Appendix A. Detailed Flow Diagram of a Synfuel Park/Polygeneration Plant

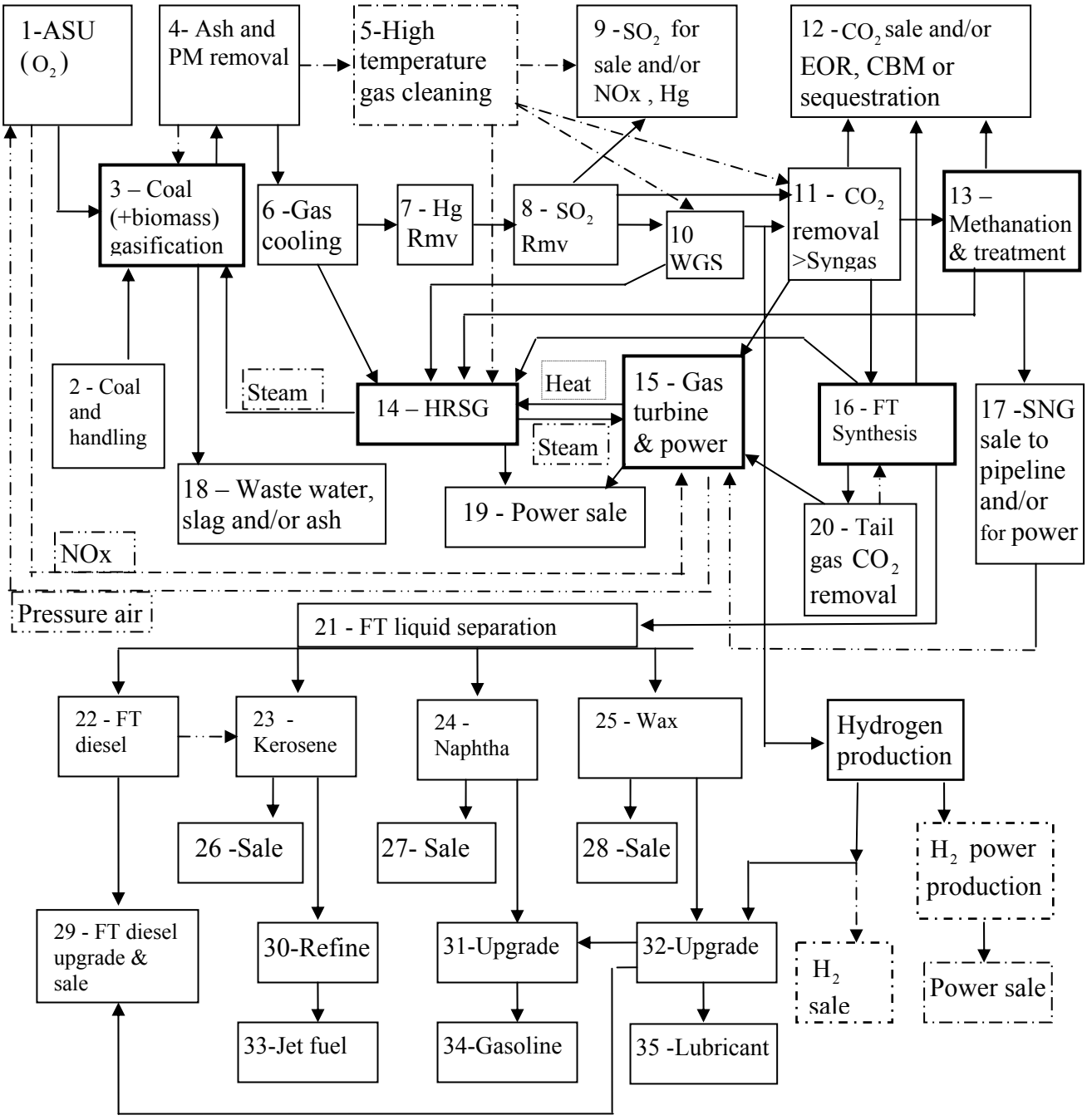


Figure A.1. Detailed flow diagram of the Synfuel Park/Polygeneration plant process

Notes: The WGS can be put before the Selexol block. In this case, we need a WGS catalyst that can tolerate SO_2. Heat and steam may be generated from various blocks, which may be fed back to the HRSG block. A WGS unit may be needed in methanation for making the H_2 /CO ratio close to 3:1. A catalyst for methanation is described in [3]. Blocks with dashed lines are alternative choices. If high temperature syngas cleaning is to be used, lower temperature cleaning blocks will be removed. A gas turbine burning clean syngas produces CO_2, while hydrogen power production does not. Jet fuel could be J-BUFF (Joint Battlespace-Use Fuel of Future) [I.8].

Appendix B. Transportation of Large Equipment to Synfuel Parks

Sisi Guo
Research Assistant and Graduate Student
School of Industrial Engineering
Purdue University

B.1. Introduction

Some key equipment for synfuel parks, such as gasifiers and FT reactors, can be large and heavy. An FT reactor with a capacity of 2500 TPD may weigh several hundred tons; the diameter could be around 5 meters (16.4') and the height may be near 20 meters (65.6'). The dimension and weight of this FT reactor far exceeds the common freight loads measurements for both trucks and rail cars; thus, the shipment requires specially designed types of trucks and rail cars. Consequently, transportation of large equipment forms a bottleneck in the feasibility of synfuel park construction. The purpose of this study is to provide insight into transportation issues and some analysis tailored to the specific candidate sites for synfuel parks.

B.2. Transportation Methods for Large Equipment

B.2.1. Highway/ Road

B.2.1.1.General Regulations for Freight Trucks on Indiana Highways:

The Indiana Driver Manual [1] lists the following size limitations on all vehicles:

"General Size Limitations for Commercial Vehicles without Special Permit:
"Maximum Width ..... 8 feet, 6 inches
"Maximum Height of Any Vehicle ..... 13 feet, 6 inches
"Maximum Length of Any Single Vehicle ..... 36 feet
"Maximum Length
(2-vehicle combination) ..... 60 feet
(3-vehicle combination) ..... 65 feet"

It also specifies maximum weight limitations:
"You may not move any vehicle or combination with a gross weight over 80,000 pounds on any highway without a special permit. Vehicle weight must be distributed within the following limits:

"Maximum single axle weight ..... 20,000 lbs.
"Maximum wheel weight ..... 800 lbs. per inch width of tire rim
"Maximum tandem axle weight ..... 17,000 lbs. per axle
"The federal bridge formula may restrict gross weight on shorter wheel based vehicles.
"Overweight trucks may be impounded by law enforcement."

Finally, the Driver Manual provides some information on special permits:
"Before moving loads on public highways that exceed the size and weight limits described above, you must secure a special permit from the Indiana Department of Revenue for state-maintained routes, and from local authorities for routes that are not maintained by the state."

B.2.1.2. Regulations for Special Permits

Below are some regulations for extreme cases with special permits from the Federal Motor Carrier Safety Administration's website. The regulations may be applicable to our study of shipping oversized equipment on highways.

Combination Limits for a Truck Tractor and 2 Trailing Units to Operate on Interstate Highways in Indiana [2]:

"LENGTH OF THE CARGO–CARRYING UNITS: 106 feet
"MAXIMUM ALLOWABLE GROSS WEIGHT: 127,400 pounds

"OPERATIONAL CONDITIONS:

"WEIGHT: Single axle = 22,400 pounds. Axles spaced less than 40 inches between centers are considered to be single axles.

"Tandem axle = 36,000 pounds. Axles spaced more than 40 inches but less than 9 feet between centers are considered to be tandem axles."

B.2.1.3. Summary

Given the above regulations, it is almost impossible to ship large FT reactors and gasifiers via public highways. In 1989, Crane had the experience of shipping a reactor vessel from the Tennessee Valley Authority Yellow Creek Power Plant. The vessel weighed around 500 tons with a diameter over 19 feet and a length of about 40 feet. It was first transported via barge to Jeffersonville, Indiana, then via train, and finally via a 48-wheeler flatbed truck on a specially constructed short-haul road to the destination. It is reasonable to follow the same methods for other synfuel park sites: ship the equipment first by barge to a nearby port, then by heavy duty trains to the nearest station, and finally by truck to destinations on specially constructed roads.

B.2.2. Railroad

B.2.2.1. Indiana Railroad System

Indiana has 4,255 railroad route miles; 91 percent of them are operated by Class I railroads. The remaining miles are regional or local railroads-- in other words, shortline rails. These railroads, which include both Class II and Class III rails, are also a vital element of IN rail systems. Short lines seem to carry fewer rail tonnages than branch lines. According to the Indiana Rail Plan [3] in Oct. 2002, the Indiana DOT has been making progress in improving the infrastructure conditions of short lines in order to accommodate 286,000 lbs. gross weight on rail.

The freight capacity of railroads is also limited by bridges and overpasses. The width and weight limit of current bridges and the clearance of overpasses could be the main obstacles to oversized shipping. As a result, Google Earth was used to identify bridges, overpasses, and tunnels along several shipping routes. In future studies, more specific information may needed to develop an optimized shipping strategy.

B.2.2.2. Heavy Duty Freight Cars

Two main types of cars can handle oversized equipment. Heavy capacity flatcars are designed to carry more than 100 tons. As an example of flatcars, ACMX 403 has a load limit of 690,400 lb (or about 345 tons); the length of the loading platform is 24'7'' [4]. Another type of heavy duty car is the Schnabel car. A Schnabel

car is a specialized type of railroad freight car. It "supports its load between two individual car halves. The load is suspended on arms with self-contained power systems for lifting and lowering. The lifting arms can rotate laterally 45 degrees to either side of the car" [5]. The largest Schnabel car in operation is CEBX 800 owned by ABB, which can support 880 total tons of load. Some additional specifications of CEBX 800 are listed below in Table B.1.

Table B.1. Specifications of CEBX 800 [5]

Capacity	1,779,260 lbs.
Light Weight	740,890 lbs.
Load Limit	1,779,260 lbs.
Number of axles (33" wheels)	36
Empty Car Length	231' 8"
Maximum Loaded Length	345' 0"
Maximum Vertical Load Shifting Ability	44"
Maximum Horizontal Load Shifting Ability (either side of car center line)	40"

Thirty-six axles on the under carriage allow the CEBX 800 to navigate horizontal curves having a 191-foot radius and vertical curves having a 2000-foot radius. The maximum speed of CEBX 800 is 15 mph. [5] The power systems of the Schnabel car have the ability to shift the position of the load by as much as 44 inches vertically and 40 inches horizontally. This feature may be helpful to get huge reactors through low overpasses and narrow bridges (see Figures B.1 and B.2).

One of the largest and heaviest shipments ever to move by rail occurred in July/ August 1982. Two 790-ton steam generators and a 490-ton reactor vessel were shipped from near Charleston, S.C. to Duke Power Company's Cherokee Nuclear Station near Gaffney. Southern Railway and S.C. CSX made the delivery. "Railroad personnel accompanying the Schnabel train to the Duke power plant removed and replaced more than 350 small obstructions, such as signs, switch stand targets, poles and wires along the route. In addition, the car had to be shifted, raised or lowered more than 200 times to get around or under permanent obstructions and to provide stability on curved super elevated track along the route." [5]

Figure B.1. A CEBX 800 car operating on April 15, 2005 [5]

Figure B.2. CEBX 800 passing under an overpass [5]

B.2.3. Waterway

The transportation of cargo in barges is the most energy-efficient and cost-effective form of transportation. With a capacity of 1,500 tons per barge, this transportation form is an ideal way for bulk movement, as indicated in Figure B.3. Figure B.4 shows America's Inland Navigation System. For 358 miles, the state of Indiana borders the Ohio River, which carries thousands of tons of coal, aggregates, grain, petroleum

products and chemicals each year. The two major ports on the Ohio River in Southern Indiana offer year-round access to the waterway. The Clark Maritime Centre, located 45 minutes west of Madison in Jeffersonville, has three berths, a 450-ton lift capacity and averages 1.1 million tons of shipping per year. The Southwind Maritime Centre, located in Mount Vernon, is the 4th largest port in the Ohio Basin, averaging 4 million tons per year. [6] Other ports taken into consideration here are located in Evansville and Tell City.

Sasol, which has contracted with Korean and Japanese firms, is one of the few manufacturers of FT reactors in operation. Most of the Sasol reactors are made in Japan. If Sasol FT reactors are chosen, they could be barged up the Mississippi and Ohio Rivers. If U.S. technology is used for FT plants, equipment will be possibly manufactured in the U.S., and it could be transported either via the rail system or by waterway.

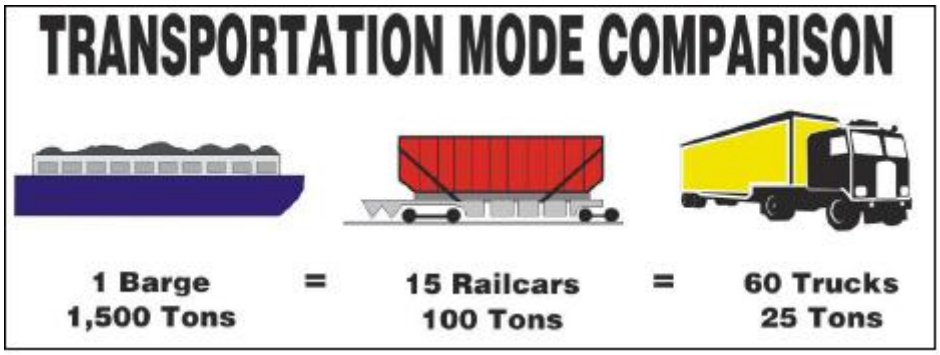


Figure B.3. Transportation mode comparison [7]

Figure B.4. America's Inland Navigation System [8]

B.2.4. Heavy-lifting Helicopter

A military heavy-lifting helicopter can carry a load of up to 60 tons. In contrast to truck and rail freight, there will be no narrow places along the helicopter route to restrict the diameter of large equipment. However, although helicopter transportation is fast and efficient, it is not economical.

B.3. Fairbanks/Breed

Fairbanks is near the Breed power station by the Wabash River, about 15 miles northwest of Sullivan. There are many overpasses from either Evansville or Jeffersonville to Sullivan by rail, but no additional overpasses were found along the rail from Sullivan to Fairbanks, as summarized in Tables B.2 and B.3.

Table B.2. Overpasses and bridges from Evansville to Sullivan

#	**Intersection with roads or rivers**	**Location**
1	West Lloyd Expy	Evansville
2	West Delaware St.	Evansville
3	IN-66	North of Evansville
4	Darmstadt Rd	North of Evansville
5	Old State Rd	North of Evansville
6	I-64	South of Haubstadt
7	US-41	South of Princeton
8	US-41 Parallel	South of Princeton
9	W Brumfield Ave	Princeton
10	A bridge	South of Patoka
11	A bridge	South of Decker
12	US-41	South Vincennes
13	US-50	North of Vincennes
14	Old US-41	South of Oaktown
15	US-41	North of Oaktown
16	US-150	North of Oaktown

Table B.3. Overpasses and bridges from Jeffersonville to Sullivan

	#	**Intersection with roads or rivers**	**Location**
From Jeffersonville to Crane	1	IN-62	North New Albany
	2	I-265	North New Albany
	3	W IN-56	Salem
	4	IN-450	Bedford
	5	IN-37	West Bedford
	6	IN-37 parallel	West Bedford
	7	IN-450	West of Bedford
	8	A Farm Bridge	East of Crane
	9	A tunnel	Crane
	10	IN-45	Crane
From Crane to Sullivan	11	A bridge	North of Elnora
	12	IN-54	Dugger
	13	N Cr-525 E	East of Sullivan

B.3.1. Routes and overpasses

1) From Evansville to Sullivan, all the railroads belong to CSX Transportation (CSXT) [9].

2) The railroad from Jeffersonville to Sullivan passes through Crane. All of the rail segments belong to the Indiana Rail Road (INRD). [9]

B.4. Minnehaha

The Minnehaha region is near Dugger, which is about 10 miles east of Sullivan. Transportation could take the same route as from Evansville to Sullivan, plus an additional rail line leading to Dugger. With one overpass and one bridge along the 15 mile rail track from Sullivan to Dugger, there are a total of 18 bridges and overpasses along the whole route, as listed in Table B.4. Another route to Minnehaha is to ship from Jeffersonville to Dugger; there are 12 overpasses, as we can see from Table B.3.

Table B.4. Overpasses and bridges from Evansville to Dugger

#	**Intersection with roads or rivers**	**Location**
1	West Lloyd Expy	Evansville
2	West Delaware St.	Evansville
3	IN-66	North of Evansville
4	Darmstadt Rd	North of Evansville
5	Old State Rd	North of Evansville
6	I-64	South of Haubstadt
7	US-41	South of Princeton
8	US-41 Parallel	South of Princeton
9	W Brumfield Ave	Princeton
10	A bridge	South of Patoka
11	A bridge	South of Decker
12	US-41	South Vincennes
13	US-50	North of Vincennes
14	Old US-41	South of Oaktown
15	US-41	North of Oaktown
16	US-150	North of Oaktown
17	N Cr-525 E	East of Sullivan
18	IN-54	Dugger

B.5. Merom

Merom is located about 10 miles west of Sullivan. The equipment could be shipped out either from Evansville or from Jeffersonville, with both routes going through Sullivan. A railroad leading from Sullivan to Merom belongs to INRD [9], and there are no overpasses along the track. The total overpasses are the same as those listed in Tables B.2 and B.3.

B.6. Francisco

Francisco is located about 25 miles north of Evansville. Norfolk Southern rails go through Francisco in an east-west direction. The two junctions with north-south rail lines are within several miles distance. Consequently, there are many choices for the transportation routes. Two of them have less than five overpasses, but they go through short line rails, which may bear less tonnage than the branch lines. More information is needed to decide the best shipping strategy.

B.6.1. Routes and overpasses

1) There are two rail tracks leading from Evansville to Francisco.

   a. Go north along CSXT Rail and then head east along Norfolk Southern (NS) Rail. [9] The overpasses are summarized in Table B.5.

Table B.5. Overpasses and bridges from Evansville to Francisco through CSXT

	#	**Intersection with roads or rivers**	**Location**
From Evansville to Baldwin Heights (Princeton) through CSXT Rail	1	West Lloyd Expy	Evansville
	2	West Delaware St.	Evansville
	3	IN-66	North of Evansville
	4	Darmstadt Rd	North of Evansville
	5	Old State Rd	North of Evansville
	6	I-64	South of Haubstadt
	7	US-41	South of Princeton
	8	US-41 Parallel	South of Princeton
From Baldwin Heights (Princeton) to Francisco through NS Rail	9	S Main Street	South Princeton

   b. Take Shortline railroads to Oakland City, and then go west along NS rail. [9] The overpasses are summarized in Table B.6.

Table B.6. Overpasses and bridges from Evansville to Francisco through shortlines

	#	**Intersection with roads or rivers**	**Location**
From Evansville to Oakland City	1	A bridge	Evansville
	2	I-164	Northeast of Evansville
	3	I-64	Northeast of Elberfeld
	4	Cr 450 S	Northeast of Somerville
From Oakland City to Francisco	5	IN-57	West of Oakland City

2) All rails from Jeffersonville to Francisco are owned by Norfolk Southern (NS). [9] The overpasses are summarized in Table B.7.

Table B.7. Overpasses and bridges from Jeffersonville to Francisco

	#	**Intersection with roads or rivers**	**Location**
From Jeffersonville to Oakland City	1	I-64	New Albany
	2	A tunnel	East of Georgetown
	3	Tunnel Hill Rd NW	East of Milltown
	4	IN-64?	East of Milltown
	5	Main St.	Northwest of Milltown
	6	A tunnel	West of Marengo
	7	A tunnel	West of English
	8	S Overhead Bridge Rd	West of Silling Ln
	9	IN-64	East of Huntingburg
From Oakland City to Francisco	10	IN-57	West of Oakland City

3) The route is from a port in Tell City to Francisco: Head northwest along short lines and NS rails to Huntingburg, and then go west along NS trail to Francisco. [9] The overpasses are summarized in Table B. 8.

Table B.8. Overpasses and bridges from Tell City to Francisco

	#	**Intersection with roads or rivers**	**Location**
From Tell City to Huntingburg	1	I-64	Northeast of Dale
	2	I-64 Parallel	Northeast of Dale
From Huntingburg to Francisco	3	IN-57	West of Oakland City

B.7. Mount Vernon

Shipment to Mount Vernon could be made by barge transportation along the Ohio River.

B.8. Rail Map

Below is a part of the Indiana rail map from the INRD website. [9] Green squares with numbers indicate the locations of corresponding sites (Figure B.5).

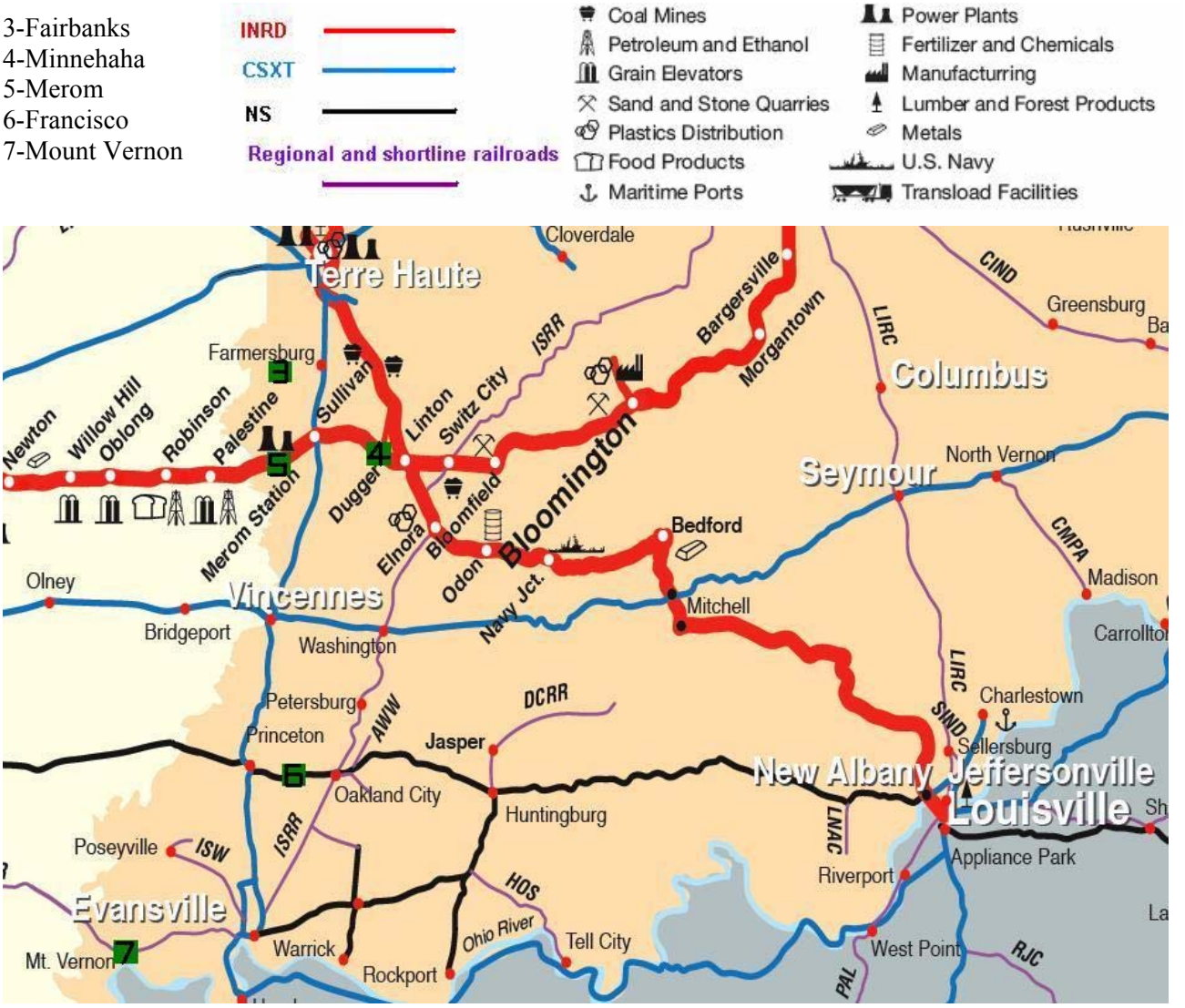


Figure B.5. Part of Indiana Rail Map [9]

B.9. Conclusion

Transportation becomes an important issue when some equipment for synfuel parks is large and can not be disassembled. Four transportation methods are examined here. Barge shipping, because of its huge capacity, is the most favorable method. One kind of heavy capacity rail car, the Schnabel car, can handle up to 800-ton loads, but it is doubtful whether all the bridges along the railroad can bear the weight. In addition, the diameter of the large equipment will be limited to the narrowest or the lowest part of bridges or overpasses, which is very likely to be around 12 to 13 feet. Trucks need to be specially designed for loads heavier than 60 tons; special permits are required to operate on Indiana highways. Clearances of overpasses also restrict the shipment. The fastest but the most expensive way is to use heavy-lifting helicopters, which can lift up to 60 tons payload. Using helicopters, there will be fewer restrictions for the dimension than the case using rails and trucks. Except for Mount Vernon, all the other synfuel sites have to use combinations of these transportation methods. Additionally, rails and roads may need to be extended to reach specific construction sites.

In the latter part of the appendix, possible shipping routes were selected for each synfuel park site and overpasses identified. The optimal shipping strategy can only be determined when the limitations on rail lines and the exact dimensions of large equipment are known. Given this information, main obstacles along the route could still be found. If the budget is sufficient, these obstacles could be removed and rebuilt after the facility has passed. Because FT reactors and gasifiers can be manufactured in various sizes, another solution is to use smaller equipment to avoid transportation problems. However, to achieve the same capacity as the large equipment, several small facilities need to be used, which will increase the capital cost and decrease the plant's efficiency. In a word, all transportation problems in this study can be solved if cost and plant efficiency are not the primary concerns.

B.10. References

[1] The Bureau of Motor Vehicles, "Indiana Driver Manual"
[2] From Federal Motor Carrier Safety Administration website
APPENDIX C TO PART 658 — TRUCKS OVER 80,000 POUNDS ON THE INTERSTATE SYSTEM AND TRUCKS OVER STAA LENGTHS ON THE NATIONAL NETWORK
[3] Indiana Department of Transportation, Multi-Modal Transportation Division, "Indiana Rail Plan", October, 2002
[4] http://southern.railfan.net/scl/scl_book.html
[5] http://southern.railfan.net/schnabel/cars/cebx800/cebx800.html
[6] http://www.midcor.com/Location_transportation/Transportation.htm
[7] Carol King, "McClellan-Kerr Arkansas River Navigation System"
[8] R. Barry Palmer, "Modernizing the Ohio River Navigation System"
[9] http://www.inrd.com/system_maps.shtml

.

Appendix C. Water Resources and Regulation in Southwest Indiana

Sika Gbègbèlègbè Dofonsou
Research Assistant and Ph.D. Candidate
Department of Agricultural Economics
Purdue University

C.1. Introduction

At each of the potential synfuel sites, water is needed for the following:

- Surface water: for cooling purposes, especially machinery cooling
- Groundwater: for steam production

The purpose of this appendix is to provide insights on the use of water resources at the potential synfuel sites. The rest of the appendix is composed of the following sections:

- Brief presentation of the potential synfuel sites
- Water use regulations at the potential synfuel sites
- Wastewater disposal at the potential synfuel sites
- For each potential synfuel site, a description of surface water availability
- For each potential synfuel site, a description of groundwater availability
- Costs of building and maintaining wells
- Conclusion

C.2. Potential Synfuel Sites

Figure IV.1 showed the location of the potential synfuel sites targeted by the study. As was shown in this figure, the potential synfuel sites are all located in southwestern Indiana at the following locations (from north to south): Breed/Fairbanks, Minnehaha, Merom, Crane, Francisco, and Mount Vernon.

C.3. Surface Water Use Regulations in Indiana: Water Withdrawal from Lakes and Rivers

Any entity withdrawing at least 100,000 gallons per day from any river or lake in Indiana must register its activities with the Department of Natural Resources (DNR). If it withdraws less than 100,000 gallons per day, no requirements apply (Harding, 2003). The registration's main purpose is to allow DNR to monitor the amount of water being withdrawn per year. In case of drought, the Indiana governor can set emergency restrictions on water withdrawal from rivers and lakes.

Additional requirements apply specifically to lakes considered public fresh water lakes or lakes with legal water levels established by DNR (DNR, 2005; Public Freshwater Lake). Surface water restrictions also apply to all lakes in Indiana. These restrictions imply that if an entity lowers a lake level so as to cause damages to an owner of the lake, this **OWNER** can sue, and the entity will be held liable for the damages (DNR, 2005; Emergency Regulation of Surface Water Rights).

Additional regulations applying specifically to rivers include riparian rights, restrictions for navigable waters, and restrictions on building structures close to the lake. Riparian rights imply that downstream users

can sue upstream users for damages they endure due to upstream water use (Natural Resource Conservation, 1999). Similarly, a permit is needed to withdraw water from rivers categorized as navigable waters, although this regulation is not yet fully enforced (Mark Basch, personal communication, April 2007). A permit delivered by DNR is also needed to build structures close to rivers (Indiana Flood Control Act; 1945).

C.3.1. Surface Water Regulations: Crane Site

Crane site has three main sources of surface water: Lake Greenwood and the east and west forks of the White River. Lake Greenwood is not a public fresh water lake, nor does it have any legal water levels established by DNR. Therefore, registration of water withdrawal activities with DNR is the only requirement for withdrawing water from Lake Greenwood, assuming that synfuel production requires that more than 100,000 gallons of water per day will be withdrawn from Lake Greenwood. Additional regulations applying to Lake Greenwood include surface water rights and emergency restrictions by the Indiana governor in case of drought.

The East Fork and West Fork of the White River are navigable waters. Therefore, permits should be required for water withdrawal from these rivers on top of satisfying the requirement to register water withdrawal activities equal to or above 100,000 gallons/day with DNR. However, the regulation surrounding the permits is not yet enforced. Additional regulations applying to the White River are riparian rights. Moreover, permits are also needed to build structure(s) close to the river (Indiana Flood Control Act; 1945).

C.3.2. Surface Water Regulations: Francisco Site

Patoka River is the main source of surface water for the Francisco site. The river is navigable starting at its junction with the Wabash River for about 147 river miles. Therefore, water withdrawal for synfuel activity will likely involve the navigable portion of the Patoka River. As a result, permits might be needed for water withdrawal in this water body for synfuel activity.

Again, if water withdrawal activities will involve more than 100,000 gallons per day, registration of these withdrawal activities with DNR will also be required.

C.3.3. Surface Water Regulations: Minnehaha (Fairbanks) and Merom

The Minnehaha and Merom potential synfuel sites are all located in Sullivan County. Main sources of surface water for these two sites include the Wabash River, Lake Sullivan and Lake Glendora. For all these sources, water withdrawal activities will need to be registered with DNR if they involve more than 100,000 gallons per day. The Wabash River is navigable on most of its area, and water withdrawal for synfuel sites in Minnehaha and Merom will occur on the navigable portion of the Wabash River. Therefore, permits for water withdrawal in this river might be needed. As for Lake Sullivan, it is under the jurisdiction of the DNR due to a dam built close to it; this dam is classified as high hazard, because if it fails, it could cause significant damage to people, flora and fauna. The lake is also owned by the Southern County Park and Recreation District in Sullivan County. Therefore, various regulations might govern water withdrawal in this lake. There currently exists no information on Lake Glendora.

C.3.4. Surface Water Regulations: Mount Vernon

The Wabash and Ohio Rivers constitute the major sources of surface water for the potential synfuel site in Mount Vernon. Again, the registration of water withdrawal activities involving more than 100,000 gallons per day is the major requirement to satisfy. The Wabash River is composed of navigable waters and so is the Ohio River. Therefore, permits might be needed for water withdrawal activities.

C.4. Surface Water Use Regulations in Indiana: Wastewater Disposal in Lakes and Rivers

There is no limit on the amount of wastewater that can be discharged into surface water bodies in Indiana. However, entities have to pay fees to discharge wastewater, and these fees must be paid to the Indiana Department of Environmental Management (IDEM) office of water quality. The fee system involves an annual operation fee ranging from $240 for discharges of less than 50,000 gallons per day to $3,600 for discharges of more than 1 million gallons per day, to $28,300 for discharges of more than 50 million gallons per day. Fees for discharges of more than 90-percent non-contact cooling water are discounted by 20-percent. (Indiana department of Environmental Management, 2007)

The National Pollutant Discharge Elimination System (NDPES) general permit as defined under the NDPES general permit rule is needed by coal mining companies to discharge wastewater in any surface water body located in Indiana. This permit can be obtained from the IDEM office of water quality (Indiana department of Environmental Management, 2007, available at http://www.in.gov/idem/permits/guide/water/industrialdischarge.html). Article 15 on the NDPES general permit rule program provides specific rules that entities involved in coal mining, processing and reclamation activities must follow to discharge wastewater into surface water bodies in Indiana (NPDES General Permit Rule Program, 1992). Specific regulations on the quality of the wastewater to be discharged into the surface water bodies of Indiana are found in Rule 7 of Article 15 on the NDPES general permit rule program (NPDES General Permit Rule Program, 1992). Regulations on the flow rate at which wastewater is being discharged into the surface water bodies, the Total suspended Solids (TSS) found in wastewater, the acidity of wastewater (Ph), and the mineral content of wastewater are defined for post-mining areas and various types of active mining areas. Additional restrictions imply that Ph adjustment of the wastewater cannot be done with anhydrous ammonia. Moreover, the discharge should not produce too much foam in receiving waters, contain any floatable or settleable solids, contain substance(s) in amounts sufficient to create visible film on receiving waters, or contain substance(s) in amounts so as to create nuisance. Discharges consisting of precipitation runoff contaminated by coal products must also be subject to best management practices, since they usually are not regulated by the NPDES permit.

C.5. Surface Water Availability in Potential Synfuel Sites

C.5.1. Surface Water Availability – Crane site

The report entitled "A Feasibility Study for the Construction of a Fischer-Tropsch Liquids Fuels Production Plant with Power Co-Production at NSA-Crane" provides detailed information on surface water availability at the Crane site. The report states that major sources of surface water at the site are found in Lake Greenwood, East Fork of the White River, West fork of the White River, and West Boggs Lake.

C.5.2. Surface Water Availability – Francisco Site

The gauging station closest to Francisco is located upstream of the city and is found in the Patoka River near Princeton. The second closest gauging station is located downstream of Francisco and is found in the Patoka River at Winslow. Water data differ significantly between the upstream and downstream stream gauging station. Therefore, distance weights were used to estimate the approximate stream flow right at Francisco. The distance between Francisco and the downstream gauging station is twice as high as the one between Francisco and the upstream gauging station. Therefore, coefficient weights of 2/3 and 1/3 were applied to the water data for the downstream and upstream gauging stations, respectively.

Figure C.1 illustrates the evolution of mean daily water flow in the Patoka River near the potential synfuel site in Francisco. The information in Figure C.1 can be used to determine whether there is enough surface water for synfuel production at the Francisco site.

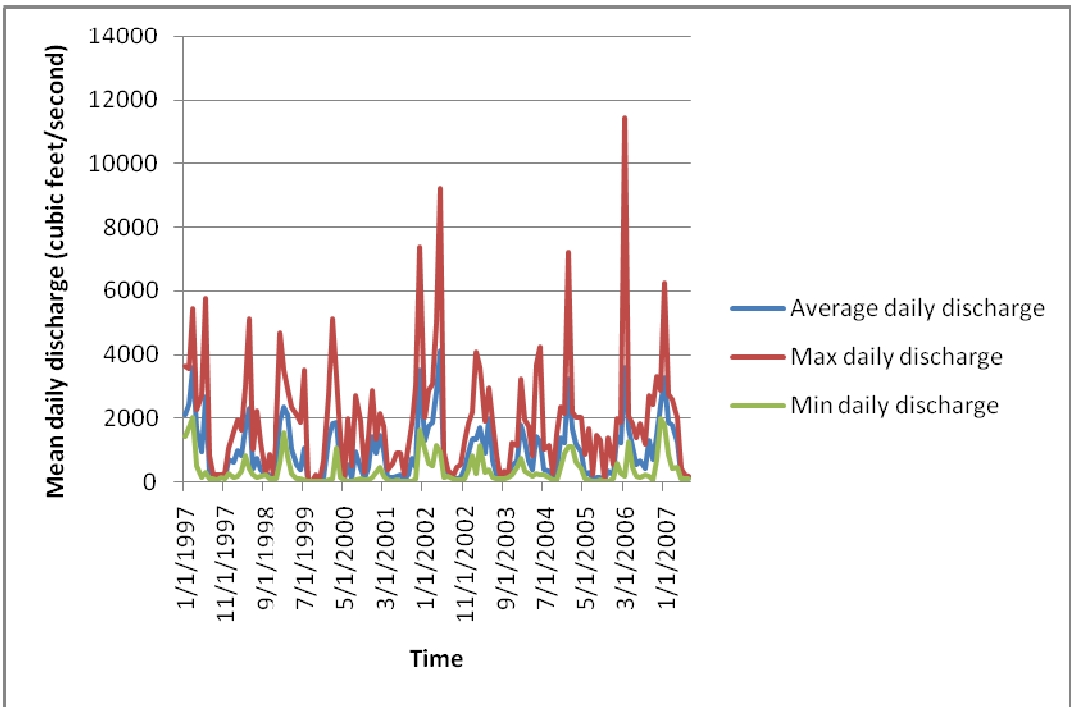


Figure C.1. Illustration of mean daily flow near Francisco site (Source: US Geological Survey, 2007; USGS 03376500 and USGS 03376300)

C.5.3. Surface Water Availability – Minnehaha (Fairbanks) and Merom

Figure C.2 shows the location of Merom in Indiana. Minnehaha is not shown on the map, but it is located very close to Fairbanks which is also on the map. Based on Figure C.2, Fairbanks and therefore the Minnehaha site is quite far from Merom and is about halfway between Terre Haute and Riverton. There is no stream gauging station on the Wabash River right in front of Fairbanks. Rather, stream gauging stations are found in Riverton and Terre Haute. Since Riverton is very close to Merom, water data from the stream gauging station in Riverton are used to estimate surface water availability for the Merom site. For the Minnehaha site, distance weights are applied to water data from the stream gauging stations in Riverton and Terre-Haute. The weight applied to water data from the stream gauging station in Riverton is 4/9 and the coefficient applied on the data from the station in Terre-Haute is 5/9.

Figure C.3 shows the evolution of the mean daily flow of the Wabash River near the Minnehaha site, while Figure C.4 illustrates the evolution of the water flow in the Wabash River near the Minnehaha site.

Figure C.2. Map of Merom and Fairbanks (Source: Microsoft Corporation, 2007)

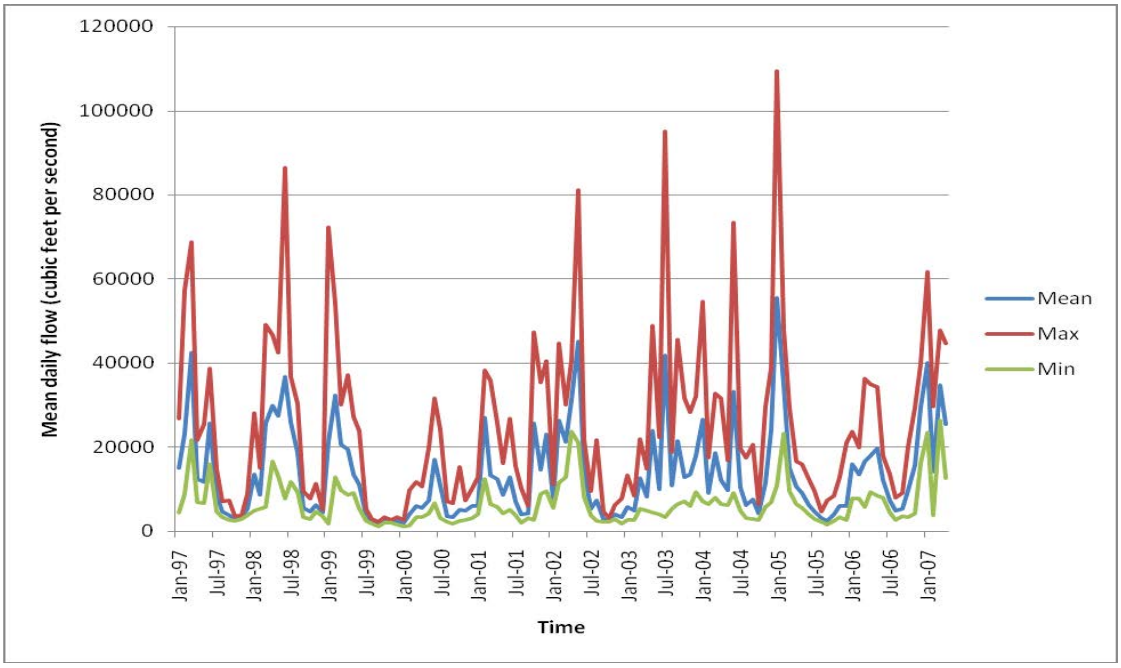


Figure C.3. Evolution of mean daily flow of Wabash River near Minnehaha site (Source: US Geological Survey, 2007; USGS 03341500 and USGS 03342000)

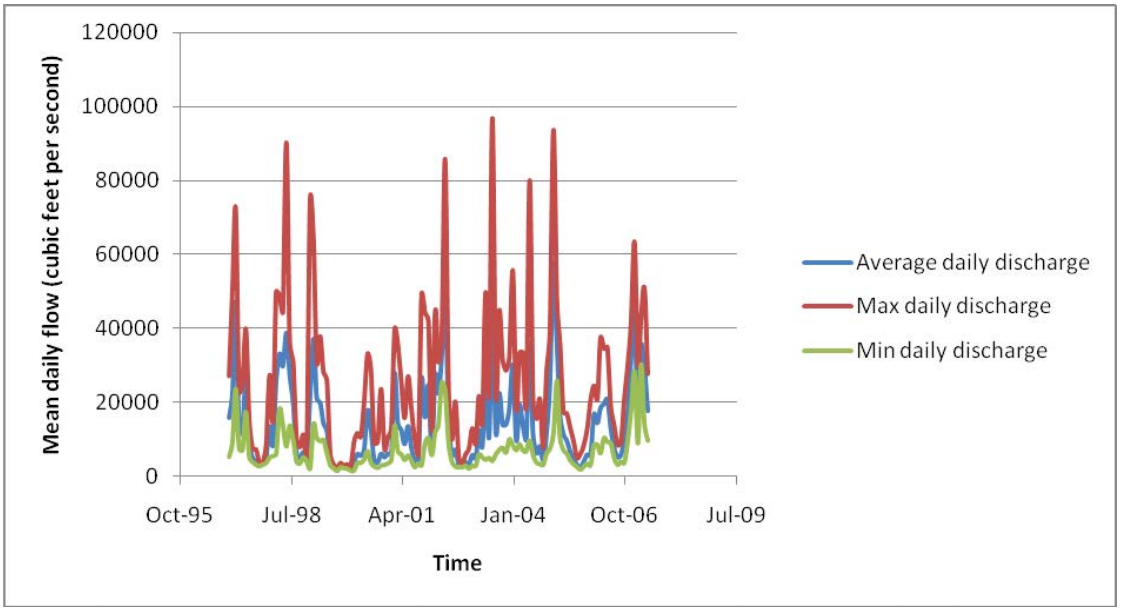


Figure C.4. Evolution of mean daily flow of Wabash River near Merom site (Source: US Geological Survey, 2007; USGS 03342000)

Based on 1964 data, the normal storage volume in Lake Sullivan is 4,936 acre feet of water. The maximum discharge in this lake is 18,845 cubic feet per second, and the surface area of the lake is 461 water acres. The rainfall area contributing flow to the lake is 11.3 square miles. Lake Sullivan is close to a dam and therefore falls under the jurisdiction of DNR. This dam is classified as a "high hazard" dam, because it can cause significant damage to people, fauna and flora if it fails. The lake is owned by the Southern County Park and Recreation District in Sullivan County. Therefore, it is very likely that water withdrawal from this lake would be subject to various regulations (Ron Carter, May 2007).

There is no water data available for Lake Glendora.

C.5.4. Surface Water Availability - Mount Vernon

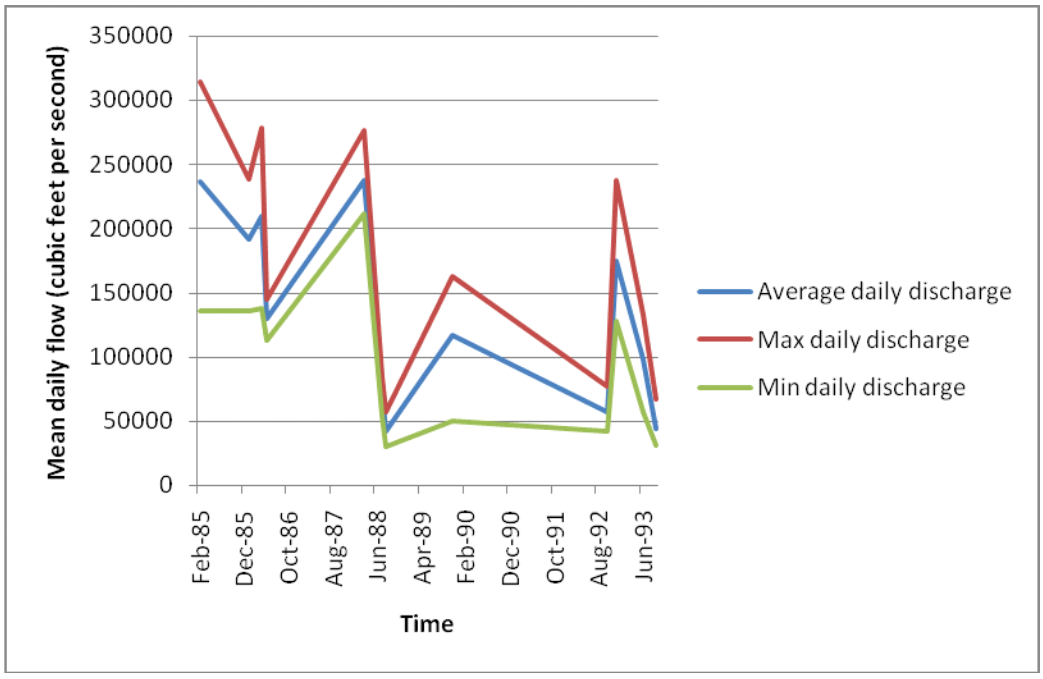


Figure C.5. Evolution of mean daily flow of Wabash River near Mount Vernon site (Source: US Geological Survey, 2007; USGS 3322420)

C.6. Groundwater Availability in Potential Synfuel Sites

Figure C.6 illustrates groundwater availability for all Indiana. This section discusses whether there is enough groundwater available in potential synfuel sites for steam production.

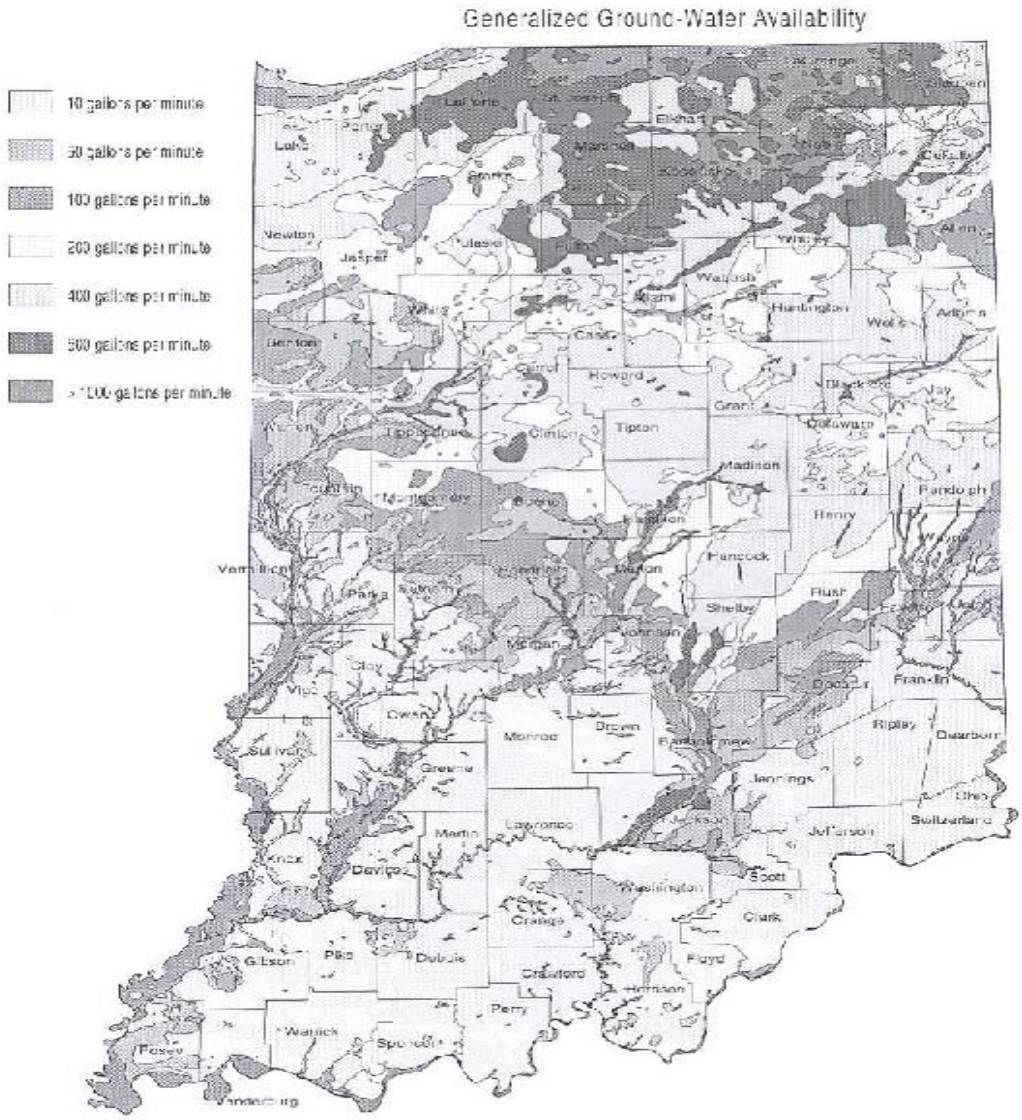


Figure C.6. Illustration of groundwater availability in Indiana (Source: DNR Division of Water, 2005; Groundwater Availability)

C.7. Building and Maintenance Costs for Wells

Figure C.7 illustrates the components of a typical water well (DNR, division of water, 2007).

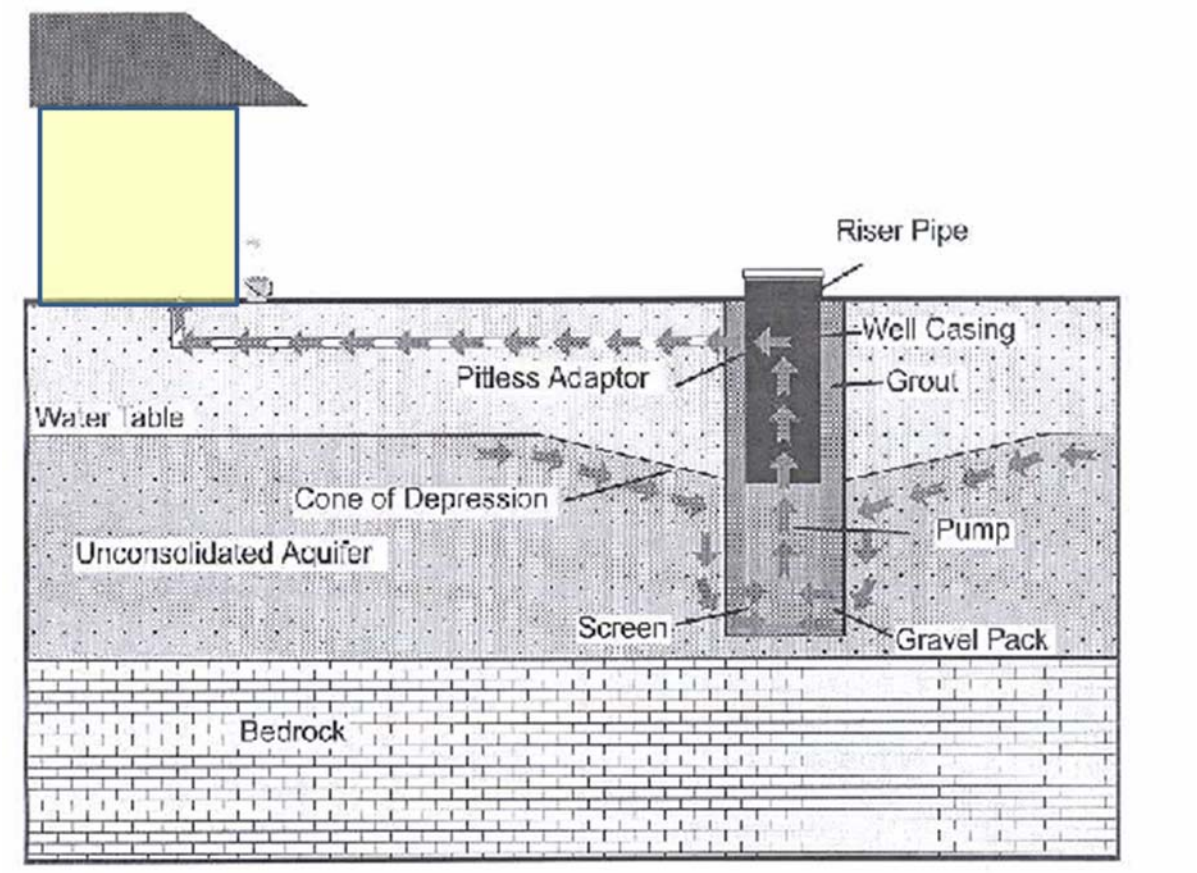


Figure C.7. Illustration of typical water well (Source: DNR, Division of Water, 2004; Water Well Animation)

C.7.1. Cost of Well Construction in Indiana

The cost of building one well is around $US 30,000 to $US 50,000. This cost covers the well and pump only. Piles for piping and the power of the pump are not covered by this estimate (Tim Hacker, 2007).

C.7.2. Laws to Follow in Relation to Water Well Construction in Indiana

Minimum law requirements for well construction:

- There are minimum standards to follow in Indiana for water well construction. These minimum standards are presented in the Water Well Drilling Contractors Act and the Water Well Drillers Rules. However, most of these standards aim at preventing groundwater contamination (DNR, Division of Water, 2005; Groundwater / Wells – Frequently asked questions).

Legal requirements to fill after a well is constructed:

- Water well drillers must submit accurate records of wells to the Division of Water in DNR. Moreover, a landowner can ask for a copy of the well records as a pre-condition to drilling the well (DNR, Division of Water, 2005; Groundwater / Wells – Frequently asked questions).

C.8. References

DNR, Division of Water, 2004; Water Well Animation; http://www.in.gov/dnr/water/DOW_kids/education/waterwell.html

DNR, Division of Water, 2005; Groundwater / Wells – Frequently asked questions; http://www.in.gov/dnr/water/DOW_kids/education/waterwell.html

DNR, Division of Water, 2005; Groundwater Availability; http://www.in.gov/dnr/water/ground_water/ground_water_avail/index.html

DNR, Division of Water; 2005; Emergency Regulation Of Surface Water Rights - Indiana Code 14-25-5; http://www.in.gov/dnr/water/surface_water/SWemergencyrights.html

DNR, Division of Water; 2005; Public Freshwater Lake - Legal and Average Normal Water Levels; http://www.in.gov/dnr/water/surface_water/lake_levels/index.html

Harding R. J., 2003; Water Withdrawals Programs in Indiana and Minnesota and their Implications to Michigan; 6 p.; http://www.michamber.com/nr/studies/WaterWithdrawlStudy.pdf

Indiana department of Environmental Management, 2007; Permitting Industrial Wastewater Discharges to the Waters of the State; http://www.in.gov/idem/permits/guide/water/industrialdischarge.html

Indiana Flood Control Act, Article 28, Indiana Code 14-28 (1945); http://www.in.gov/legislative/ic/code/title14/ar28/ch1.html

Microsoft Corporation, 2007; Map of Sullivan, Sullivan, Indiana, United States; http://encarta.msn.com/map_701530912/Sullivan_(city_Indiana).html

Natural Resource Conservation, 1999; A Synthesis of Major Topics in the Lake Michigan Coastal Area; http://www.state.in.us/nrc_dnr/lakemichigan/watquan/watquanb.html

NPDES General Permit Rule Program, Article 15, Indiana Administrative Code 15 (1992); http://www.ai.org/legislative/iac/T03270/A00150.PDF

Tim Hacker, 2007; personal communication on costs of creating and maintaining wells

US Geological survey, 2007; USGS 03341500 WABASH RIVER AT TERRE HAUTE, IN and USGS 03342000 WABASH RIVER AT RIVERTON, IN; http://water.usgs.gov/waterwatch/?m=real&r=in

US Geological survey, 2007; USGS 03342000 WABASH RIVER AT RIVERTON, IN; http://water.usgs.gov/waterwatch/?m=real&r=in

US Geological survey, 2007; USGS 03376500 PATOKA RIVER NEAR PRINCETON, IN and USGS 03376300 PATOKA RIVER AT WINSLOW, IN; http://water.usgs.gov/waterwatch/?m=real&r=in

US Geological survey, 2007; USGS 3322420 OHIO RIVER AT UNIONTOWN DAM; http://water.usgs.gov/waterwatch/?m=real&r=in

Appendix D. FT Processes – A Brief Description

Akiner Tuzuner
Research Assistant and Ph.D. Candidate
School of Industrial Engineering
Purdue University

The Fischer-Tropsch (F-T) process is a synthesis reaction of carbon monoxide (CO) and hydrogen (H_2) gases in order to produce a mix of hydrocarbons (olefins, paraffins, and oxygenated products), which form the ingredients of the various fossil fuels (such as gasoline, diesel, kerosene, etc.) as well other non-fuel commodities such as lubricants or waxes. The input gas and the various liquid products of the F-T process are often called, respectively, "syngas" and "synfuel" (also, the unrefined raw output from the process is sometimes referred to as a "syncrude"). F-T products are produced in four steps: (1) syngas generation, (2) syngas cleaning, (3) F-T synthesis and (4) product separation and upgrading. Our overview here will be concentrated on the last two steps, F-T synthesis and product separation and upgrading. Our overview is based on information compiled from several publicly available sources; a list of the major references used is provided at the end of the section.

D.1. F-T Synthesis (major sources: [Steynberg&Dry2004], [ZE_2007], [Radke_etal2006]; other sources indicated within):

D.1.1. Chemical Reactions Background

F-T synthesis is basically a chemical synthesis of hydrocarbon chain molecules from carbon monoxide and hydrogen, aided by a catalyst and under a high-pressure and high-temperature environment. The principal reaction is between CO and H_2 molecules, where the carbon atom separates from the oxygen and attaches to the hydrogen molecule forming free CH_2 groups. Hydrocarbons of different length and form are then formed in a chain-building fashion where the free CH_2 attaches to other hydrogen molecules or to an already formed hydrocarbon chain. Carbon dioxide (CO_2), water vapor (H_2O) and other oxygenated gases are by-products of the process. The form and mix of the precise reactions taking place in the reactor and how they are induced/catalyzed are still matters of discussion. Research and commercial experience has shown that the mix of the hydrocarbon products (and of the by-products) is strongly influenced by the reactor temperature, feed gas composition (H_2/CO), pressure and catalyst type and form. This knowledge is consequently utilized in designing gasifiers and reactors that yield the desired syncrude composition.

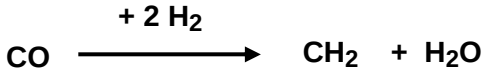
The scope of the reactions taking place in an F-T reactor can generally be described as follows:

$$nCO + \left(n + \frac{m}{2}\right) H_2 \rightarrow C_n H_m + n H_2 O$$

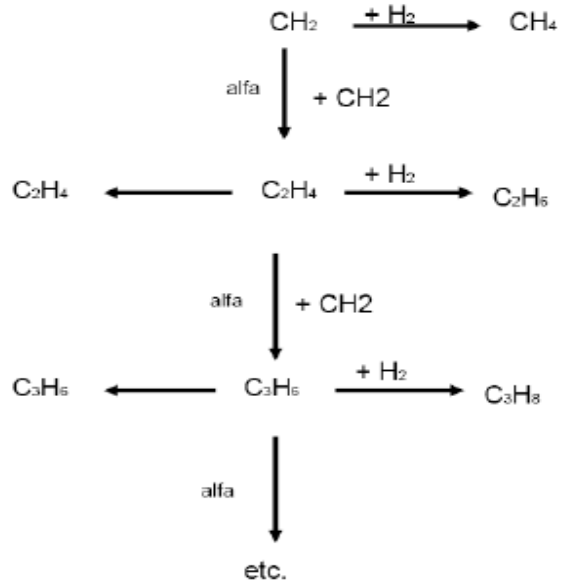
$$CO + 2H_2 \rightarrow -CH_2- + H_2O \qquad \Delta H^{\circ}_{FT} = -165\,kJ/mol$$

The main reaction in the F-T synthesis is essentially a hydrocarbon chain-building process. During the reaction, an already formed hydrocarbon chain either gains length by absorbing another free-floating CH_2, or terminates growing and leaves the catalysis environment as either a paraffin (C_nH_{2n}) or an olefin (C_2H_{2n+2}). The overall process can be described as a "chain initiation" reaction and a "chain growth and termination" reaction. Graphical descriptions of these reactions are presented below:

Chain Initiation:



Chain Growth and Termination:



Other and more controversial reactions taking place are argued to be the following:

Reaction:	Reaction enthalpy: $\Delta H_{300\,K}$ [kJ/mol]
$CO + 2H_2 \rightarrow -CH_2- + H_2O$	- 165.0
$2\,CO + H_2 \rightarrow -CH_2- + CO_2$	-204.7
$CO + H_2O \rightarrow H_2 + CO_2$	-39.8
$3CO + H_2 \rightarrow -CH_2- + 2CO_2$	-244.5
$CO_2 + 3\,H_2 \rightarrow -CH_2- + 2H_2O$	-125.2

The F-T reactions above are all highly exothermic, so substantial heat is generated by the F-T reactor. The total heat of reaction amounts to 25% of the heat of combustion of the synthesis gas, yielding 75% as the theoretical maximum efficiency of the FT process.

A theoretical model of the F-T product distribution was developed by Anderson, Schultz and Flory (1951). The ASF model assumes a stepwise chain growth (polymerization) by addition of the CH2 monomer to an already formed hydrocarbon. The chain growth probability (α) and the chain termination probability (1- α) are assumed to be the same for all intermediate-length hydrocarbons. The final product distribution, therefore, depends on the chain growth probability α (theoretically between 0 and 1), which in practice should depend on the reaction conditions (temperature, pressure, etc.) and the catalyst type and form. The weight fractions of different length hydrocarbons as predicted by ASF distribution is plotted below versus varying values of the chain-growth probability α.

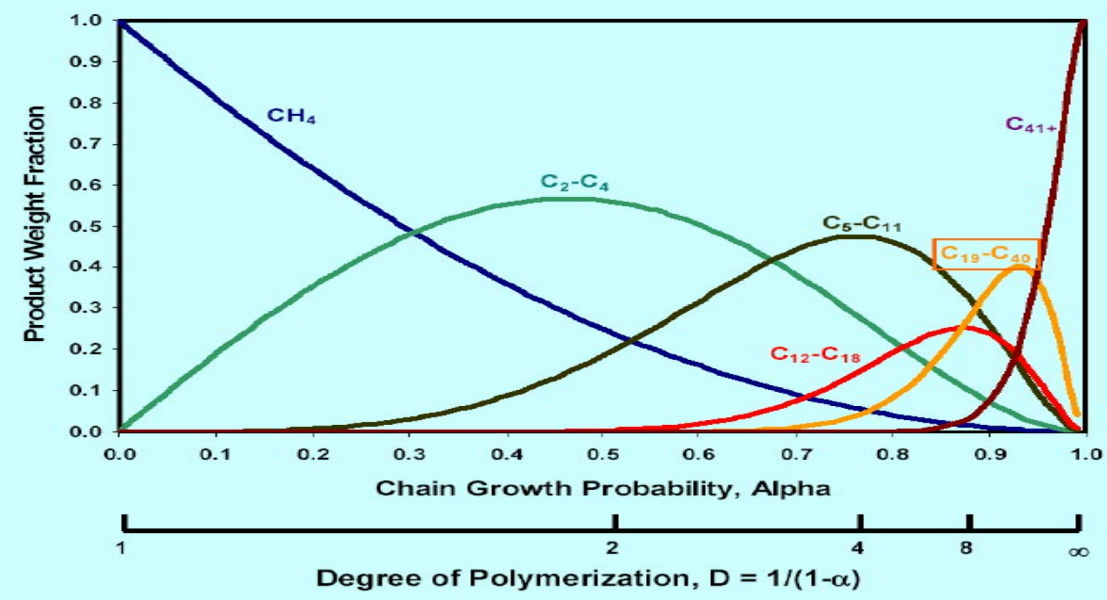


Figure D.1. Distribution of F-T hydrocarbons versus probability of chain growth

Table D.1. Major categories of petroleum products and their carbon number ranges

Petroleum Fractions			
Gases	C_1	to	C_3
Gasoline	C_4	to	C_{10}
Kerosene	C_{11}	to	C_{13}
Diesel fuel	C_{14}	to	C_{18}
Heavy gas oil	C_{19}	to	C_{25}
Lubricating oil	C_{26}	to	C_{40}
Waxes		over	C_{40}

In some laboratory tests it has been confirmed that the ASF distribution (with some α value) successfully approximates the real F-T product distribution, although there is a bit of controversy and confusion about the combined effect of the underlying factors that determine α. Two examples of product distributions are given in the plots below, the first with an iron catalyst, and the second with a cobalt catalyst. The experiments have been carried out at the Technical University of Vienna. The reactions take place in a bench scale F-T reactor (~250 ml reactor volume). The x-axis indicates the chain length, while the y-axis shows the percentage on weight basis.

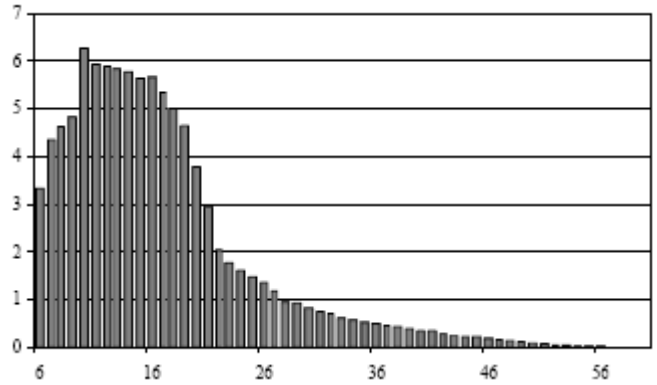


Figure D.2. F-T product distribution with iron catalyst

The reactions with iron catalyst are conducted with 30 bars and 280°C. The iron catalyst provides high selectivity in the important intervals between C_5 –C_{22}, which means a high yield of naphtha (for gasoline and light oils) and middle distillates (diesel and kerosene).

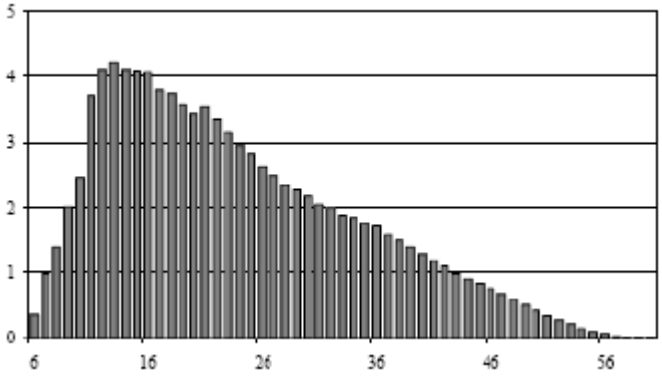


Figure D.3. F-T product distribution with cobalt catalyst

The cobalt catalyst provides a higher growth probability, as heavier products are produced. The reaction conditions were 30 bar and 240°C. Naphtha yield is lower, while middle distillate and wax yield is higher. The heavier waxes can be hydro-cracked by conventional refining methods into desired lighter products.

Controlling the reactor's temperature and pressure is imperative for maintaining stable reaction conditions and the desired product composition. As a rule of thumb, higher temperatures favor lighter hydrocarbons that compose naphtha, light oils, and gases, while lower temperatures favor heavier hydrocarbons that compose diesel, kerosene, heavy oils and waxes. Since water is used for temperature control, the by-product steam can also be utilized for power generation and other purposes. The condition of the metal catalyst is also important for a stable synthesis process. Impurities in the syngas as well as the unavoidable results of the synthesis reactions cause the catalyst to lose its activity over time. Impurities in the syngas, such as sulfur and nitrogen compounds (and, to a lesser extent, carbon dioxide), poison the catalyst, and, hence, the syngas requires deep cleaning before entering the F-T reactor. Syngas cleaning also yields a purer mix of hydrocarbons from the F-T reactor, which allows the production of cleaner liquid fuels (e.g., virtually sulfur-free diesel). The F-T catalyst also loses activity due to a decreased active area resulting from oxidation, carbon deposition and sintering. This requires periodical replenishment of the catalyst.

D.1.2. F-T Catalysts and Process Temperatures

The success of the F-T synthesis depends on a metal catalyst to facilitate the production of free CH_2 (or, −CH2−). Four types of catalysts have been reported to work most effectively: iron, cobalt, nickel, and ruthenium. Nickel and ruthenium are undesirable since the first one produces too much methane and has poor high-pressure performance, and the second one is just too expensive. Iron and cobalt have become two commercially viable F-T catalysts due to their effectiveness and affordability. Iron is cheap but cobalt has higher activity (especially under lower temperatures necessary for heavier hydro-carbons) and a longer life. Cobalt, however, on a purely weight basis is 1,000 times more expensive than iron. The F-T synthesis temperature can theoretically be chosen from a relatively wide range, depending on what mix of hydrocarbons is desired and what type of catalyst will be used (which certainly affects the design of the F-T reactor). In commercial and large scale demonstration applications, however, we see two basic types of process: the Low-Temperature process and the High-Temperature process (LTFT and HTFT), with temperatures ranging between 200-240°C for LTFT and 300-350°C for HTFT. HTFT applications use an iron catalyst, and the LTFT applications use either an iron or a cobalt catalyst. The HTFT process favors the lighter (i.e., lower carbon number range) of the hydrocarbon spectrum and is the process of choice for the production of lighter hydrocarbon fuels such as synthetic natural gas (SNG), liquefied petroleum gas (LPG), light and heavy oils that compose gasoline, and, to a lesser extent, diesel. The LTFT process favors the heavier (i.e., higher carbon number range) hydrocarbons, and thus it is more suitable for the production of heavier fuels and non-fuel products such as diesel, kerosene, softwax and hardwax. With a conventional refining process following product separation, the LTFT hydrocarbons can be "hydro-cracked" and blended into the desired lighter products such as gasoline.

D.1.3. Basic Reactor Designs

Different FT reactor designs have been used in large-scale commercial production, while several others have been lab-tested. In these reactors, heat removal and temperature control are the central design features in order to provide a stable reaction environment and the desired hydro-carbon selectivity and catalyst life. Over the 70 years of F-T synthesis history, four major reactor designs have been used. What differentiates these designs is essentially the medium for the catalyst-syngas interaction. The four designs are listed below in historical order of development.

- Multi-Tubular Fixed Bed (ARGE)
- Circulating Fluidized Bed (Synthol)
- Fixed Fluidized Bed (SASOL Advanced Synthol)
- Fixed Slurry Bed

These reactor designs are sketched in Figure D.4 (source: [ZE2007]).

a. Multi-tubular Fixed Bed. In 1937 Pichler found out that an iron catalyst could produce desirable results under "medium temperatures." Development started by six German firms in 1943 after the supply of cobalt from Belgium-controlled Congo was cut off. Iron catalysts were never, however, used in Germany. Two German firms developed the ARGE multi-tubular fixed bed reactor using a silica-supported iron catalyst. These were installed in the 1950's at SASOL and became the early commercial FT reactors. The fixed bed reactor consists of thousands of small tubes with the catalyst as surface-active agent in the tubes. Water surrounds the tubes and regulates the temperature by settling the pressure of evaporation. A schematic picture and photograph of an ARGE reactor is given in Figure D.5 below.

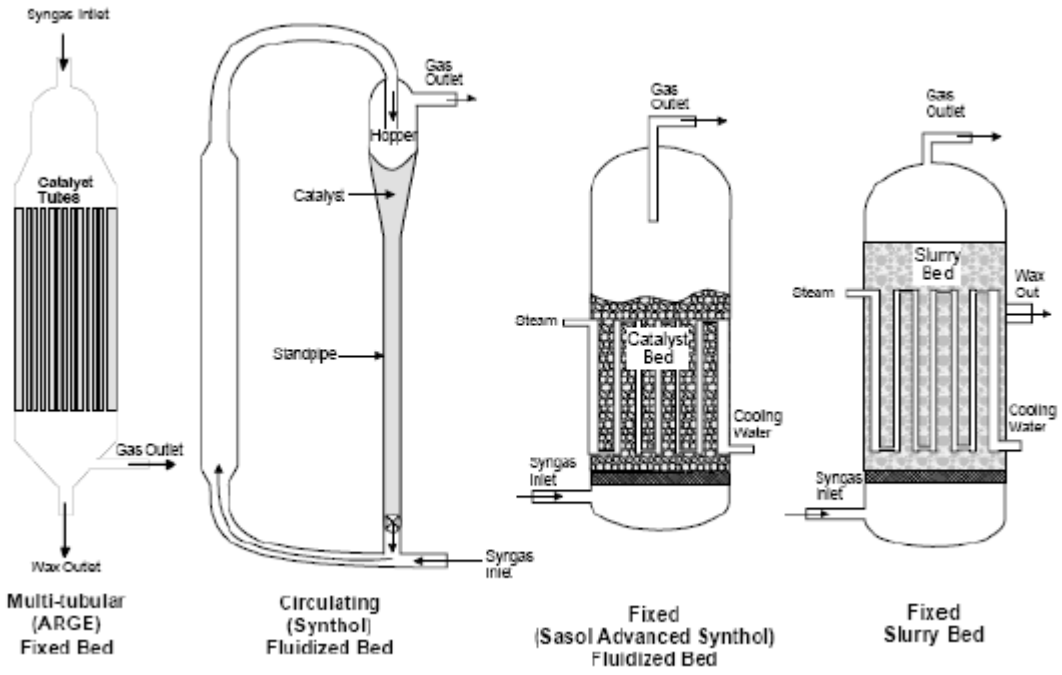


Figure D.4. Commercial Fischer-Tropsch synthesis reactors

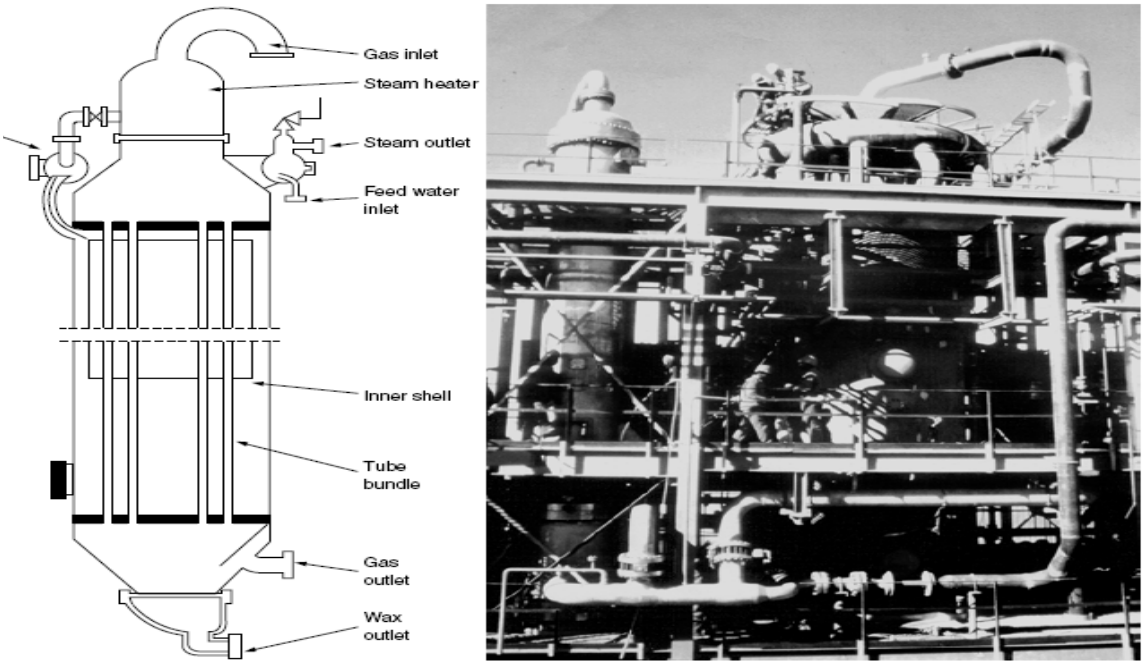


Figure RE1-4.3 Packed-bed reactor. (Schematic and photograph courtesy of Sasol/Sastech PT Limited.)

Figure D.5. Sasol Arge Reactor (also called Tubular Fixed Bed Reactor, TFBR)

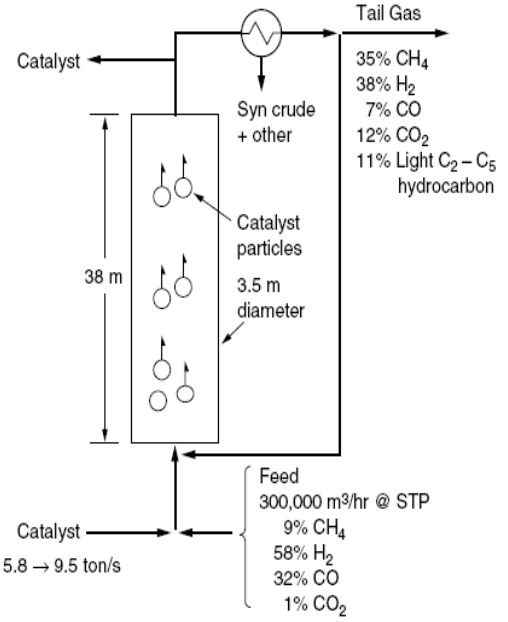


Figure RE1-4.1 Schematic of Sasol Fischer–Tropsch process.

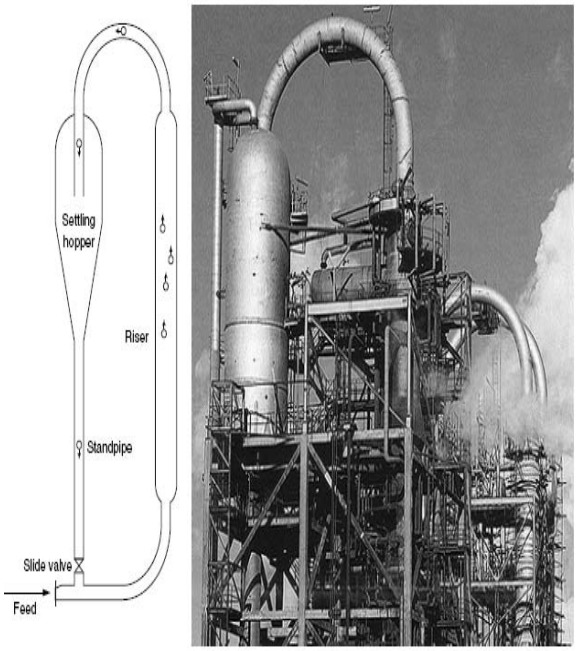


Figure RE1-4.2 The reactor is 3.5 m in diameter and 38 m tall. (Schematic and photo courtesy of Sasol/Sastech PT Limited.)

Figure D.6. Sasol Synthol Reactor (also called the Circulating Fluidized Bed Reactor, CFBR) with dimensions 3.5 m diameter x 38 m height

b. Circulating Fluidized Bed. From 1928 onwards the U.S. Bureau of Mines laboratories carried out FT research using various types of iron catalysts (including those prepared by fusing iron oxide together with various promoters). Hydrocarbon Research investigated the use of fused catalysts in high temperature fluidized bed reactors (the Hydrocol process). A commercial plant operated in Brownsville, Texas for a number of years in the 1950s. Kellogg developed a circulating fluidized bed reactor (Synthol) also using a fused iron catalyst. Two of these reactors were installed at the Sasol plant (Sasolburg) in the mid 1950s. A schematic picture and photograph of a Synthol reactor are given in Figure D.6 above.

c. Fixed Fluidized Bed. Since 1989 SASOL has been using and improving upon a commercial scale fluidized bed unit. By the end of the decade, all the production at Secunda site will be only from these reactors, called Sasol Advanced Synthol (SAS) reactors. These SAS reactors have significant advantages over the traditional circulating fluidized bed reactors. The capital cost per ton of product is only 40% of that of the old units, and the operating costs have been drastically reduced. The catalyst consumption is 60% less than before and maintenance 85% less. These high-temperature reactors produce predominantly gasoline and light olefins. A range of oxygenated chemicals (such as alcohols and ketones) are also produced and are either recovered for chemical value or are processed to become fuel components. Of the olefins, ethylene, propylene, pentene-1 and hexene-1 are recovered at polymer grade purity and sold into the polymer industry. Surplus olefins are converted into diesel to maintain a gasoline-diesel ratio to match market demand.

d. Fixed Slurry (Bubble Column) Bed. The slurry reactor consists of fluid and solid elements, where the catalyst has no particular position, but flows around as small pieces of catalyst together with the reaction components. The Sasol Slurry Phase Distillate (SSPD) reactor has been developed and has been in commercial operation since 1993 at more than 98% availability. The SSPD reactor operates under similar conditions as the ARGE reactors and produces a very similar product spectrum but uses a slurry phase

system rather than a tubular fixed bed configuration. The unit in operation in Sasolburg, South Africa has a diameter of 5 meters and is 22 meters high. It produces 2,500 BPD of products. Each of the two reactors in Ras Laffan, Qatar has a capacity of 17,000 BPD. The SSPD technology is the favored technology for the commercial conversion of natural gas to synfuels. The SSDP product stream is less complex than that of the SAS technology and more suitable to be worked up to predominantly high quality diesel.

e. Multi-Tubular and Slurry Bed. These reactors operate at lower temperatures (~250ºC) and are more suitable for the production of middle distillates (that can be refined into diesel and kerosene with reforming and mild hydro-cracking) and waxes (that can be refined into the lighter fuels with strong hydro-cracking). The fluidized bed reactors operate at higher temperatures (~350ºC) and are more suitable for the production of gasoline and lighter olefins (LPG and SNG). Table D.2 below provides some information about the various SASOL reactors.

Table D.2. SASOL Fischer-Tropsch reactors

Process Type	**Reactor Type**	**Dimensions**	**Weight**	**Year On-Stream**	**Capacity, BPD**	**Real/ Claimed/ Design**	**References**
HTFT	SAS	5m diam x 22m height	N.A.	1989	3500	real	[Geertsema], [Ganter2005]
HTFT	SAS	8 m diam x 38 m height	N.A.	1995	11000	real	[Geertsema], [Ganter2005], [Zhang_etal2000]
HTFT	SAS	10.7 m diam x 38 m height	N.A.	1999	20000	real	[Geertsema], [Ganter2005], [Zhang_etal2000]
HTFT	CBF (Synthol)	N.A.	N.A.	1955	2000	real	[Ganter2005]
HTFT	CBF (Synthol)	N.A.	N.A.	1982	6500	real	[Ganter2005], [Zhang_etal2000]
HTFT	CBF (Synthol)	N.A.	N.A.	1991	7500	real	[Ganter2005], [Zhang_etal2000]
LTFT	Arge	N.A.	N.A.	1955	500	real	[Ganter2005], [Zhang_etal2000]
LTFT	Arge	N.A.	N.A.	1987	700	real	[Ganter2005], [Zhang_etal2000]
LTFT	SSDP	5m diam x 22m height	N.A.	1993	2500	real	[Ganter2005], [Zhang_etal2000]
LTFT	SSDP	~ 10.7 m diam x 38 m height	N.A.	N.A.	10000	claimed	[Geertsema], [Zhang_etal2000]
LTFT	SSDP	10 m diam x 60 m height	2200 tons	2006	17000	real	[Ganter2005]

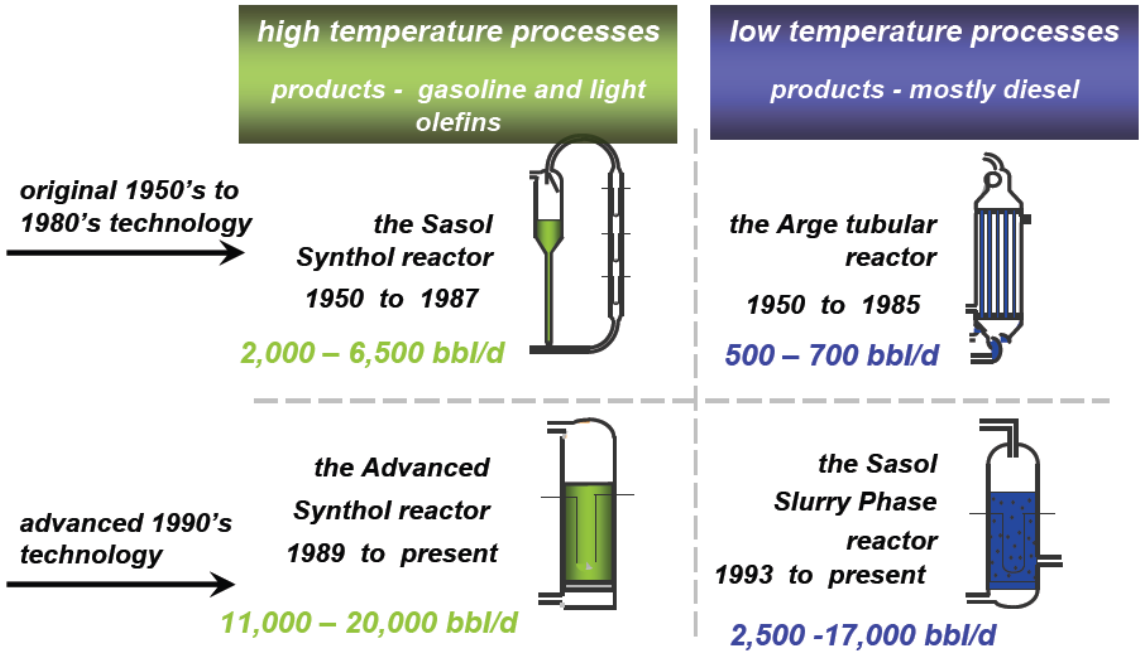


Figure D.7. SASOL reactors (Source: [SasolChinaCTL2007])

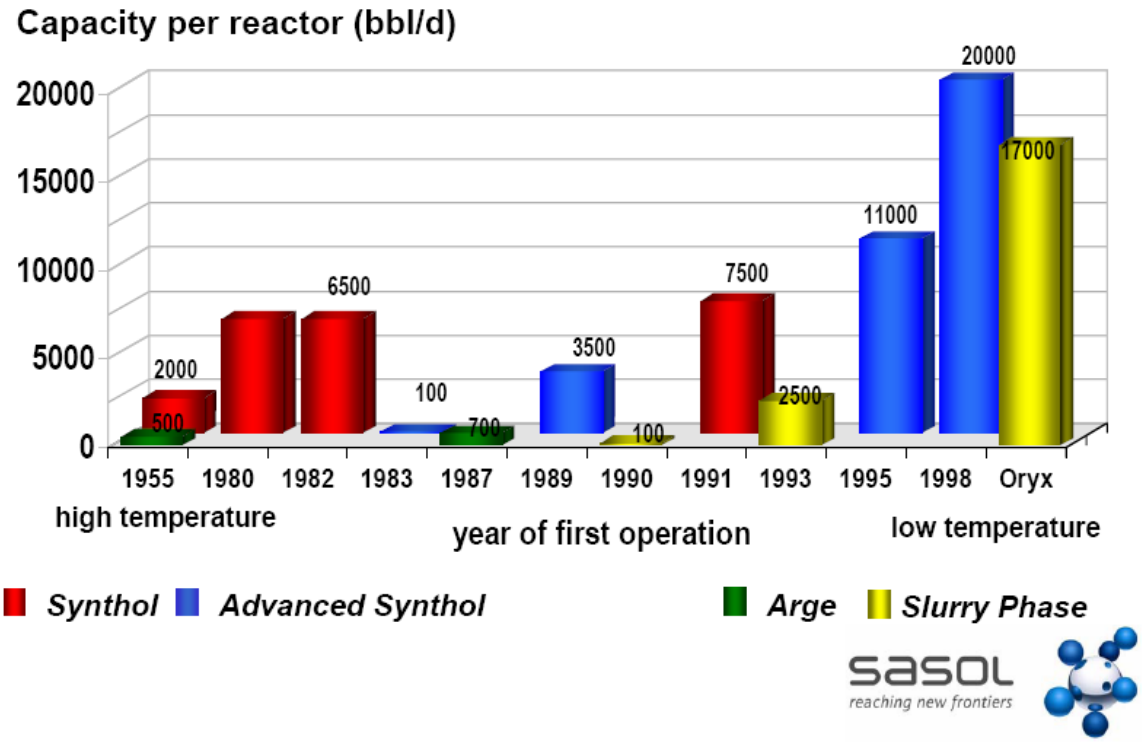


Figure D.8. SASOL reactors timeline (Source: [Ganter2005])

D.1.4. F-T Product Distributions

The F-T synthesis produces a wide range of hydrocarbons and oxygenated products under a variety of operating conditions. The fraction of each product depends on the interactive effects of various reaction conditions and reactor design. Given a set of reaction conditions, the product fractions can also be highly sensitive to a change in one of these parameters. All of the hydrocarbon products, except for methane (CH_4) in the lower extreme and hardwaxes (τ C40) on the higher extreme, reach their peak fraction at intermediate values for the various reaction conditions. Methane (CH4), excess quantities of which is undesirable (since it is readily available in the form of natural gas), is always produced and its selectivity can vary from as low as about 1% up to 100% depending on the reaction temperature and type and form of catalyst. At the other end of the product spectrum, the selectivity of long chain linear waxes can vary from zero to over 70%. The higher selectivity can be obtained with a ruthenium catalyst operating at 170°C. Operated at 400°C, the same catalyst will produce mainly methane. The intermediate carbon number products can be produced only in limited and trading-off amounts. According to [1], it does not seem possible to produce (without follow-up refining) on a carbon atom basis more than about 18% C2, about 16% C3, about 42% gasoline/naphtha (C5 to 200 C boiling-point) and about 20% diesel (200 to 320 C).

The distribution of the F-T products can be varied by the combined effect of several reactor design and operating factors. These are primarily the following: (i) syngas composition, (ii) operating temperature, (iii) operating pressure, (iv) type and form of catalyst, (v) amount and type of promoter, and (vi) design of the reactor and of the process route. Given a set of conditions and reactor and process route design, however, there is always a strong interrelationship between all of the various hydrocarbons comprising the syncrude (see Figure D.1 above). A similar kind of interrelationship also holds for the various oxygenated hydrocarbons products (alcohols, acids and aldehydes). The molecular mechanism of the F-T reactions has been a very controversial matter since the process has been invented over 80 years ago. Controversy has been especially intense concerning the effect of the catalyst type and form, and closely related to this, the design of the reactor and of the process route (including the recycling of the different hydrocarbons from the F-T reactor and/or the refining process). It is claimed, however, that there is no convincing evidence to date that a catalyst has been developed that will markedly improve the three crucial factors of the F-T process: the catalyst lifetime, activity and selectivity.

The F-T product distribution generally conforms to the ASF distribution, with the constant probability of chain growth α depending on the reaction conditions and reactor design. One exception is the C_2 hydrocarbons, of which the ASF model predicts a maximum production of 30% (on a mass basis). In practice, however, both with iron and cobalt catalysts under various reaction conditions, the maximum fraction obtained has not exceeded 20%. Except for this misfit of the ASF model, it is usually found that over the C_1-C_{12} range (which covers SNG, LPG and gasoline) the model's assumption of a constant α is confirmed by laboratory results. For commercial HTFT reactors operating in the "gasoline" mode, this α value is reported to be around 0.7. When substantial amounts of higher carbon-number products are present in the catalyst (as in the commercial LTFT process), the chain growth probability is observed to shift over the $C_{12} - C_{20}$ range to a higher value (α_2) for the C_{20}+ hydrocarbons. With commercial iron-catalyst LTFT reactors operating in the "wax producing" mode, the α_2 is reported to be 0.95 at the start of the run. Similar observations have been reported for cobalt catalysts. There is discussion surrounding this duality of the chain growth probability and possible refinement of the ASF model to better represent the F-T product distributions obtained in practice.

Today, LTFT is the major focus of attention in all GTL and CTL projects in the world. The LTFT syncrude contains a wide spectrum of mainly paraffinic and waxy products. A significant fraction of these products is "straight-run" diesel. Most of the remaining portion can be processed in the product work-up section to produce an ultra-clean synthetic diesel fuel. This diesel product has a very high cetane number in excess of 70 and is virtually free of sulfur, aromatics and nitrogen. Engine tests have shown that burning this diesel product produces significantly less particulate matter, NO_x, CO and hydrocarbons than conventional diesel.

Blends of conventional diesel with minor amounts of ultra-clean synthetic diesel are successfully marketed (e.g., by Shell).

D.2. Commercial F-T Plants (major source: [Steynberg&Dry2004]; other sources indicated within)

Currently, three companies have been successfully operating commercial F-T plants. These are SASOL, PetroSA (formerly Mossgas) and Shell. Others such as Syntroleum, BP and Rentech have been developing liquefaction technologies and are seeking opportunities to license their technologies out to investors and/or build commercial facilities themselves. In this section, we will present the commercial scale plants, especially those of SASOL, in more detail since SASOL is by far the most experienced in the industry and has been employing a variety of different processes and producing a wide range of products. Table D.3 below (adopted from Steynberg&Dry2004 and expanded using other references) summarizes the commercial F-T applications worldwide. Table D.4 below (adopted from [Radke_etal2006]) lists current and potential F-T technology licensors.

Table D.3: Commercial F-T applications

Feedstock	F-T Technology	Products	Location
High Ash Coal	Synthol (HTFT)	**Primary –** Gasoline **Co-products –** Diesel, Kerosene, LPG, Ethylene, Propylene, 1-Hexene, Oxygenates, Gasifier by-products, Pipeline gas.	Secunda, South Africa (since 1982)
High Ash Coal	Arge (LTFT) and SSPD (LTFT) w/ Iron Catalysts	Waxes, Paraffins, LPG, Ammonia, Hydrogen, Gasifier by-products	Sasolburg, South Africa (from 1955 to 2004)
Petroleum Coke	LTFT w/ Iron Catalyst	Diesel, Naphtha, Lubricant Base Oils, Electrical Power	ChevronTexaco and Rentech Proposals
Low Ash Coal	Synthol (HTFT)	**Primary**- Diesel and Electrical Power **Co-products –** Naphtha, LPG and various commodity chemicals	Proposed for China
Associated Gas	SSPD w/ Cobalt Catalyst (LTFT)	**Primary –** Diesel **Co-products –** Naphtha, LPG	Proposed for Escravos, Nigeria
Lean Natural Gas	Arge (LTFT) and SSPD (LTFT) w/ iron catalyst	Waxes, Paraffins, LPG, Ammonia, Hydrogen	Sasolburg, South Africa (since 2004)
Lean Natural Gas	Synthol (HTFT)	**Primary** – Gasoline **Co-products** – Diesel, LPG, Oxygenates	Mossel Bay, South Africa (since 1992) and Brownsville, Texas, U.S.A.
Lean Natural Gas	LTFT w/ Cobalt Catalyst	Waxes, Paraffins, Diesel, Naphtha, LPG	Bintulu, Malaysia (since 1993)
Lean Natural Gas	SSPD w/ Cobalt Catalyst	**Primary –** Diesel **Co-products –** Naphtha, LPG, Detergent feedstock, Lubricant base oils, Electrical power	Ras Laffan, Qatar (since 2006) and other proposals for Iran, Australia, Indonesia
Lean Natural Gas	Synthol (HTFT)	**Primary –** Gasoline **Co-products –** Diesel, Kerosene, LPG, Ethylene, Propylene, 1-Hexene, Oxygenates	Proposed for Oman

D.2.. SASOL (Sasolburg and Secunda, South Africa and Ras Laffan, Qatar)

The South African Coal, Oil and Gas Corporation, SASOL, was established in 1950 motivated by the political and economic reasons surrounding South Africa. SASOL was established by the government and subsidized for decades in order to operate profitably. SASOL currently operates four plants, one in Sasolburg, South Africa, two in Secunda, South Africa and one in Ras Laffan, Qatar (whose ownership is 51% Qatar Petroleum and 49% SASOL).

Table D.4. Current and potential F-T licensors (Source: Radke_etal2006)

Licensor	Commercial References – gas based – coal based	Reactor System	Catalyst
SASOL	Yes (67,000 b/d)[1] Yes (150,000 b/d)	fixed bed/slurry phase fluidised bed	iron/cobalt
SHELL	Yes (12,500 b/d)[2] No	fixed bed	cobalt
CONOCO PHILLIPS	No No	slurry phase	cobalt
RENTECH	No No	slurry phase	iron
SYNTROLEUM	No No	fixed bed	cobalt
BP	No No	fixed bed	cobalt
STATOIL	No No	slurry phase	cobalt
EXXON MOBIL	No No	slurry phase	cobalt
ENI	No No	slurry phase	cobalt

[1] includes the ORYX I GTL plant in Qatar (34,000 b/d)
[2] does not include the Pearl GTL project in Qatar (2 x 70,000 b/d)

D.2.1.1. Sasolburg, South Africa

The Sasolburg plant came on-stream in 1955. Due to stagnant oil prices during those years, the plant was not immediately a financial success. The plant's early survival was aided by the export/domestic sales of linear waxes, ammonia and other chemicals produced in a later installed complex, and the F-T tail gas as industrial fuel gas. The Sasolburg plant used coal to produce its syngas until 2004. From that date, it has been using methane piped from Mozambique. LTFT reactors are used at the plant. There are five multi-tubular (ARGE) reactors (500 –700 BPD) and one high capacity slurry phase (SSDP) reactor (2,500 BPD). Four of the multi-tubular reactors, the first one which came on-stream in 1955, each have a capacity of about 500 BPD. The other multi-tubular reactor, which came on-stream in 1957, has a capacity of about 700 BPD. The SSDP reactor that came on-stream in May 1993 has a capacity of 2,500 BPD. The reactors are operated to yield maximum linear alkanes/alkenes and waxes. All alkenes and oxygenated products are hydro-processed into alkanes. LPG (C3 and C4) is recovered from the F-T tail, and hydrogen is also extracted to be used in ammonia (NH_3) production. The remainder of the tail gas is sold as fuel gas. The

Sasolburg plant was established with the primary purpose of producing a syncrude that can be processed into liquid transportation fuels (diesel and naphtha as a gasoline hydro-cracking source). The plant served this purpose to a significant degree. However, SASOL early on realized that in order to improve the company's long-term profitability, especially against volatile oil prices, it had to diversify its product spectrum, concentrating especially on high-value chemicals that were readily a by-product of the operations or by converting more of the F-T products to such higher value chemicals. The Sasolburg plant no longer produces liquid fuels but a variety of petrochemicals (See Table D.3). A block diagram of the plant is in Figure D.9 below.

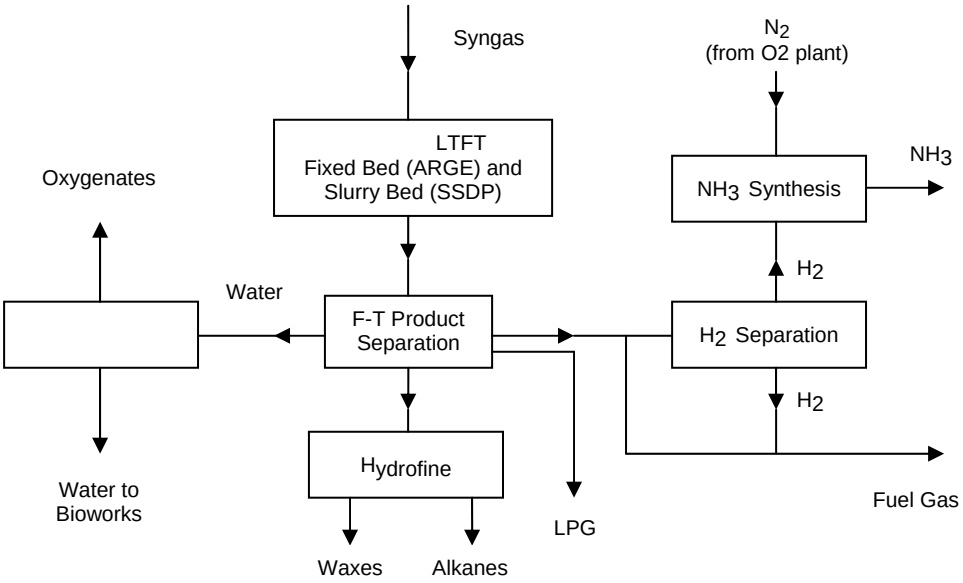


Figure D.9. SASOL Sasolburg plant block diagram (Source:[SteynbergandDry2004], Chapter 5)

D.2.1.2. Secunda, South Africa

The first SASOL plant in Secunda (named Sasol 2) came on-stream in 1980 after 4 years of construction. Due to rising oil prices during the 1970's and the shock effect of the Iranian revolution at the end of the decade, a second plant (named Sasol 3) was constructed at the same site, and it came on-stream in 1983. These two plants were financially successful from the beginning since oil prices were at their peak during the early 1980s. Since they came on-stream, the two Secunda plants have used syngas from coal gasification and fluidized-bed HTFT reactors, more specifically, Sasol Advanced Synthol (SAS) reactors. The operation at these plants is aimed at the production of 1-alkenes and gasoline. The F-T products from the reactors are a wide spectrum of hydrocarbons and oxygenates, and their separation and refining is complex. A bird's-eye view of the different sections of the Secunda site is in Figures D.10, D.11, and D.12 below.

Figure D.10. SASOL Plants (Sasol 2 and Sasol 3) in Secunda, South Africa (Source: Google Earth, July 2007)

Figure D.11. Coal preparation areas for the SASOL Plants (Sasol 2 and Sasol 3) in Secunda, South Africa (Source: Google Earth, July 2007)

The Secunda plants were originally each designed to produce 50,000 BPD of gasoline together with a variety of other chemical feedstocks using Synthol CBF (Circulating Fluidized Bed) reactors. With the installment of SAS reactors in 1995, the two plants have a combined current capacity of about 150,000 BPD of crude equivalent fuels plus other chemical products. In these plants, the F-T products leaving the reactors are condensed into a gaseous, an oily and an aqueous phase, which are processed as follows:

- **The Gaseous Phase** is obtained from the F-T tail gas after condensation of any aqueous or oil elements. This stream includes unconverted syngas (CO + H_2) and gaseous hydrocarbons (C_1 – C_4) and is separated into a hydrogen-rich, a methane-rich and three streams of light hydrocarbon steams. A portion of the H_2-rich stream is processed in a pressure swing absorber unit to produce the hydrogen necessary for the various hydro-treating processes in the plant. The remainder is fed back into the F-T reactors with the syngas. The bulk of the CH_4-rich stream is fed into autothermal catalytic reformers to produce syngas that is recycled into the F-T reactors (methane is not a very high-value F-T end product and recycling it is economically sensible).

Figure D.12. Ash/slag and waste water disposal areas for the SASOL Plants (Sasol 2 and Sasol 3) in Secunda, South Africa (Source: Google Earth, July 2007)

The balance of the methane is sold as fuel gas. The three light hydrocarbon streams are fractioned and purified into high value 1-alkenes[1]. Ethylene[2] (C_2H_4) and propene (C_3H_6) are sent to chemical processing units to produce high value chemicals. The remaining portion of the C_3 cut and the C_4 cut are oligomerized to yield LPG, gasoline and diesel.

- **The Aqueous Phase** contains alcohols[3], aldehydes[4], ketones[5] and acids. The non-acid chemicals are distilled out, and the alcohols and ketones are hydro-processed as end products. The other chemicals produced are N-crotonaldehyde[6], n-butanol[7], acetic acid[8] and propionic acid[9]. The effluent water from the separation and upgrading of the aqueous phase is biologically cleansed to remove any remaining organic compounds and then used as cooling water in the plant.

- **The Oily Phase**. C_5-C_8 1-alkenes are separated and sold as feedstock for polyethylene production. Longer chain linear olefins are hydro-processed to manufacture detergent alcohols (120,000 tons per year). The light naphtha is hydro-treated and catalytically reformed to produce gasoline. The diesel fuel cuts (the straight-run F-T diesel and that produced in the oligomerization plant) are hydro-treated into a high-cetane diesel fuel. The process flow at the Secunda plants is illustrated in the block diagram in Figure D.13 below. In 2004, the Secunda plants' total production provided about 30% of South Africa's liquid fuel requirements.

[1] Alkenes, or olefins, are unsaturated hydrocarbons with at least one carbon-to-carbon double bond. 1-Alkenes have exactly 1 C-C double bond and have the general formula C_nH_{2n}.

[2] Ethylene (C_2H_4) is the simplest alkene and has very important uses in industry and even in biology as a hormone. It is the organic compound produced at the largest scale worldwide. It is a very important building block in the petrochemical industry since it can be processed into a huge variety of products via different chemical reactions (such as polymerization, oxidation, halogenation, hydrohalogenation, alkylation, hydration, oligomerization, oxo-reaction).

[3] Alcohols correspond to a large family of organic compounds with a hydroxyl group attached to a carbon atom of an alkyl. The general formula for an acyclic alcohol is $C_nH_{2n+1}OH$. Alcohols (primarily ethanol and methanol) have found many uses throughout history, the best-known ones of which are as depressant beverages, for medical hygiene, and (increasingly) as fuels.

[4] The chemical term "aldehyde" corresponds to a family of organic compounds with many household and industrial uses. The following are some examples: formaldehyde (methanal) and compounds derived from/produced using it are used in permanent adhesives, wet-strength resin in toilet paper, paper towels, insulation materials, spray on insulating foams, paints, explosives etc. Acetaldehyde (ethanal) is a commonly used building block compound in various organic and inorganic chemical syntheses. Propionaldehyde is used as a chemical intermediate in the production of resins.

[5] Ketones are used in perfumes and paints as stabilizers, and also as solvents and intermediates in the chemical industry.

[6] N-Crotonaldehyde is a lachrymatory (eye tear inducing) liquid that is also used as an intermediate in organic synthesis.

[7] N-Butanol (*normal* Butanol or 1-Butanol), with the molecular formula $C_4H_{10}O$, is the most common isomer of the primary alcohol butanol (also called Butyl Alcohol). It is used as a solvent in various chemical applications (textiles processing, paint thinner, etc.), as an intermediate in chemical synthesis, various other products (perfumes, hydraulics and brake fluids) and as a fuel (it yields as much power as gasoline and, in contrast to ethanol, requires no modification to the engine).

[8] Acetic acid is an organic compound with the molecular formula CH_3COOH and best recognized as giving vinegar its sour taste and pungent smell. It is otherwise used as a solvent, as a reagent (reaction starter) in the chemical industry, and in many other industry and household applications. Most primarily, its esters are used in producing such products as solvents, inks, paints, wood stains, varnishes etc.

[9] Propionic acid and its esters are used in the production of food preservatives, pesticides, pharmaceuticals, solvents and as an intermediate in the chemical industry.

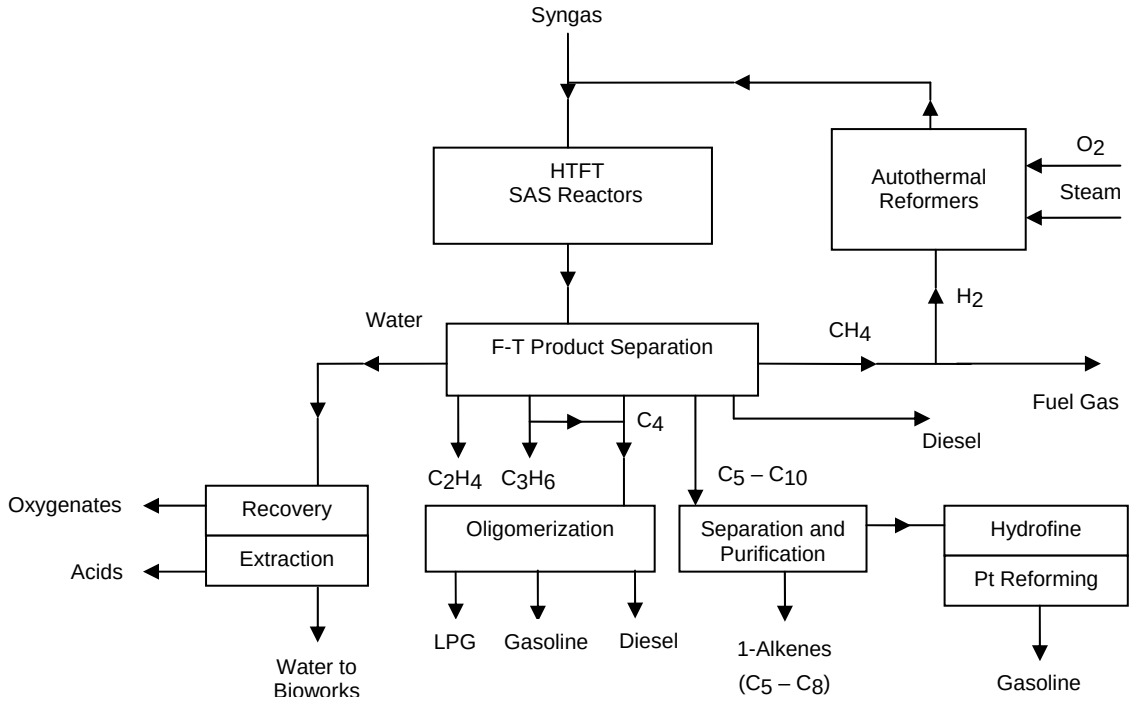


Figure D.13. SASOL Secunda Plants block diagram (Source: [SteynbergandDry2004], Chapter 5)

D.2.1.3. Ras Laffan, Qatar (other sources: Swanepoel2005], [SasolNews2005], [FW2006] and [dti1999])

A joint venture of Qatar Petroleum (51%) and SASOL (49%), the Oryx gas-to-liquid (GTL) plant in the Ras Laffan industrial city in Qatar came on-stream in June 2006. The plant uses lean natural gas from Qatar North Field as feedstock. The plant uses two SSPD (SASOL Slurry Phase LTFT) reactors, each being the largest of their kind with 17,000 BPD capacity. The reactors were manufactured in Japan's Yokohama Works by Ishikawajima-Harima Heavy Industries (IHI). The reactors use an advanced cobalt catalyst especially developed for the SSPD reactor. Each reactor measures 10 meters in diameter by 60 meters in length and weighs 2,200 tons. It is planned to expand the Oryx project to ultimately produce 100,000 BPD of liquid fuels and 8,500 BPD of lubricants. A bird's-eye view of the Oryx plant is given in Figure D.14 below. Photographs of the Oryx SSDP reactors and the construction site are shown in Figure D.15. The weights of the heavy plant components are listed below (Source: [Swanepoel2005]):

- Slurry Phase Reactor (2): 2,100 tons each (world's heaviest, lifted by land crane)
- Hydro-cracker Reactor: 470 tons
- Autothermal Reformer Reactors (2): 160 tons each
- Waste Heat Boilers (2): 210 tons each
- MP Steam Drums (2): 225 tons each
- Fractionator Column: 130 tons
- Catalyst Hoppers (2): 220 tons each
- Air Separation Cold Boxes (2): 550 tons each (world's largest)
- Main Air Compressor & Turbine (2): 360 tons each (world's largest)
- Booster Air Compressor (2): 220 tons each

Other facts about the Oryx site construction are given below (Source: [FW2006]):

- 72 hectare site
- 1.5 million m^3 earth moved during site preparation
- 70,000 m^3 of concrete
- 7,000 tons of steel
- 15,000 tons of steel pipe
- 1,700 km of cable
- Over 800 items of equipment
- 3,000 hydro tests
- 8,500 instruments loops
- 30 million construction man hours expended
- Peak construction workforce of over 6,000
- Over 200 commissioning systems

The process at the Oryx plant is designed to produce primarily liquid fuels. The overall process can be described as follows: (1) Using Haldor Topsoe's autothermal reforming technology, the natural gas is reacted with oxygen and steam over a catalyst to produce the necessary syngas. (2) Syngas is fed to the bottom of the SSPD reactor where it bubbles up into the slurry consisting of liquid wax and catalyst particles. As the syngas bubbles move upwards through the slurry, it diffuses into the catalyst and is converted into a waxy syncrude. The syncrude is separated from the catalyst particles in a proprietary SASOL process and is sent to the product upgrading unit. The lighter hydrocarbon fractions leave in a gas stream from the top of the reactor. This gas stream is cooled to recover the lighter cuts and water. The hydrocarbon streams are sent to the product-upgrading unit. (3) In the product upgrading step, the waxy hydrocarbons are cracked catalytically and upgraded to middle-distillate products of GTL diesel, kerosene and naphtha. Hydro-processing of the products is very mild. The diesel and kerosene products are of excellent quality and ultra clean burning. The naphtha, because of its paraffinic nature, has a low octane number and as such is poor quality for gasoline, but it is a very good hydro-cracker feedstock.

Figure D.14. SASOL Oryx Plant in Ras Laffan, Qatar (source: Google Earth, July 2007)

Figure D.15. Construction of the SASOL Oryx Plant in Ras Laffan, Qatar

D.2.2. PetroSA (Mossgas) (Mossel Bay, South Africa)

The South African government built the F-T complex Mossgas (now PetroSA) at the coastal town of Mossel Bay. The plant came on-stream in 1992 and uses lean natural gas from the offshore rigs. The plant has three Synthol (HTFT CFB) reactors each having a capacity of 8,000 BPD (the plant was designed, however, such that two reactors on-line could produce 80% of the total throughput). The real capacity of the plant is thus 20,000 BPD. The plant produces mainly gasoline and diesel. Syngas is produced by purification of the natural gas feed, followed by steam reforming in multi-tubular reformers and autothermal reforming. The syngas is then fed to Synthol reactors that use fused iron catalysts. The product mix leaving the reactor is separated into an F-T water phase fraction, a straight-run diesel fraction, a naphtha fraction, a light fraction (C_3 – C_4) and the F-T tail gas fraction. The F-T water phase contains oxygenates such as alcohols, ketones and aldehydes, which are extracted. The ketones and aldyhydes are further hydrogenated into alcohols. The F-T tail gas passes thru a chilling unit where C_3 and heavier hydrocarbons in the tail gas are recovered. The tail gas (mostly containing unconverted syngas, CO_2, C_2H_4 and C_2H_6) is then recycled to the autothermal reformers. Butane from the natural gas is isomerized and then alkylated to be used with the F-T C_3 – C_4 alkenes to produce high octane gasoline. The remaining C_3+ alkenes from the tail gas are oligomerized to produce diesel fuel and gasoline. The C_5-C_6 alkanes are isomerized and the C_7+ alkanes are catalytically reformed to produce high octane gasoline. All the gasoline and diesel cuts are hydrotreated. The total production is 1,020,000 tons per year.

D.2.3. Shell SMDS (Bintulu, Malaysia)

The SMDS (Shell Middle Distillate Synthesis) plant uses offshore natural gas in Bintulu, Malaysia. The natural gas is converted to syngas via partial oxidation at high pressure and temperatures. The H_2/CO ratio of the syngas is about 1.7. The plant uses multi-tubular LTFT reactors with a cobalt catalyst. The reactors

have a similar design to the Lurgi methanol reactors. They operate at about 3 MPa pressure and 200–230°C temperature and are claimed to achieve 80% conversion of the syngas and 85% selectivity of C_5+ hydrocarbons. Since the F-T reactor design requires an H_2/CO ratio of about 2.1, the syngas is hydrogen enriched by catalytic steam reforming of the F-T tail gas and injecting it back into the syngas stream (which is a low efficiency and costly process). The same catalytic reformer also provides hydrogen for the hydro-treating/hydro-cracking operations in the product upgrading units. The SMDS is aimed at high wax production. In the product separating unit, the F-T tail gas is obtained by condensing the F-T water, liquid oils and waxes. The tail gas is then fed to the catalytic steam reformer to generate hydrogen rich syngas which is recycled to the F-T reactor. The oils and wax are sent to product upgrade units. The oils are hydrofined into naphtha, diesel and kerosene. The plant has 2 modes of wax product upgrade. In one mode, the waxes are hydrofined and fractionated into different grades of waxes. In the other mode, the waxes are hydro-isomerized/hydro-cracked to produce high quality diesel and kerosene fuels.

D.3. References

[dti1999] Coal Liquefaction Technology Status Report, Department of Trade and Industry, 1999.

[FW2006] Foster Wheeler News, Summer 2006.
Available at http://www.fwc.com/publications/pdf/fw_summer_2006.pdf

[Ganter2005] Commercialization of Sasol's GTL technology, Enrico Ganter, Sasol Limited, UBS Global Oil & Gas Conference, 21st September 2005.

[Geertsema1999] Gas to Synfuels and Chemicals, Arie Geertsema, Corporate Technical Consultant, SASOL Technology (PTY) LTD., 1999.

[SasolChinaCTL2007] Sasol's CTL Experience: Bringing new energy to China through beneficiation of abundant coal reserves, Jan 30, 2007, Sasol Company Presentation author NA.

[SasolSSI2004] SASOL Synfuel International Brochure, May 2004.

[Schaberg2005] Application of Synthetic Diesel Fuels: "Future Fuels: Issues and Opportunities", 11th Diesel Engine Emissions Reduction Conference, Chicago, August 21-25, 2005, Paul Schaberg, Sasol Technology.

[Steynberg&Dry2004] Fischer-Tropsch Technology, Edited by Andre Steynberg (SASOL, Sasolburg, South Afric) and Mark Dry (University of Cape Town, South Africa), Studies in Surface Science and Catalysis, Vol. 152, Elsevier, 2004.

[Radke_etal2006] New Wave of Coal-to-liquids: An Opportunity to Decrease Dependency on Oil and Gas Imports and an Appropriate Approach to a Partial Revival of Domestic Coal Industries, Karsten R. Radtke, Max Heinritz-Adrian and Claudio Marsico, Volume 86, Issue 5, 2006, pp. 78 – 84.

[Wikipedia] http://www.wikipedia.org.

[ZE2007] Zero Emission Resource Organization (http://www.zeroemission.org).

[Zhang_etal2000] Indirect Liquefaction - Where Do We Stand? Yongqing Zhang and Burthon H. Davis, Catalysis Volume 15 (A Review of Recent Literature), Chapter 5, The Royal Society of Chemistry, Thomas Graham House, Science Park, Milton Road, Cambridge CB4 OWF, UK, 2000.