PDVSA

8.0 TECHNOLOGY EVALUATION

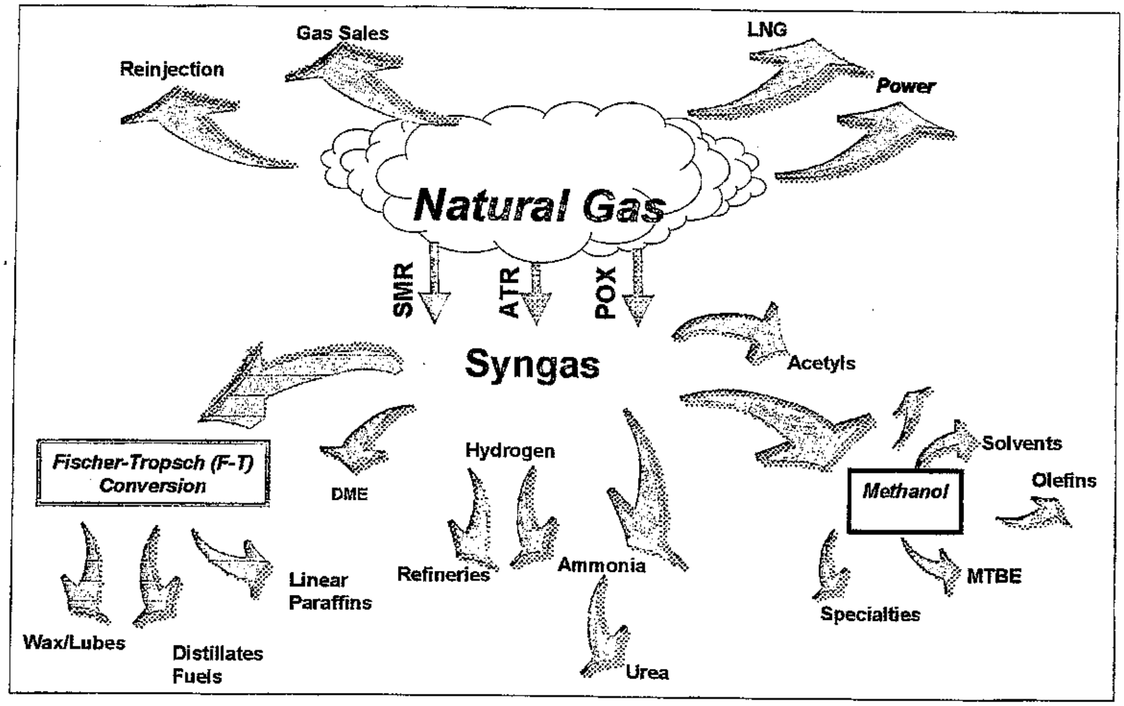
CONTENTS

8.1 OVERVIEW

8.1.1 Gas To Liquids (GTL) Conversion Technology

The term "Gas to Liquids" covers a wide range of possible technologies. The basic concept is to convert natural gas including gas associated with crude oil production, into a liquid form. Figure 8-1 shows the possible routes for utilizing natural gas.

Fig. 8-1 **Possible Routes for Utilizing Natural Gas**



Production of Liquefied Natural Gas (LNG) is currently the primary means of transporting remote gas to markets. It is characterized by large scale, very capital intensive investments, and "long term" supply contracts with customers, which typically are utilities in East Asia, Europe, and North America. Various conversion routes go through a syngas step, such as petrochemical production (methanol, ammonia, di-methyl ether) in addition to Fischer-Tropsch (F-T) Synthesis. These chemicals are characterized by product markets that are small relative to the quantities of remote and associated gas available. F-T synthesis offers an alternate means of converting natural gas to liquid fuels on a scale compatible with the natural gas resource size.

The technologies considered in this study were all based on natural gas conversion to synthesis gas, followed by Fischer-Tropsch synthesis, with subsequent upgrading to final products (See Figure 8-1).

Fischer-Tropsch, by its fundamental nature, produces a wide range of products (See Section 7.0, Table 7-1). The products considered for this study were:

- LPG
- Linear Paraffins
- Lube base oil
- Naphtha
- Diesel
- Synthetic Crude
- Kerosene
- Wax

Some of these products (diesel, naphtha, kerosene, LPG) can be produced both by upgrading "straight run" primary F-T streams and by hydroprocessing the primary streams in the product work-up units. Wax is a primary F-T product. Lube base oil and linear paraffins are products of the work-up units. The market study survey provided guidance on which were the most desirable products to produce from natural gas in Venezuela. The technology evaluation focused on determining the most attractive means of producing this product slate from both technical and commercial viewpoints.

8.1.2 GTL Facility

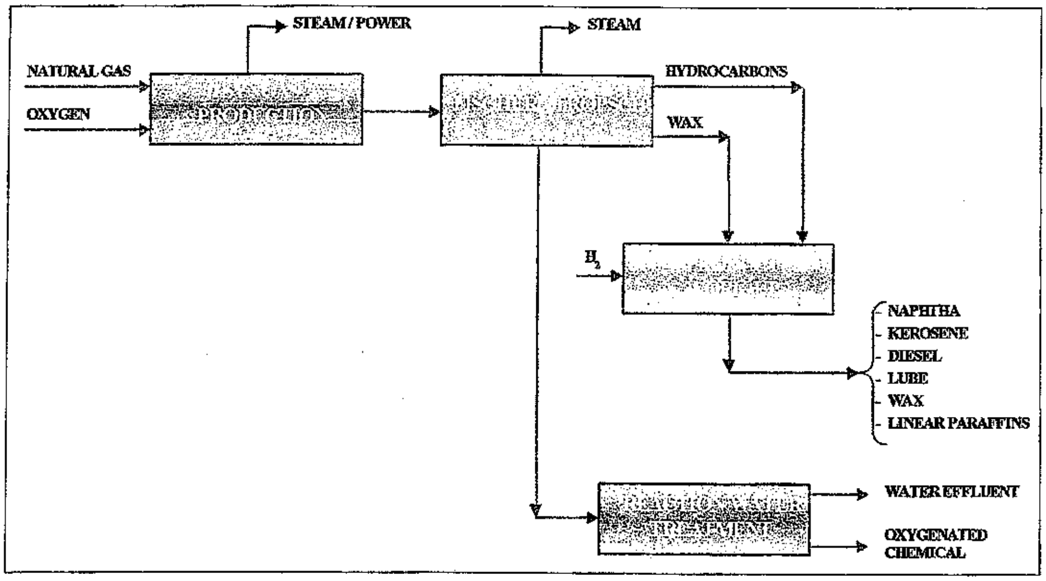
The GTL facility consists of four basic process units:

- Syngas Production
- Fischer-Tropsch Synthesis
- Product Work-up
- Reaction water treatment

In addition to these units, there are extensive utilities, offsites and infrastructure required to support the process.

A generalized flow scheme, depicting the units considered in the linear progam used for this study, is shown in Figure 8-2.

Fig. 8-2 **Four Basic Process Units in GTL Facility**



The technical evaluation was carried out by sending the same enquiry document, shown as "Licensor Enquiry Document # 1" (Attachment A), to pre-selected technology providers that could provide information on individual process units or on the entire GTL plant. These providers were selected based on an initial survey of publicly available and in-house (Raytheon and PDVSA) information. Another document, "Licensor Enquiry Document # 2" (Attachment B), was sent to technology providers who, to our knowledge, were licensing technology only in the "Product Work-up" process unit. Both documents are attached as appendices at the end of this section.

The following licensors were contacted to provide information on their technologies in the areas noted below:

Full GTL Plant:	Exxon
	Shell
	Sasol
	Syntroleum
Syngas Production:	Texaco
	Lurgi
	Krupp/Uhde
Fischer-Tropsch:	Rentech
	PDVSA/Intevep
Product Work-up:	UOP
	IFP

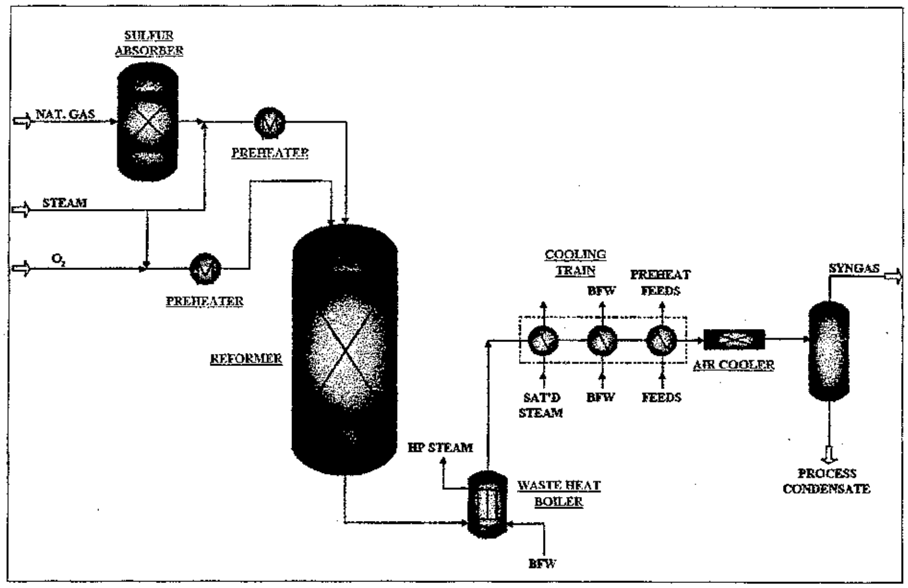
The objective in selecting these organizations was to cast a wide enough net to obtain a sufficient diversity of responses to make an evaluation, while limiting the study to a manageable number of qualified companies.

The information received was checked for consistency, and adjusted where deemed necessary to put all data on as equivalent a basis as possible. The summaries of the information gathered both from the licensor responses and from published sources are presented in this section.

8.1.2.1 Syngas Production

In the Syngas Production unit, natural gas is preheated and fed to the reforming reactor. Specific reactor types are discussed under licensor information below. Both catalytic AutoThermal Reforming (ATR, see Fig. 8-3) and non-catalytic Partial Oxidation (POx, see Figure 8-4) were considered in the study. Steam Methane Reforming (SMR) was eliminated early in the study, as it produces a syngas with too high a H_2/CO ratio for Fischer-Tropsch synthesis and is usually not cost-effective in comparison to ATR or POx at the syngas rates being considered.

Fig. 8-3 **Schematic Drawing of AutoThermal Reformer (ATR)**



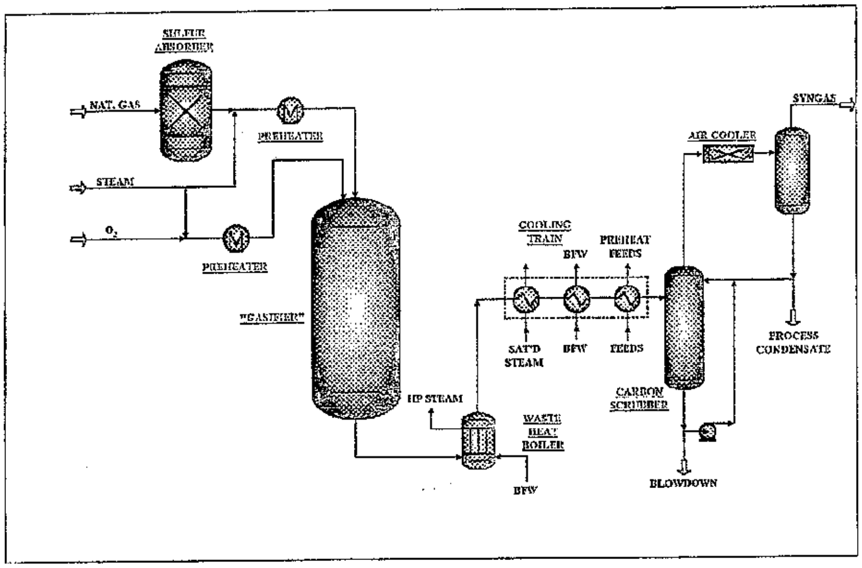
Irrespective of the type of reformer used, the major reactions taking place are:

Steam reforming: $CH_4 + H_2O \rightarrow CO + 3\,H_2$

Partial Oxidation: $CH_4 + \frac{3}{2}O_2 \rightarrow CO + 2\,H_2O$

Water gas shift: $CO + H_2O \rightarrow CO_2 + H_2$

Fig. 8-4 **Schematic Drawing of Partial Oxidation (POx) Unit**



All of these are equilibrium reactions, so the composition of the syngas leaving the reactor is a function primarily of the operating temperature and pressure. All syngas production technologies utilize these same reactions to convert the methane in natural gas to hydrogen and carbon monoxide. The main differences between licensed technologies are in the reactor designs and heat integration schemes employed.

Additional reactions to note are those that form carbon, the so called Boudouard reactions:

$$2\,CO \rightarrow 2\,C + O_2$$
$$H_2 + CO \rightarrow C + H_2O$$

Carbon formation cannot be tolerated in a catalytic reactor as it is seen as soot, which can plug the catalyst bed. In catalytic autothermal reactors, steam is added to suppress these reactions and prevent soot formation. Steam also has the effect of increasing the syngas H_2/CO ratio, through the water gas shift reaction.

The minimum steam required to prevent soot formation may result in too high a ratio for Fischer-Tropsch synthesis, and in this event CO_2 is added to the feed, typically by recycling from the syngas, or Fischer-Tropsch tail gas.

In a non-catalytic partial oxidation reactor, soot formation can be tolerated, and a scrubber is typically provided downstream of the reactor to remove it.

Heat recovery from the hot syngas stream exiting the reactor is necessary to maintain thermal efficiency. Typically this is done by raising high pressure steam in a waste heat boiler in which the syngas is cooled from the exit temperature (between 1000°C and 1350°C) to a temperature low enough to eliminate the possibility of metal dusting on the process side of the boiler. Metal dusting is a complex phenomenon, which can occur within a range of temperatures and gas compositions. If not accounted for, it can rapidly degrade the tube material in a waste heat boiler and lead to early failure. An experienced licensor will have process and mechanical designs to avoid this. The balance of the heat conservation in the syngas unit is achieved by careful integration of the syngas cooling duties with various heating duties, including steam superheating, natural gas preheat, and boiler feed water preheat.

8.1.2.2 <u>Fischer-Tropsch Synthesis Unit</u>

In the Fischer-Tropsch (F-T) synthesis unit, hydrogen and carbon monoxide in the syngas are converted to hydrocarbons, via a complex combination of reactions that can be simplified as follows:

$$2nH_2 + nCO \rightarrow (\text{-}CH_2\text{-})_n + nH_2O$$

$$(2n+1)H_2 + nCO \rightarrow C_nH_{2n+2} + nH_2O$$

Depending on the catalyst and operating conditions, the product distribution can range from light olefins to linear and branched paraffins to high molecular weight paraffin waxes. A small amount of oxygenated hydrocarbons are byproducts. The technologies being developed for GTL applications tend towards maximizing the yield of wax and linear paraffins in the F-T unit. This is typically achieved though use of cobalt based catalyst, and relatively low temperatures in the range 220°C to 250°C.

Both iron and cobalt catalysts have been used for F-T synthesis. Cobalt catalysts have the advantages of being more active for the F-T reaction with very little activity for the water gas shift reaction. Iron has considerable activity for water gas shift, resulting in potential yield losses by converting CO to CO_2. Cobalt is, however, more expensive than iron on a weight basis, so the benefits need to be weighed against possibly higher catalyst cost. It is not clear which catalyst will have a lower operating cost per unit product produced as catalyst cost, life and consumption rate information is not readily available from licensors. The general consensus is that cobalt is preferred, as it is used by all but one of the licensors considered in the study.

Three basic types of reactors are being proposed by licensors, slurry phase (See Figure 8-5), tubular fixed bed (See Figure 8-6) and ebullated bed (See Figure 8-7). Slurry phase (also called bubble column) and ebullated reactors have the advantage of being mechanically simple to scale up to very large scale, while tubular reactors are mechanically limited to relatively small scale capacities. The fluid dynamic properties of the three-phase system in a slurry bed complicates the process scale-up of the reactor. Typically a fairly large scale pilot or demonstration unit is used to confirm the scale-up. One licensor (Intevep) is developing a F-T process in a third type of reactor, an ebullated bed.

Fig. 8-5 **Fischer-Tropsch Slurry Phase Reactor**

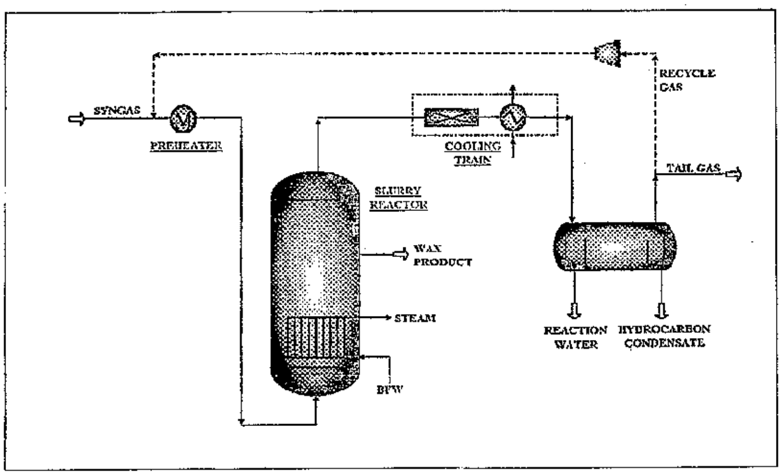


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Fig. 8-6 **Tubular Fixed Bed Reactor**

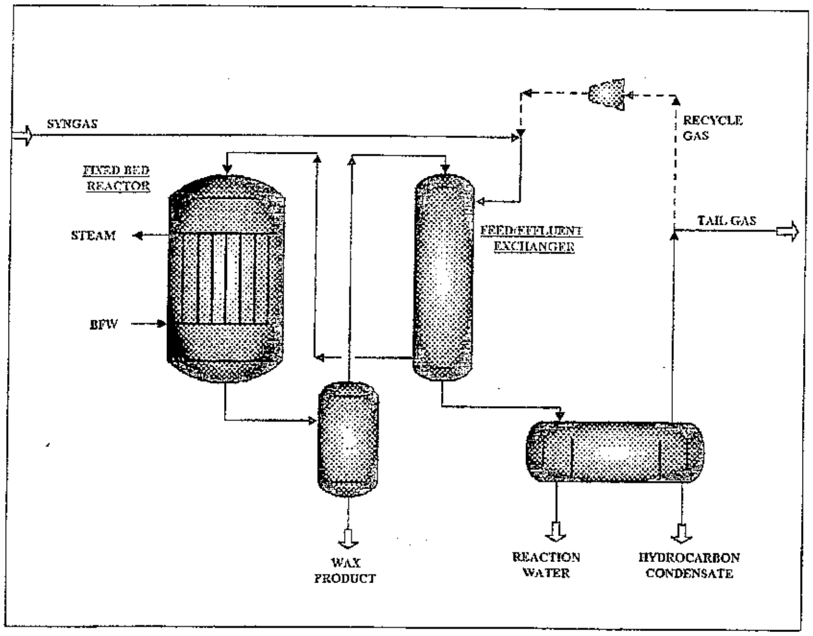
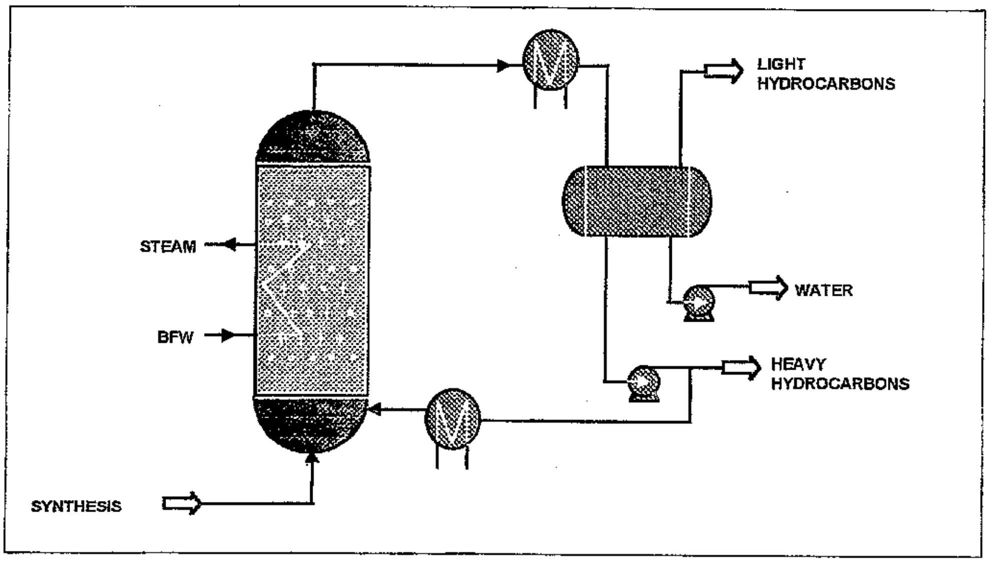


Fig. 8-7 **Ebullated Bed Reactor**



8.1.2.3 Product Work-up

The primary products of the F-T unit are the synthetic hydrocarbons (which may be in one or more stream depending on the unit design), the tail gas consisting of light hydrocarbon products and unreacted syngas, and the reaction water stream. To get the maximum value from F-T unit hydrocarbon product, it needs to be upgraded into saleable products in the Product Workup Unit.

The major result of the marketing portion of this study is that the FT wax markets are small and specialized, and the recommended product slate is to maximize diesel by hydrocracking the heavy F-T wax stream. This unit needs to operate under conditions to maximize diesel. It should also be designed with sufficient flexibility to vary the slate somewhat in the future to accommodate changes in the product markets.

Liquids produced by low temperature F-T synthesis are predominantly paraffinic, but the lighter products contain some olefins and oxygenates that need to be removed to stabilize the product for transportation. The diesel and lighter components are separated from the wax in a main fractionator upstream of the mild hydrocracker, and are hydrotreated to eliminate the olefins and oxygenates.

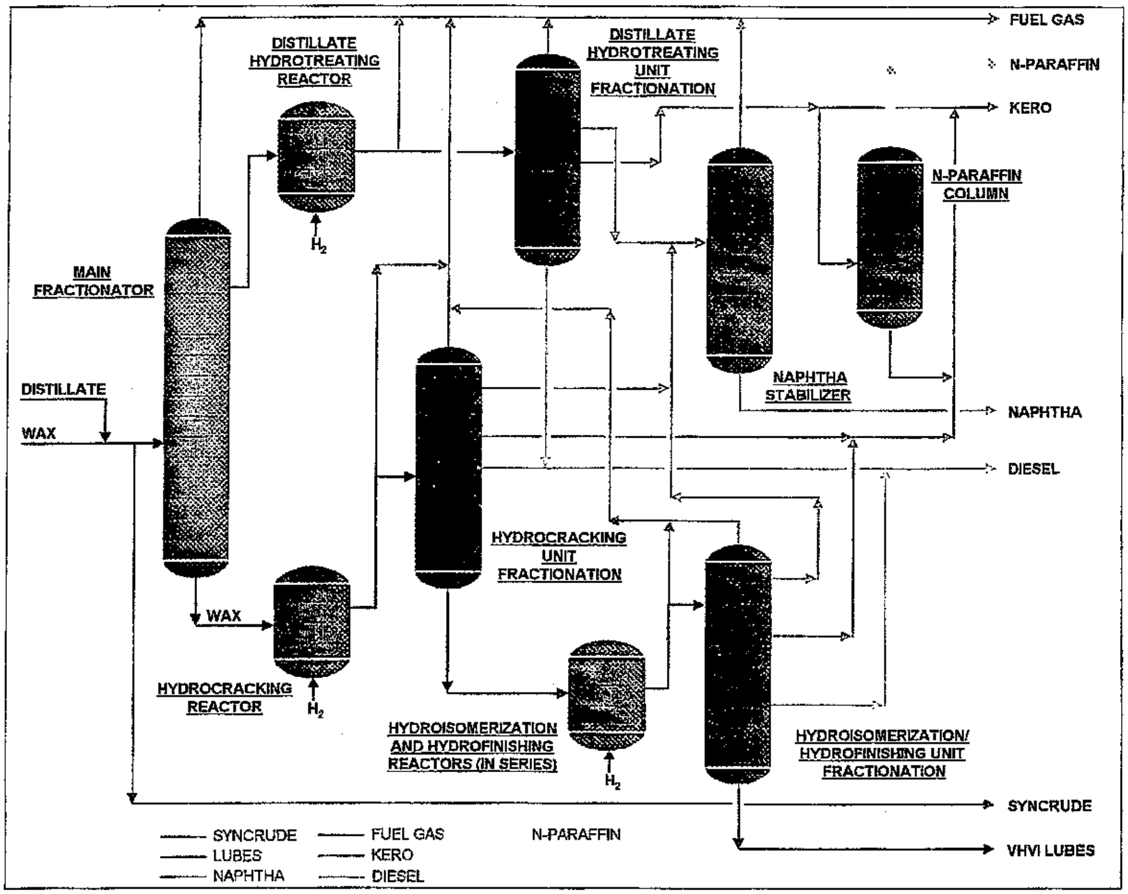
The product work-up section of a GTL plant contains process units (See Fig. 8-8) that are required for conversion of the F-T reactor streams into final products. The units that are contained in the product work-up section are a main fractionator, distillate hydrotreating unit, a wax hydrocracker, a hydroisodewaxing/hydrofinishing unit and the fractionation associated with these hydroprocessing units.

The hydrotreater is required to saturate the highly olefinic straight run naphtha and eliminate the olefin content of the heavier fractions produced in the F-T reactor. The hydrocracker converts the F-T heavy wax into naphtha, kerosene and diesel products. The hydrocracker can function with a full recycle of the unconverted hydrocracked bottoms, or this stream can be sent to a hydroisomerization/hydrofinishing unit to produce very high viscosity index lube oils as well as some additional diesel and naphtha.

The fractionation sections associated with the hydroprocessing units usually contain a stripper that takes fuel gas and light naphtha overhead followed by a fractionator (atmospheric or vacuum) to recover heavy naphtha, kerosene and diesel.

A n-Paraffin column recovers n-Paraffins from the hydrotreated straight run kerosene stream.

Fig. 8-8 **Product Work-up Process Units**

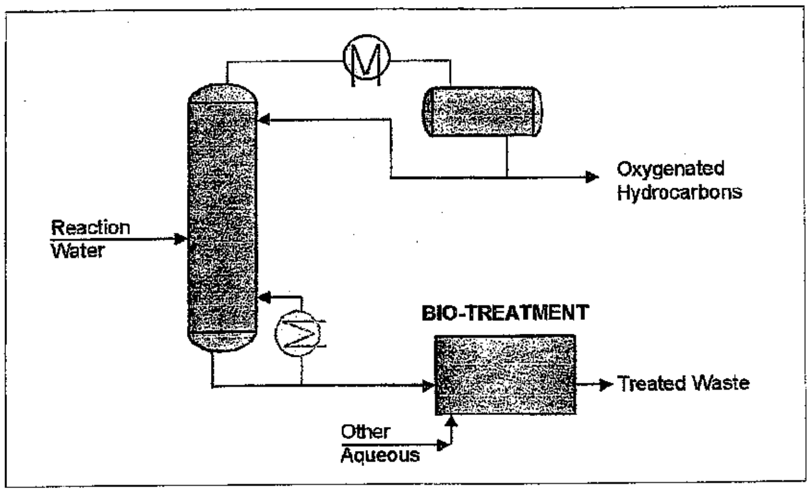


8.1.2.4 Reaction Water Treatment

The reaction water produced as a byproduct of Fischer-Tropsch synthesis contains a mixture of oxygenated hydrocarbons, including acids, alcohols, ketones, and aldehydes. Depending on the disposal or use of the water, these need to be removed prior to meet a required level of purity. Typically, a simple distillation system (See Figure 8-9) will remove the bulk of the chemicals overhead, except for the acids, which remain in the bottoms stream. The overhead will typically be burned in fired heaters as the quantities involved are usually too small to warrant isolation and purification for sale.

The bottoms stream will typically be fed to a biological waste water treatment unit, together with the other aqueous wastes from the facility.

Fig.8.9 **Reaction Water Treatment**



8.2 LICENSOR INFORMATION

The inquiry document was flexible in its request for information, and licensors were requested to provide information on any or all areas of a GTL plant in which they had expertise and/or licensable technology. In general, the responses from licensors were very limited and lacked depth for a thorough comparative evaluation of the technology providers. A brief summary of the individual responses follows:

Exxon: Declined to respond as they are not offering the process for license at this time. They are in general interested in joint venture projects but would approach potential partners directly.

Shell: Declined to provide information as they do not want to publicly release process or economic data. Stated that this "does not represent any position with respect to a possible invitation to bid on a gas contract from PDVSA".

Sasol: Responded for diesel and naphtha production only. Provided overall plant information, based on their own F-T technology combined with Haldor Topsoe reforming and Chevron product work-up technologies. No detail on individual units was provided.

Syntroleum: Responded with overall plant information with no breakdown on cost or technical information for the various units.

Texaco: Initially declined to provide information as they are privately in discussions with PDVSA. Referred to published information on their POx technology. Some information was provided towards the end of the study.

Lurgi: Declined to response due to heavy workload.

Krupp/Uhde: Provided technical and cost information on their autothermal reforming process.

Rentech: Provided technical and limited cost information on their F-T technology.

PDVSA/ Intevep: Provided investment & yield information on their F-T technology.

UOP: Provided technical information on F-T wax hydrocracking.

IFP: F-T technology still in development, not yet offering for license. Provided technical and cost information on hydrocracking of F-T wax to produce fuels and lube cut.

In view of the very limited or no response from the technology providers, Raytheon used a combination of licensor responses with available information in the public domain to evaluate the status of individual licensor technology. A discussion follows on each technology supplier.

8.2.1 Full GTL Plant

8.2.1.1 Exxon Advanced Gas Conversion for the 21st Century (Agc-21)

Exxon declined to provide any data on their technology. The following summary has been prepared by Raytheon based upon information available in the public domain.

8.2.1.1.1 Background.

Exxon has spent a reported $300 MM over the past 20 years developing the AGC-21 process. They have over 400 US and 1500 international patents covering various aspects of the different units making up the process (ref: Chemtech October, 1999, pp 22-27). Exxon have described their strong patent position as a "strategic asset". The largest scale experience was gained on a 200 BPD pilot plant at their Baton Rouge, LA refinery, operated from 1990 to 1993. The plant included Exxon's proprietary fluid bed syngas unit and a bubble reactor F-T synthesis unit. Based on the information gained though the three year test program, Exxon claim that they have sufficient information to scale up and design world scale plants in excess of 50,000 BPD capacity.

8.2.1.1.2 Current Status.

The pilot plant has been shut down since 1993, and there are no indications that it will be restarted. Exxon state that the experience gained during that period, combined with the extensive body of information they have regarding very large fluid bed reactors, such as Flexicokers and Fluidcokers, put them in a position to design commercial scale units today in a capacity range of 50,000 barrels.

8.2.1.1.3 Process Description.

Exxon use a proprietary fluid bed syngas generation (FBSG) process. Natural gas is desulfurized and preheated and fed, together with steam and oxygen, into the fluid bed in which the steam reforming, partial oxidation, and shift reactions take place. The operating temperature is below that of an autothermal reformer or partial oxidation reactor, and the reactions all take place at one uniform temperature due to the nature of the fluid bed. The steam requirement is claimed to be less than that required for an ATR, which is beneficial, as if helps produce the desired H_2/CO ratio of approximately 2 for F-T synthesis. The pilot unit is 5-foot diameter and approximately 120-foot high. The fluid bed design is amenable to scaling up to very large capacities in a single unit. The effluent gas passes through an external cyclone for separation of entrained catalyst before passing to a waste heat boiler for energy recovery and syngas cooling for water removal before being fed to the F-T unit.

Exxon uses a bubble reactor with cobalt catalyst for F-T synthesis, called the hydrocarbon synthesis (HCS) process. This is the heart of the process, and the area where Exxon has concentrated its patent position. A proprietary titania supported cobalt catalyst system, with cobalt concentrated in the outer shell, or "rim", of the particles to maximize wax productivity, has been custom developed for the bubble reactor. A proprietary catalyst separation and product recovery technology has also been developed, but no specifics have been published. The exothermic heat of reaction is removed by generating steam in internal cooling coils. The pilot reactor is 4-foot diameter and approximately 70-foot tall.

8.2.1.1.4 Licensor Data.

Since Exxon declined to participate in this study, all information used for evaluation and comparative purposes is derived from open publications. In an article presented at the 73^RD GPA Annual Convention in 1994 (by B. Eisenberg, L.L. Ansell, R.A. Fiato, and R.F. Bauman) it was stated that about 100,000 BPD of liquid fuels could be produced from a 6 TSCF (Trillion Standard Cubic Feet Per Day) reserve operating for 20 years. Assuming that the feed gas rate was constant over the time period, and operating for 340 days per year, the feed gas rate is 882 MMSCFD. For the study capacities, this prorates to the following overall total liquid yields:

Feed Gas, MMSCFD	150	500
Total Liquid Production, BPD	17,000	56,700

These yields are used in the technology evaluation.

No capital cost information has been published by Exxon. However, an article by Morgan Stanley Dean Witter, dated September 9, 1997, projected a cost of $24,000 per daily barrel for a 50,000 BPSD plant capacity.

8.2.1.2 Shell Middle Distillate Synthesis (SMDS)

Shell declined to provide any data on their technology. The following summary has been prepared by Raytheon based upon information available in the public domain.

8.2.1.2.1 Background.

Shell has been involved in the development of the three major technologies, syngas production, F-T synthesis, and hydroprocessing for many years. They were very active in F-T development during the 1970s and 1980s, a key event being the purchase of the Gulf-Badger* technology from Chevron, after Chevron's takeover of Gulf in the early 1980s. A pilot plant was constructed in 1983, and the first commercial scale plant was designed in the late 1980s, constructed at Bintulu, Malaysia, and started up in 1993. The plant produced a range of products, including wax, naphtha, kerosene, gasoil, and several grades of linear paraffins, marketed as solvents and detergent feedstocks. Shipments of gasoil were made to Californian refineries for use as a diesel blendstock to upgrade marginal diesel pools. High viscosity lube oil blendstocks have also been marketed in Japan. An explosion in the air separation unit in December 1997 forced the shutdown of the plant.

8.2.1.2.2 Current Status.

The Bintulu plant is being repaired, and the air separation unit is being completely rebuilt. Startup is planned for April 2000 (ref: World Refining, September/October 1999, pp 74-76). Plant capacity is being increased 25%, by a combination of increased reactor capacity in the syngas unit (Shell Gasification Process, "SGP") and new larger reactors with improved catalysts in the F-T synthesis unit (Heavy Paraffins Synthesis, "HPS").

*Badger is now part of Raytheon.

8.2.1.2.3 Process Description

The syngas production unit uses the Shell Gasification Process, which is a non-catalytic partial oxidation process. Feed gas is preheated, desulfurized, and fed to the reactor, or "gasifier" (so called as it can be designed to handle solid and liquid feeds in addition to gas) together with oxygen and steam (if required for controlling the H_2/CO ratio of the syngas). The effluent from the gasifier is cooled by raising high pressure steam in a waste heat boiler, then further cooled by a combination of feed preheating, steam superheating, and boiler feed water preheating for optimizing thermal efficiency, Any soot produced in the gasifier is removed in a scrubber. The syngas is further cooled in an air cooler to remove the bulk of the water from the syngas.

In the HPS unit, F-T synthesis is carried out in tubular fixed bed reactors, with cobalt catalyst on the tube side and boiling water on the shell side to remove the heat of reaction. While many other licensors have developed slurry phase reactors to enable large single train capacities, Shell has reportedly improved the tubular reactor and catalyst system to the point where capacities up to 9,000 BPD can be obtained in a single reactor (ref: World Refining, September/October 1999, pp 74-76). Reactor wax, which is liquid at reactor conditions, is removed from the effluent stream, which then is used to preheat the feed in a heat exchanger, before final cooling to remove the rest of the hydrocarbon product and reaction water. It is not clear whether Shell operates the tubular reactors in series or parallel, or whether a portion of the tail gas is recycled.

In the product workup section, the F-T wax is selectively hydrocracked and hydroisomerized in one reactor to produce the desired middle distillate products, with acceptable cold flow properties. Shell has designed the unit with flexibility to operate over a range of product modes as follows:

Product Split, wt%	Diesel Mode	Kerosene Mode
Tops/naphtha	15	25
Kerosene	25	50
Diesel	60	25

8.2.1.2.4 Licensor Data.

Shell did not supply any information for this study, so the yield and cost data used for evaluation purposes was derived from published papers. In an article "The Markets for Shell Middle Distillate Synthesis Products" (Peter Tijm of Shell at the Alternate Energy '95 conference in Vancouver, Canada, May 2-4, 1995) the product yield was stated as being 500,000 ton/year of total hydrocarbons produced from 100 MMSCFD. Using an average product density of 745 kg/m^3, based on product slates and specifications presented in the paper, this is approximately 11,500 BPD. Since the feed gas for this study is not typical (it is low in methane at 80.95% and high in CO_2 at 8.5%) a quick check was made to confirm that yields that are presumably based on "typical" natural gas can be prorated without any adjustment. The analysis showed that although the different natural gas compositions would have a cost impact as different quantities of oxygen, steam, and in one case CO_2, need to be fed to the unit, approximately the same quantity and composition syngas can be produced from each natural gas feed.

Cost information is more difficult to assess. While the Bintulu plant was reported to have cost $850MM for the nominal 12,500 BPD capacity, Shell have stated that much has been learned since then and many process improvements have been made. For larger scale plants (25,000 to 50,000 BPD) in remote sites, Shell estimate that total capital cost can be brought down to below $30,000 per daily barrel capacity, or $450MM for a 15,000 BPD plant. An article by Morgan Dean Witter, September 9,1997, indicated a cost of $26,000 per daily barrel for a 50,000 BPSD Plant.

8.2.1.3 <u>Sasol</u>

8.2.1.3.1 Background.

Sasol are a highly experienced technology provider having operated Fischer-Tropsch plants in South Africa since the 1950's. These plants, which still are in operation today, all use coal gasification as the syngas source, and have combined capacity of approximately 150,000 BPD of fuels, chemicals, and petrochemical intermediates. Sasol have also licensed their F-T technology to another South African company, Mossgas, which operates a 25,000 BPD facility fed by off-shore gas. It is the largest GTL plant in the world utilizing F-T technology.

The bulk of Sasol's operating units use the so-called high temperature F-T reactors, which produce mainly gasoline and light olefins, plus a full spectrum of fuels including LPG, diesel, jet fuel, and kerosene. At its Sasolburg facility Sasol operates two types of so-called low temperature F-T reactors, namely tubular fixed bed ("ARGE" reactors) and slurry phase reactors. These units produce a heavier product spectrum, with wax being the major hydrocarbon product.

All the commercial reactors use iron catalyst. The commercial slurry phase reactor is 5-meter diameter and 22-meter high, and has a capacity of 2500 BPD. Sasol also have a pilot reactor (1-meter nominal diameter) that has been operating with cobalt catalyst for the past several years. Sasol has recently commissioned the new Sasol Advanced Synthol (SAS) high temperature Fischer-Trossch reactors in South Africa. These vessels are 10.3-meter fluid bed reactors, which Raytheon believes to be similar size to those envisioned for a 15000 BPSD slurry reactor.

8.2.1.3.2 Current Status.

Sasol has formed a global joint venture with Chevron to develop GTL projects. This development gives Sasol more exposure outside of its home market, and brings the gas reserves and financial strength of Chevron to any projects the venture pursues. In addition, each partner is contributing technology, Fischer-Tropsch from Sasol and hydroprocessing (including mild hydrocracking, hydroisomerization, and catalytic dewaxing for lubes production) from Chevron. A few years ago, Sasol entered into an agreement with Haldor Topsoe to use their autothermal reforming technology for syngas production.

Each of the technology licensors in this venture is continuing to support technology development:

- Sasol is demonstrating the F-T technology at their Sasolburg, South Africa pilot plant.
- Chevron are further developing the product work-up technologies at their Richmond, California research facilities.
- Haldor Topsoe have demonstrated the commercial ATR operating conditions in their Houston pilot plant.

Sasol are not currently licensing the technology, but are interested in developing projects in which they have an equity stake. They are currently planning a 30,000 BPD grassroots GTL plant in Nigeria using associated gas as feed.

8.2.1.3.3 Process Description.

Natural gas is desulfurized, preheated and fed to an AutoThermal Reformer (ATR), together with steam and oxygen. In the ATR reactor a portion of the feed hydrocarbon is partially combusted to provide the heat requirement for the endothermic reforming reactions. The hot syngas exiting the reformer is cooled by generating and superheating high pressure steam, which is used to provide energy to other sections of the complex. The syngas is further cooled to remove the bulk of the water before being fed to the F-T unit.

In the F-T unit, the syngas is preheated and feeds Sasol's proprietary slurry phase reactor, which uses their own cobalt based catalyst to convert syngas to hydrocarbons. In the reactor the gas bubbles through a slurry of solid catalyst particles in liquid products. Operating conditions are in the range 20 to 25 bar and 200 to 250 °C. The exothermic heat of reaction is removed by steam generation coils in the slurry bed. The liquid and vapor products are removed form the reactor and cooled to produce wax, a hydrocarbon condensate stream, and reaction water as the primary F-T products. The tail gas, consisting of light hydrocarbon products and unconverted syngas, is the prime source of fuel gas for the complex.

The product work-up unit uses what Sasol describe as hydroprocessing of the "waxy syncrude" under mild conditions to produce diesel and naphtha. The technology is licensed by Chevron. Based on in-house Raytheon data and studies, this is interpreted as hydrocracking/hydroisomerization of the F-T wax under mild conditions to maximize diesel yield and produce no net wax product, and hydrotreating of the hydrocarbon condensate to saturate double bonds and hydrogenate trace oxygenates.

8.2.1.3.4 Licensor Data.

Sasol elected to supply fuels only yield data, and did so treating the entire GTL plant as a "black box". Instead of the requested 500 MMSCFD feed gas capacity for the "long term" case, Sasol provided data for a 465 MMSCFD plant that would comprise three maximum scale process trains each consisting of an air separation unit, the ATR syngas unit, and a F-T unit. The rest of the plant is a single train. The information provided, and prorated information (shown in *italics*) for the two study cases, is as follows:

Natural Gas (MMSCFD)	465	150	*500*
Oxygen Consumed (TPD)	10580	*3412*	*11376*
Diesel Product (BPD)	35200	11350	*37850*
Naphtha Product (BPD)	12200	3940	*13120*
Export Power (MW)	50 max.	*15 max.*	*50 max.*
Make-up Water (m^3/hr)	3100	*1000*	*3333*
Capital Cost	$972MM	$395MM	*$1030MM*
Operating Cost	$3.70/bbl	$5.56/bbl	*$3.70/bbl*

8.2.1.4 <u>Syntroleum</u>

8.2.1.4.1 Background.

Syntroleum is a small process development and licensing company that has been responsible for much of the interest and publicity in GTL technology in recent years. It was founded in 1984, and since then has developed both autothermal reforming and Fischer-Tropsch synthesis technologies. Syntroleum have developed proprietary cobalt based F-T catalysts, and have announced progress in the area of "chain limiting" catalysts. These would stop the F-T reaction at a given chain length, theoretically removing the need for downstream cracking. Such catalysts are still developmental, and are not currently being offered. They have been very actively licensing their technology, to date having sold licenses to ARCO, Texaco, Marathon, YPF, Enron and Kerr-McGee. In addition, alliances have been made with a catalyst vendor (Criterion), gas turbine vendors (GE and ABB) for combustion of low energy content tail gas, and an automobile manufacturer (Daimler Chrysler) for demonstration of the "designer fuel" products.

8.2.1.4.2 Current Status.

A pilot unit based on Syntroleum's technology in both AutoThermal Reforming and Slurry Phase F-T was constructed at ARCO's Cherry Point, WA, refinery to demonstrate the process. It has a rated capacity of 70 BPD, and was successfully commissioned in July, 1999. No further information on this pilot plant has been made available. Several plans to develop commercial plants have been released over the past several years, the most recent being the "Sweetwater" project, either in Australia or Trinidad.

8.2.1.4.3 Process Description.

The major distinguishing feature of Syntroleum's technology is that there is no air separation unit. Instead, air is compressed and fed to the AutoThermal Reformer, together with preheated desulfurized feed gas and steam. Syntroleum do not have their own reforming catalyst, and state that commercially available catalyst is used. The resulting syngas, after waste heat recovery, cooling, and water separation, will be approximately 50% nitrogen (based on Raytheon's simulations).

In the F-T unit, the syngas is fed to the slurry phase reactor where Syntroleum's cobalt catalyst converts the hydrogen and carbon monoxide into hydrocarbons and water. The nitrogen in the syngas aids in controlling the reactor temperature rise as it is heated from inlet to outlet temperature. Liquid products are cooled and separated for downstream processing.

While Syntroleum have no product workup technology of their own, the hydrocarbons would be converted into final products in much the same way as the other technologies, i.e., hydrocracking the wax to maximize diesel production.

8.2.1.4.4 Licensor Data.

Syntroleum provided yield and cost data for a complete GTL plant. A summary of the yield and cost data is provided below:

Natural Gas (MMSCFD)	150	500
Diesel Product (BPD)	6,000	20,000
Naphtha Product (BPD)	3,000	10,000
Kerosene Product (BPD)	3,000	10,000
Product Water (BPD)	15,600	52,000
Capital Cost, ($MM)	351	1,097
Operating Cost, ($/BBL)	5.36	4.96

8.2.2 Syngas Production

8.2.2.1 <u>Texaco</u>

Texaco initially declined to provide any specific data (some data was provided towards the end of the study) in response to Raytheon's enquiry document. The following summary has been prepared by Raytheon based upon information available in the public domain.

8.2.2.1.1 Background.

Texaco have for many years been the leading licensor of partial oxidation technology (POx) for converting gas, liquid and solid feedstocks into synthesis gas. In recent years, most of their efforts have been focused on low value, heavy refinery streams such as atmospheric and vacuum resid and petroleum coke, for steam, power and hydrogen production coupled with combined cycle technology. Texaco also have interests in the areas of GTL and refinery based F-T production, and have licensed F-T technology from both Syntroleum and Rentech.

8.2.2.1.2 Current Status.

Texaco have recently been awarded a contract by the US Department of Energy to develop the "Vision 21" concept, in a consortium with Rentech, General Electric, Praxair, and Brown and Root. The "long term" objective is to develop technology and designs for the coproduction of fuels, chemicals, and power from low value feeds. Texaco's POx technology will be used for syngas production, and Rentech's F-T technology for liquid fuels production. At the time of this study, Texaco was also in confidential talks with PDVSA, and declined to make information available for this evaluation in a timely fashion.

8.2.2.1.3 Process Description.

In Texaco's POx technology, desulfurized natural gas is preheated and fed to the partial oxidation reactor ("gasifier") together with oxygen and steam (as required) to produce the desired H2/CO ratio syngas. The effluent from the gasifier is cooled by generating steam in the waste heat boiler, and then further cooled by a combination of steam superheating, boiler feed water and feed gas preheating, upstream of a carbon scrubber. In the scrubber, water is circulated to collect any soot formed in the gasifier. The soot is removed from the unit via a blowdown stream. The clean gas is cooled in an air cooler before being fed to the F-T unit.

8.2.2.1.4 Licensor Data.

As stated above, Texaco initially declined to provide information for this study in a timely fashion. Generic in-house information on the heat and material balance, and capital costs of POx units, was used in the economic evaluation section of the study. Towards the end of the project, Texaco provided syngas composition, oxygen requirements and total investment cost for both "short term" and "long term" projects. These data were used to validate the in-house information used for this study.