction in plant cost. If the syngas generation cost can be cut in half, it would correspond to a 33% decrease in total capital. As shown in Figure 2, the effect on the overall process economies would be substantial.

Figure 3 shows the portion of the calculated COE price attributable to various capital and operating cost items at the hypothetical southern Illinois site with 2.0 \$/MMBtu gas. At this gas price, the natural gas cost dominates the process economics. It contributes about 51% of the calculated COE price. Capital servicing costs account for about 34% of the COE price. Other items contribute the remaining 15% of the COE price with the operating and maintenance labor accounting for about half of this amount.

For a potential remote site where low cost natural gas is available (e.g., 0.5 \$/MMBtu), the COE distribution is very different, as shown in Figure 4. Capital servicing costs now predominate and drive the overall project economies. It constitutes about 55% of the calculated COE price. The contribution of advanced technologies to reducing the total capital cost will be greatly enhanced at a remote site.

CONCLUSIONS AND RECOMMENDATIONS

A conceptual plant design with cost estimates has been developed for a Fischer-Tropsch natural gas liquefaction plant producing 43,200 BPD of high-quality, liquid transportation fuels from about 410 MMSCF/day of natural gas. In addition, this plant produces about 1,700 BPD of liquid propane and 25 MW of surplus electric power for sale. The capital cost of this plant is estimated at about 1.84 billion mid-1993 dollars. Since US Gulf coast construction costs are somewhat lower than those in southern Illinois, the above plant at a US Gulf coast location will produce liquid transportation fuels from 2.00 \$/MMBtu gas which will be competitive with those produced from crude oil priced below 30 \$/bbl. With 0.50 \$/MMBtu natural gas, the crude oil equivalent (COE) price will drop still lower, to below 19 \$/bbl.

Thus, it is evident that attractive natural gas F-T economics currently only can be attained with low cost gas. There are numerous reserves located at remote areas and/or offshore where the gas has little value because transportation systems are not available to ship it to market. F-T synthesis offers an option to convert these resources into liquid hydrocarbons which can be easily transported to existing refineries. Under this scenario, capital servicing costs are the predominant factor driving the overall process economics. However, there are various opportunities to reduce the plant cost. Examples include:

- Simplifying the F-T design at the expense of a minor sacrifice in overall process thermal efficiency. It is also possible (and probably desirable) to eliminate and/or simplify the upgrading area to produce only a F-T syncrude which can be shipped to a conventional petroleum refinery where it would be coprocessed with crude oil.

- Integrating the F-T design with the existing infrastructure. This will be relevant, for example, for a F-T plant at the Alaskan North Slope which converts either the 'gas-cap' or 'associated' gas into a transportable syncrude. The design will utilize the considerable assets/infrastructure at the North Slope and available pipeline capacity as crude production declines to maximize cost savings.

- Investigating and incorporating more advanced processes for syngas generation such as combined autothermal reforming, fluid-bed autothermal reforming, and ceramic membranes oxidation (e.g., DOE Contract No. DE-AC22-92PC92113). Such processes have the potential to significantly reduce the plant cost and improve the economics.

- Developing a practical design for larger diameter slurry-bed reactors. The current plant design has 24 slurry-bed F-T reactors, each about 16 feet in diameter. Larger slurry-bed reactors can significantly reduce the cost of the F-T synthesis plant.

ACKNOWLEDGMENT

Bechtel, along with Amoco who was the main subcontractor for a major portion of this study, expresses our appreciation to the DOE/Pittsburgh Energy Technology Center for both technical guidance and financial funding under Contract No. DE-AC22-91PC90027.

REFERENCES:

1. Topical Report, Volume I, Process Design - Illinois No. 6 Coal Case with Conventional Refining, Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, October, 1994.
2. Final Report, Design of Slurry Reactor for Indirect Liquefaction Applications, Contract No. DE-AC22-89PC89870, December, 1991.
3. Final Report, An Innovative Catalyst System for Slurry-Phase Fischer-Tropsch Synthesis: Cobalt Plus a Water-Gas Shift Catalyst, Contract No. DE-AC22-87PC79816, July 1991.
4. Choi, G. N., Kramer, S. J., Tam, S. S. and Fox, J. M. III, "Simulation Models and Designs for Advanced Fischer-Tropsch Technology," Proceedings of the Coal Liquefaction and Gas Conversion Contractors Review Conference, Pittsburgh, PA, Aug. 29-31, 1995.
5. "Annual Energy Outlook 1996 with Projections to 2015," Energy Information Administration, Washington, DC, January 1996.
6. Marano, J. J., Rogers, R., Choi, G. N., and Kramer, S. J., "Product Valuation of Fischer-Tropsch Derived Fuels, Symposium on Alternative Routes for the Production of Fuels," ACS National Meeting, Washington, D.C., August 21-26, 1994.

Table 1
Overall Plant Major Input and Output Flows

Feed			
Natural Gas	412	MMSCF/day	(17,800 MMBtu/hr)
Raw Water Make-up	21	MMGal/day	
N-Butane	3	Mlbs/hr	(340 Bbl/day)
Primary Products			
F-T Gasoline	180	Mlbs/hr	(17,000 Bbl/day)
F-T Diesel	295	Mlbs/hr	(26,200 Bbl/day)
Propane	13	Mlbs/hr	(1,700 Bbl/day)
Electric power	592	MW-hr/day	

Table 2
Cost Breakdown of the Natural Gas Liquefaction Plant

Area	Description	Cost (MM$)	% ISBL
100	Syngas Preparation	707	66
200	F-T Synthesis	226	22
300	Upgrading & Refining	132	12
	Offsites	426	
	HO Service/Fee and Contingency	351	
	Total Cost:	1842	

The above plant costs are estimated to have an accuracy range of +/- 30%.

Table 3
Economic Parameters

N-Butane price, $/bbl	14.5
Electricity, cents/kwh	2.5
Plant life, years	25
Depreciation, years	10
Construction period, years	4
Owner's cost, % of initial capital	5
Owners initial equity, %	75
Bank interest rate, %/year	8
General inflation, %/year	3.2
Escalation above general inflation, %/year	
Natural gas	0.3
Crude oil	2.4
Electricity	-0.1
Federal income tax rate, %	34
State and local tax rates, %	0
Maintenance and insurance, % of capital	1
Labor overhead factor, % of salary	40
On-stream factor, %	90.8

C:\WD\PAPR497B.DOC

Figure 1
Natural Gas Fischer-Tropsch Study
Overall Process Configuration

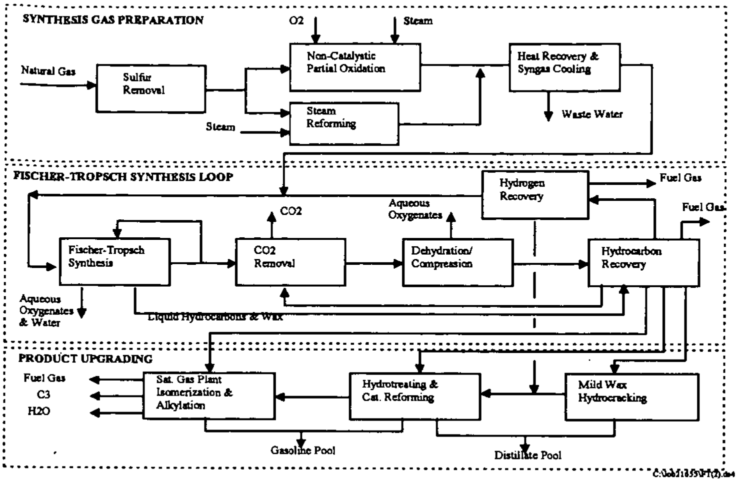

Figure 2
COE Price as a Function of Natural Gas Price and Capital Cost

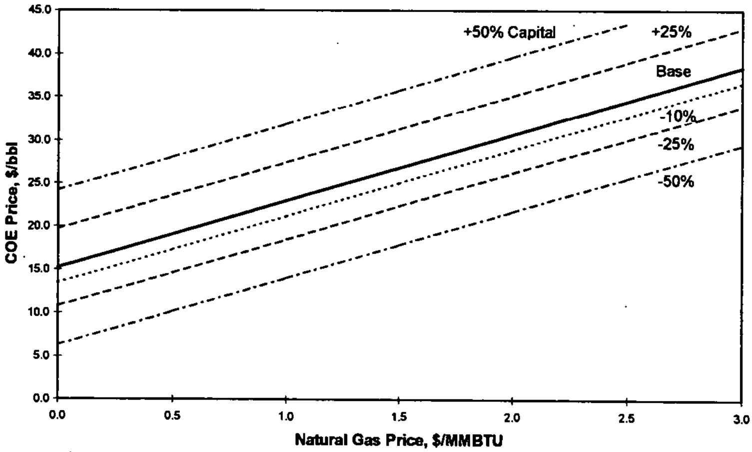

Figure 3
COE Cost Distribution @ 2.00 $/MMBTU Gas
COE = 30.7 $/bbl at Southern Illinois

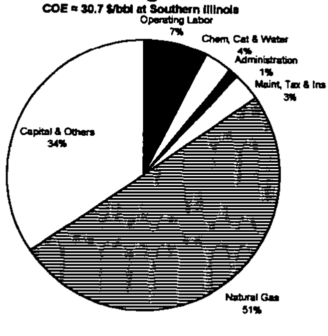

Figure 4
COE Cost Disrtibution @ 0.50 $/MMBTU Gas
COE = 19.1 $/bbl at Southern Illinois