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COMPARISON OF STG+™ WITH OTHER GTL TECHNOLOGIES

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What is GTL?

Gas to liquids (GTL) is a process to convert natural gas or other gaseous hydrocarbons into longer-chain hydrocarbons such as gasoline or other liquid fuel products. Methane-rich gases are converted into liquid synthetic fuels most commonly via synthesis gas (syngas) as an intermediate. Syngas can be produced from natural gas using several commercial methane reforming technologies such as Steam Methane Reforming (SMR) and Autothermal Reforming (ATR). The competing technologies for gas-to-liquid fuels synthesis include the Fischer-Tropsch (FT) process and methanol-to-gasoline processes such as Primus' STG+™.

GTL Technologies: Fischer-Tropsch (FT) and Methanol-To-Gasoline processes

The FT process is a complex process that converts syngas to a mixture of hydrocarbons of various lengths – the synthetic equivalent of crude oil – which then requires an expensive separation and purification process. This additional refining adds significant costs, and usable fuel represents only 10%-20% of the synthetic crude. FT processes are economic only at a very large scale.

The methanol-to-gasoline process converts methanol to gasoline through intermediate dimethyl ether (DME). Feed methanol can be commercially produced from syngas. The Methanol-to-Gasoline process is proved to be highly selective for gasoline production with nearly complete conversion of the methanol and good overall energy efficiency.

Unlike the FT process, the methanol-to-gasoline process yields high quality gasoline that requires little additional processing. Figure 1 illustrates the product distribution by carbon chain length from typical FT and methanol-to-gasoline processes. Table 1 compares the FT process with methanol-to-gasoline processes generically.

Table 1. Methanol-To-Gasoline (MTG) vs. Fisher-Tropsch (FT)

Attribute \ Path	Methanol-To-Gasoline[1]	Fischer-Tropsch (FT)
Key Catalyst Characteristic	Molecular size and shape-selective ZSM5	Unselective CO and Fe catalysts
Product Boiling Range	Narrow, gasoline-like and some light gases	Wide, crude like
Product Molecular Types	Aromatics, naphthenes, iso-paraffins	Linear paraffins, wax
Direct Selectivity to Gasoline	Excellent	Poor
Additional Required Processing Steps	Durene reduction, vapor pressure stabilization	Distillation, cracking, hydro-isomerization, cyclization, stabilization
Complexity, Economics	Simpler, lower cost	Complex, higher cost

[1] Including Methanol-to-Olefins (MTO)/Mobil Olefin to Gasoline Distillate (MOGD).

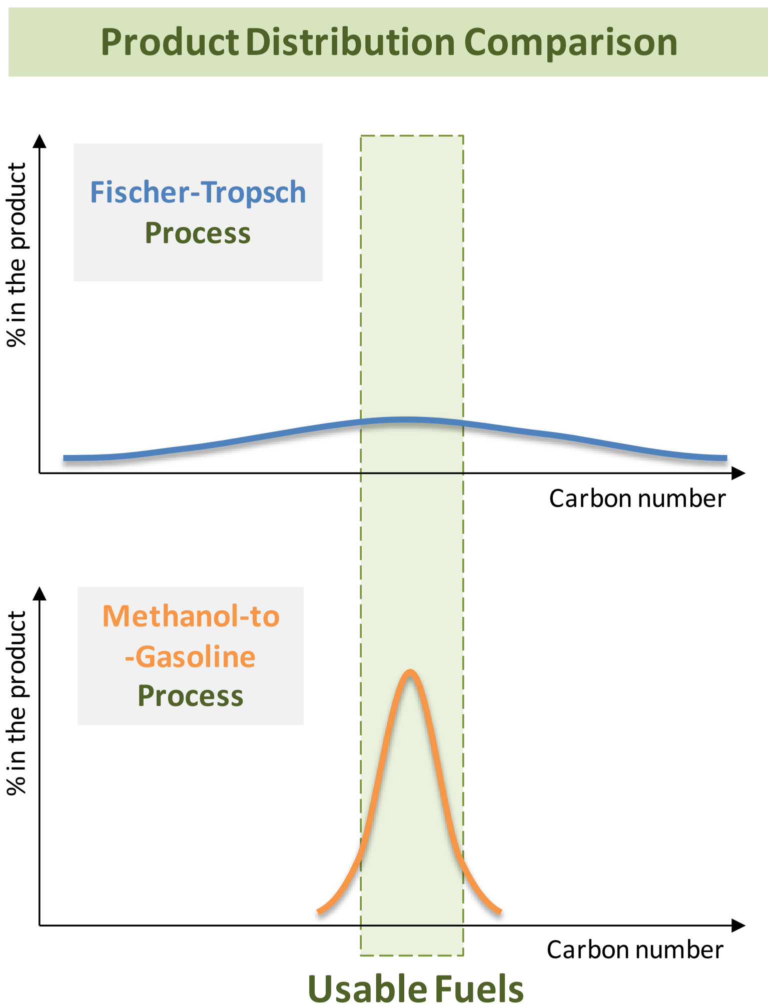

Figure 1: Illustration of product distribution from Fischer-Tropsch (FT) and methanol-to-gasoline processes.

Methanol-to-Gasoline Technologies

The competing methanol-to-gasoline processes are ExxonMobil's MTG process and Haldor Topsoe's TIGAS process. Both the TIGAS process and Primus's STG+™ process were derived from the MTG process, which was developed by Mobil in the 1970s. Table 2 indicates key differences between these processes.

The Primus STG+™ technology converts natural gas to liquid fuels through a proprietary catalytic thermochemical process that minimizes complexity, improves product quality and increases yield. The Primus STG+™ technology converts ~70% of natural gas by mass to liquid fuels, which is the highest documented conversion efficiency in the industry. The other 30% is gas and water which are recycled back into the system. The Primus STG+™ process follows three principal steps in one continuous process loop. The first step includes steam methane reforming in which hydrocarbon feed gas is transformed into syngas. For the second step, a series of fixed bed reactors convert the syngas to a high quality synthetic gasoline or diluent. The third step involves the separation of gas and liquid product; the gasoline is sent to storage; the water is recycled back to the reformer; and the residual gas is recycled back to fuel the system.

Figure 2 is a schematic diagram of the Primus STG+™ gas-to-gasoline process. The full description of Primus' STG+™ technology can be found at http://www.primusge.com/products/overview-of-primus-stg-technology/

Table 2. Comparison of Primus STG+™ process to the Methanol-to-Gasoline technologies

Factor/Process	Primus STG+™	Haldor Topsoe TIGAS	ExxonMobil MTG
Product Flexibility	Gasoline or methanol or diluent	Gasoline	Gasoline
Durene Reduction	Integrated	Separate	Separate
Number of Major Steps	2 (Syngas,Gasoline Synthesis)	3 (Syngas, TIGAS, durene reduction)	4 (Syngas, methanol, MTG, durene reduction)
Scale Flexibility	Small to large	Small to large	Limited to methanol plant size
Catalyst Sourcing	Multiple sources	In-house	Combined
Integration Economies	Highly integrated	Unknown	Little integration; separate plants
Footprint	Small	Medium	Larger

ExxonMobil's MTG process requires a substantially greater footprint and capital cost than Primus's STG+™ process, and it includes inefficiencies that Primus's process was designed to eliminate as shown in Figure 2 and 3. A key example is integration of the reactors in the STG+™ process. Primus' proprietary STG+™ process improves upon the MTG processes by recycling unconverted hydrocarbons in a single-loop process that increases yield and converts natural gas directly to high quality gasoline, and is more efficient, less expensive to build and more scalable.

Haldor Topsoe describes the TIGAS process as including some of the same features as the STG+™ process, such as the integration of the methanol/dimethyl ether synthesis and the subsequent conversion into gasoline in a single synthesis loop, however, TIGAS does not provide for durene reduction in the gasoline synthesis loop. This requires another major step to the TIGAS process whereas in the Primus' STG+™ process durene reduction is included in the Gasoline Synthesis phase. Primus provides a more simplified, efficient system which keeps Capex lower.

Primus' STG+™ vs. Other GTL Technologies

A comprehensive study from Prof. Christodoulos A. Floudas in the Department of Chemical and Biological Engineering at Princeton University shows that the Mobil and NREL (National Renewable Energy Laboratory) models of the MTG process are consistently more cost-effective, both in capital cost and overall cost, than the Fischer-Tropsch process at small, medium and large scales (representative sizes of 10 thousand, 50 thousand and 200 thousand bpd, based on current petroleum refinery capacities (Energy Information Administration, 2009)) for gasoline production.[2,3,4] And as discussed in earlier sections, Primus' STG+™ is more energy-efficient and has higher yield than the MTG process. Therefore, Primus' STG+™ technology is more efficient, cost-effective and scalable than both the FT and MTG processes.

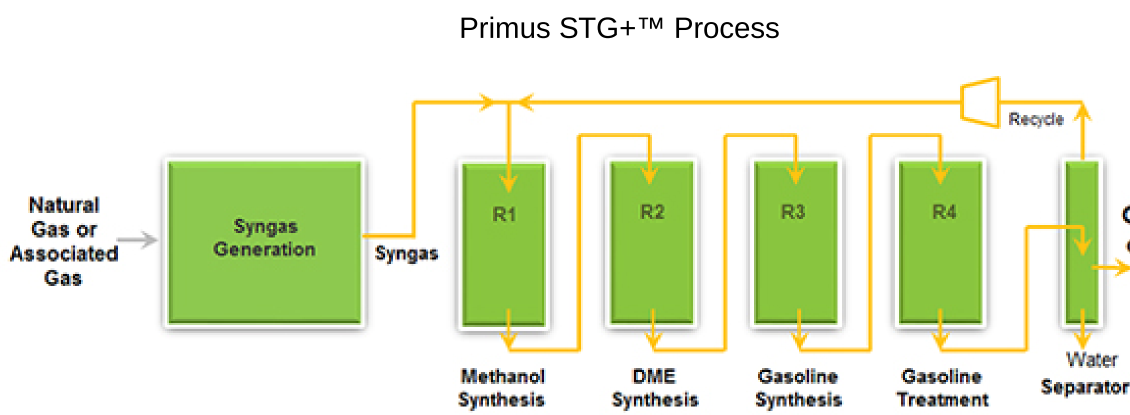

Figure 2: Schematic diagram of the Primus STG+™ process.

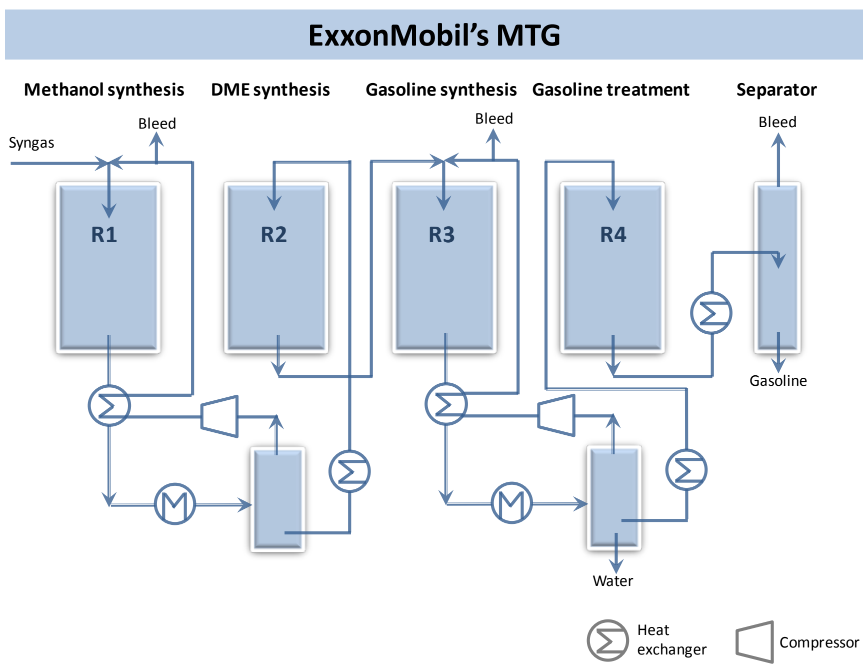

Figure 3: Schematic diagram of the ExxonMobil' MTG process.

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[2] Baliban, R. C.; Elia, J. A.; Weekman, V.; Floudas, C. A. "Process synthesis of hybrid coal, biomass, and natural gas to liquids via Fischer–Tropsch synthesis, ZSM-5 catalytic conversion, methanol synthesis, methanol-to-gasoline, and methanol-to-olefins/distillate technologies." *Computers and Chemical Engineering* **2012**, *47*, 29-56, page 41, table 6.

[3] Baliban, R. C.; Elia, J. A.; Floudas, C. A. " Novel Natural Gas to Liquids Processes: Process Synthesis and Global Optimization Strategies." *AIChE Journal* **2013**, *59*, 505-531.

[4] Baliban, R. C.; Elia, J. A.; Floudas, C. A. " Biomass to liquid transportation fuels (BTL) systems: process synthesis and global optimization framework." *Energy & Environmental Science* **2013**, *6*, 267-287.