ECONOMIC CONVERSION OF NATURAL GAS TO SYNTHETIC PETROLEUM LIQUIDS

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Introduction. Fischer-Tropsch chemistry has been applied for more than 50 years to produce clean synthetic fuels. In recent years, the feedstock focus has shifted away from abundant, available coal to abundant but stranded natural gas. The incentive to do so is huge: Most of the world's proven and discovered, undeveloped reserves of natural gas are unmarketable in their present form. Available technology has offered few options to monetize these remote resources. If they could be economically converted into clean liquid fuels, which could then be economically transported to world commodity markets, the rewards would be enormous: Instead of being locked up, representing an expensive burden of unrecovered costs, a significant percentage of idle reserves would suddenly have the potential to be converted into booked assets of great value. At a conversion rate of 10 to 1--10 MMCF of pipeline quality gas converts to 1 barrel of synthetic product--stranded reserves are equal to several hundred billion barrels of oil.[1]

It is not surprising that a prize of that magnitude would draw a crowd. Some of the world's leading research organizations, galvanized by the prospects, have poured hundreds of millions of dollars into the search. Today, we can state with confidence, these efforts have succeeded. Fischer-Tropsch chemistry can be used in many cases to convert natural gas to synthetic liquid fuels at a cost that is competitive with conventional petroleum products at current prices. In a variety of designs developed by Syntroleum Corporation, economical conversion of gas to synthetic liquids (GTL) can be accomplished in a wide range of sites and circumstances, from small plants in remote locations, onshore and offshore, to very large "natural gas refineries."

The process is competitive at crude oil prices below \$20/BBL--roughly \$10/BBL less than the level previously considered to be economic for synfuels from natural gas. It has been licensed to one major international oil company for use in projects it has under consideration. Syntroleum is negotiating similar licensing arrangements with several others.

Synfuels Products and Quality. One reason for the ready marketability of synfuels is their superior quality, earning them very high marks in performance tests.[2] Synthetic fuels produced via Fischer-Tropsch chemistry are known for being among the cleanest fuels in the world. The liquid fuels produced by the new process are free of sulfur, metals, and aromatics, and are clear in appearance. They will offer industry a timely option just as refiners are seeking ways to avoid costly "have-to" compliance capital investments that are hard to justify by market conditions.

Characteristics of Syncrude. Synthetic crude made from natural gas is characteristically extremely clean. In the Syntroleum Process, the syncrude produced tends to be mostly saturated, straight chain hydrocarbons, essentially free of sulfur, aromatics and contaminants such as heavy metals commonly found in natural crude. These characteristics make syncrude a valuable blending stock for upgrading natural crude streams.

Because of its purity, high API gravity and highly paraffinic nature, syncrude can be blended with natural crude to gain significant improvements in yields and product quality in many conventional refining applications.

Synthetic Fuels. Synthetic hydrocarbon fuels are superior in many ways to products derived from conventional crude oil (Table 1). The naphtha fraction (C_5-C_8) from syncrude is highly paraffinic. The light end components are more suitable for gasoline production than the heavy end components. However, the heavy ends can be further upgraded via conventional naphtha reforming for the gasoline market.

Synthetic kerosene makes a good linear blending component for upgrading lower-quality stock (Table 1). Because of its outstanding combustion properties, synthetic kerosene can be used to upgrade petroleum kerosene products with low smoke point and high aromatics content which would otherwise be unsuitable for use as jet fuel.

Synthetic diesel, with its high cetane index and absence of sulfur and aromatics, is an ideal blending component for upgrading lower-quality stocks to meet current and future environmental specifications. Because of its superior combustion properties, synthetic diesel is an option for compliance with the most stringent current CARB and CEN standards (Table 2).

The Syntroleum Process. Alternative F-T technologies, as well as LNG, have sought to improve their economics through large plant capacities. They have focused on sizes as large as 50,000 BPD of product as a starting point, requiring 180 BCF of gas per year or approximately 5.4 TCF over a 30-year life. One recently announced proposal for a plant of that size, costing $24,000 per barrel of daily capacity, was a significant development, but limited to a small number of possible fields. Only 2% of the 4,448 identified gas fields outside the U.S. and Canada have the reserves to qualify, and some 30 of these already have significant commitments to large LNG projects.[3]

At plant capacities as small as 5,000 BPD, the Syntroleum Process offers a potential solution for almost 40% of the world's gas fields. In various combinations, the design menu can be adapted to apply to much smaller fields. The plant's relatively small footprint also lends itself to certain offshore, platform-mounted applications. Portable (barge or ship mounted) plants could allow many of the smaller offshore fields to be monetized without the need for long-term reserves.

The Syntroleum Process is a proprietary method for converting natural gas into liquid hydrocarbons (GTL). Research was aimed at developing a process that would achieve two primary objectives: (1) commercial viability with oil prices of $15 to $20/BBL, and (2) design flexibility that would permit a wide range of economic plant sizes suitable for a multitude of site conditions and a significant share of the world's remote gas fields.

The first objective was met by significantly reducing complexity and capital costs in every area of the process. This was vital because of the crucial role of capital efficiency in the economics of synfuels processes. The second was met by creating a menu of design components which, in varying combinations, can be economically applied to plant sizes ranging from as small as 2,000 BPD of liquids production--even smaller in special circumstances--to as large as 100,000 BPD.

Syntroleum uses the same two-step chemistry found in other Fischer-Tropsch processes: Natural gas is converted into synthesis gas, then the synthesis gas is reacted in a Fischer-Tropsch reactor to polymerize hydrocarbon chains of various lengths. But the Syntroleum Process is markedly different in several important ways.

Step One: Synthesis Gas Production. In typical F-T processes, more than 50% of the capital cost relates to the production of synthesis gas, usually generated from natural gas via partial oxidation with oxygen, steam reforming, or a combination of the two. These methods are relatively expensive because the production of oxygen requires an air separation plant. They also have inherent problems that must be solved in various ways to produce an acceptable ratio of hydrogen to CO in the syngas for the F-T reaction. In these approaches, nitrogen is eliminated from the syngas stream as an unwanted inert, but not in the Syntroleum Process.

The Syntroleum syngas step is based on Autothermal Reforming (ATR) with air instead of oxygen in a reactor of proprietary design. The reactor is mechanically simple, easy to start up and shut down, and relatively inexpensive to build (Figure 1). It does not require large scale to be cost effective. Its lower cost is a large contributor to the cost savings realized in the Syntroleum Process.

The ATR consists primarily of a refractory-lined carbon steel reactor vessel and a catalyst. Air and natural gas are fed in at proper ratio and pressure, producing a nitrogen-diluted synthesis gas within the desired H_2/CO ratio of approximately 2.0. The syngas ratio can be adjusted further by the introduction of a small amount of steam or CO_2 into the ATR reactor. Synthesis gas diluted with approximately 50% nitrogen raises an obvious concern that any savings from the much simpler ATR reactor would be lost due to the increased F-T reactor section needed to handle the added inert volumes. However, in the Syntroleum Process, this is not the case.

Step two: Fischer-Tropsch synthesis. Other processes have been careful to avoid the introduction of any inerts such as nitrogen. The Syntroleum Process, on the other hand, incorporates nitrogen into the process. This is possible because its F-T section has no recycle loop. The one-pass design avoids any build-up of nitrogen in the system, thus allowing the use of nitrogen-diluted syngas without impairing performance. The Syntroleum F-T reactor configuration is comparable in size but less expensive than comparable systems with recycle: The recycle compressor loop, which must handle and be rated for hydrogen service, has been eliminated (Figure 2).

Nitrogen plays a significant role in removing the large amounts of heat generated by the Fischer-Tropsch reaction. Removing the exothermic heat of reaction and controlling reactor temperatures within close tolerances is a critical element of reactor design.

Process Development, Demonstration. After 5 years' research on the process, the company obtained its first patents in 1989. This was followed by construction and operation of a 2 BPD pilot plant in 1990 and 1991. These runs were successful but confirmed the need for a proprietary catalyst system tailored to fit the unique syngas environment created by the process. Syntroleum has since developed several proprietary catalyst systems for use with different variations of the process and continues to focus a significant amount of the company's resources in this area.

The pilot plant continues to be used to evaluate process improvements, including new catalyst systems, reactor designs, and heat integration. It is also used to provide technical information necessary for scale-up and engineering of commercial plants. The company plans to maintain the pilot plant indefinitely to support future development work.

Surplus heat generated from the two reactions combined with combustion of the low-BTU tail-gas stream provides more than enough power for all plant needs. Also, there is a surplus for potential commercial sale, either as steam or electricity, if circumstances permit. The major energy consumer is compression. The energy integration is a key component of a cost effective design and the subject of several patent applications. The only other byproduct of the process is synthesized water, which can be used as boiler feed water or made potable with proper treatment.

Catalyst Technology, Downstream Processing. The process requires a special catalyst system tailored to operate in the unique syngas environment created by the ATR. Syntroleum began development of the Fischer-Tropsch catalysts optimized for such syngas in 1991. The company's high alpha catalyst system is a proprietary, highly active cobalt catalyst. It produces a waxy syncrude that is primarily uniform straight-chain hydrocarbon molecules with relatively low yields of methane (below 10%). Test runs with commercially manufactured batches have demonstrated the viability of the high alpha catalyst system at commercial scale.

Plants designed around the high alpha catalyst produce a waxy syncrude which requires hydrocracking, similar to competing processes, for the production of fuels. With conventional hydrocracking and fractionation, the syncrude can be tailored to optimize diesel yield or kerosene yield.

Work on a "chain-limiting" F-T catalyst began in 1994, with partial funding from three major oil companies. The goal was a catalyst that limits the growth of hydrocarbon chains to eliminate wax production and minimizes the production of light hydrocarbons (C_1-C_4). Recent multiple-week test runs in a fluid bed reactor yielded a product profile that indicates success.

This catalyst promises several additional efficiencies to the process configuration, including a lower operating pressure for the process, use of higher capacity fluidized-bed reactors that cannot be effectively used with the high-alpha, wax-producing catalyst, and elimination of a hydrocracking step.

Multiple Design Combinations. In keeping with initial objectives and the needs expressed by oil and gas companies, Syntroleum focused on a broad approach, one that could be adapted to a wide range of conditions and circumstances. This led to emphasis on commercialization of a menu of components:

- Two ATR (Autothermal Reforming) designs;
- Three heat integration designs which are the subject of several patent applications.
- Four Fischer-Tropsch reactor designs to allow a wide range of flexibility. For example, the "horizontal" reactor lends itself to platform, barge and ship-mounted application.
- Two F-T catalyst systems, the latest of which offers several additional cost saving changes to the process configuration.

Economics, Capital Costs. Syntroleum has collaborated with Bateman Engineering, of Denver, to develop several commercial scale design and capital cost estimates. This was done in parallel with various technical development work over the last several years. These efforts involved refining process models and evaluation of equipment designs. Considerable attention was given to alternative compression designs, reactor designs and system integration in an effort to minimize capital costs.

A 1995 study was made for a nominal 5,000 BPD first generation plant equipped to produce three fuel feedstocks (diesel/kerosene/naphtha). The estimated installed cost for the facility was $135 million. That translated to $27,000 per barrel of daily capacity, or about $3,000 below the capital cost calculated to be the break-even point for a gas-to-synfuels plant. A more recent study of a second generation design of 5,600 BPD capacity yielded a reduction to $97 million fully installed, or $17,300 per barrel of daily capacity--well within commercial range even at product prices below current levels.

Estimates encompass all process and auxiliary facilities for a complete operating plant located on the U. S. Gulf Coast, including allowance for reasonable infrastructure and utility supply to the site (i.e., gas pipeline, cooling water, rail service, etc.), capital spares, start-up expenses and the like. On-site power generation for plant loads are also included.[4]

Further cost reductions are expected from improvements in the technology which are under development. There will also be normal "learning curve" benefits from commercial experience. Significant economies of scale are achievable with the Syntroleum Process, particularly in the air compression trains. Preliminary review of a "maximum train size" configuration indicates the likelihood of constructing a 20,000 to 25,000 BPD single-train facility for $12,000 to $14,000 per barrel of daily capacity. That is the roughly the same cost as a worldscale conventional refinery--a truly revolutionary development.

Because of the limited opportunities for large plants, Syntroleum's major goal in developing this technology has been to achieve low capital costs at relatively small scales. The company is confident that, with further development, designs will be available for the majority of the world's fields. At one end of the scale is a possible 500 BPD plant for isolated areas, justified by enabling the producer not only to monetize the gas that cannot be flared, but also to produce and sell the oil shut in by the inability to dispose of the associated gas. Syntroleum currently is working with a major company to adapt a design for a 2,000 to 2,500 BPD barge-mounted plant to be installed at a very remote location; the initial estimated cost is $55 million. At the other end of the scale is the possibility of a 100,000 BPD "natural gas refinery" in an industrial area. Between these two extremes there are myriad possibilities for tapping fields now beyond the commercial reach of gas markets.

Implications. For the energy industry, the Syntroleum Process offers a new option with potential application to a wide range of situations where current technology falls short. As the new technology is applied, there will be two immediate effects: (1) supply, with a giant boost in the size and diversity of the world's oil and gas reserves, and (2) financial, as stranded reserves are converted to booked assets on the ledgers of companies and countries that own them. Refiners and power plants will have another option to satisfy their need for cleaner fuels for themselves and their customers. Meanwhile, upstream, industry will completely re-evaluate its strategy--everything from how to retarget exploration to whether to abandon LNG and heavy oil projects or pursue them in conjunction with synfuels.

These are just a few of the possibilities. Oil and gas companies, examining their own project lists and strategies, will see many others. As always happens with any new technology, the users will find applications that the developers never thought of.

REFERENCES

[1] *Oil & Gas Journal, June 19, 1995, p. 37.*

[2] Ryan, Thomas W., III, and Daniel A. Montalvo, "Emissions and Performance of Fischer-Tropsch Diesel Fuels in a Modern Heavy Duty Diesel Engine." Southwest Research Institute paper, 1996.

[3] Ivanhoe, L. F., and George G. Leckie, *Oil & Gas Journal*, Feb. 15, 1993, p. 87.

[4] Manpower requirements, labor costs estimated by Process Technical Services, Houston, specialists in start-ups and contract plant operations.

[5] Compiled from data published by Shell and Syntroleum test data.

Table 1—Typical Properties of Fuel Feedstocks from Syncrude

Property	Test Method	Unit	Naphtha[5]	Kero./JetFuel[5]	Diesel[5]
Density @ 60 °F	ASTM D1298	lb/ft³	43.6	46.0	48.7
Distillation range	ASTM D86				
IBP		°F	109	311	394
FBP		°F	381	376	676
Sulfur	ASTM D1266	ppm	n.d.	n.d.	n.d.
Cetane number	ASTM D976	—	n/a	58	76
Smoke point	ASTM D1322	mm	n/a	>50	n/a
Flash point	ASTM D93	°F	n/a	108	190
Aromatics	ASTM D5186	%V	n.d.	n.d.	n.d.

n.d. = not detectable/below detection limits; n/a = not applicable.

Table 2—Combustion Properties of Synthetic Diesel

Property	Synthetic Diesel[5]	CARB Specs	CEN Specs
Cetane number	76	48 min.	49 min.
Density (kg/m³)	771	n/s	820-860
Sulfur (ppm)	n.d.	500	500 (1996)
Aromatics (%m/m)	n.d.	10 max.	n/s
Cloud point (°C)	-48	-5	n/s
CFPP (°C)	-2	n/s	+5 to -20*
Distillation			
90% recovery (°C)	340	288-338	
95% recovery (°C)	350		370 max.

* Depending on climatic band chosen; n/s = no specification; n.d. = not detectable/below detection limits.

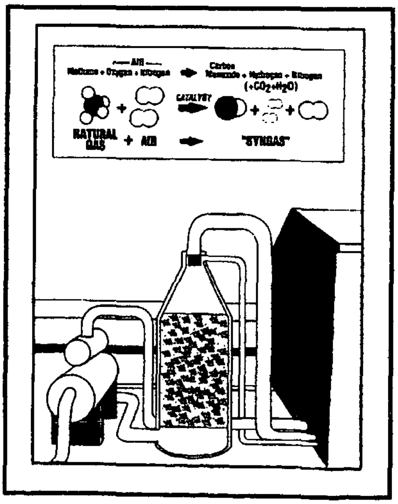

Figure 1

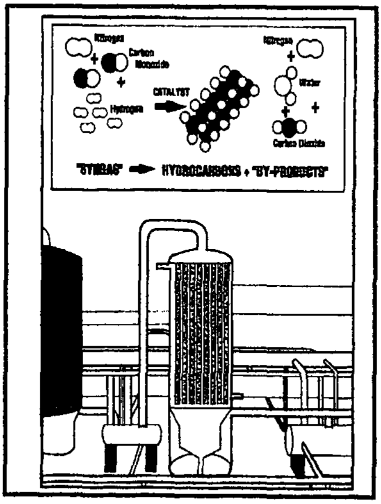

Figure 2