4-27-2022

The AICHE Student Design Competition: Modular Distributed Gas-to-Liquids (GTL) Synthesis

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Title: The AIChE Student Design Competition: Modular Distributed Gas-to-Liquid Synthesis

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Letter of Transmittal

To whom it may concern,

Contained within this report is a preliminary design package for a modular Fischer-Tropsch Reaction unit (FTR) as part of a Gas-to-Liquid network, in accordance with specifications for the 2021/2022 AIChE Student Design Competition. This report details the design of a modular Gas-to-Liquid plant capable of processing 500 MSCF/day of methane feed. The plant can be scaled to the other module sizes of 2500 MSCF/day and 5000MSCF/day using a parallel modular manufacturing system.

The AIChE Student Design Competition: Modular Distributed Gas-to-Liquids (GTL) Synthesis

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February 1st- April 26th 2022

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Abstract

Natural gas products are used as fuels and oils for many vehicles and industries. Some natural gas deposits are located in remote areas and have too little natural gas to warrant building a full natural gas plant. We have designed a modular plant using a Fischer-Tropsch reaction to be deployed to these remote deposits. Based on a natural gas flow rate of 22 million pounds per day of methane, our plant produces 340 million pounds of products, makes 900 million dollars of yearly profit, and will repay fixed investments after 13 years. The net profit of this project is a trillion dollars in present value.

Summary and Introduction

The purpose of this system is to convert natural gas into liquid fuels that can be easily stored and transported. To accomplish this, a pure methane feed is first converted into syngas (CO and H2). This syngas is eventually put through a Fischer Tropsch reaction (FTR) unit producing an array of paraffins. The paraffins are separated and the heavier products (waxes) are sent to a catalytic hydro-isomerization unit to be converted into lighter products.

Methane is first preheated by burning fuel gas in the feed preheater and going through an economizer. It is mixed with oxygen from the O2 vendor and CO2 from down the process. Steam is added in the syngas unit and the mixture undergoes multiple reactions to produce hydrogen gas and carbon monoxide in a two-to-one molar ratio. This reaction is exothermic and the heat is used to generate steam in the waste heat boiler, which functions as a heat exchanger to cool the mixture down somewhat before going into a regular water cooled heat exchanger.

The cooled syngas is then compressed and sent through an intensive freezing unit to remove water. A preliminary separator removes some of the carbon dioxide. The rest, along with leftover water and methane, is removed via a molecular sieve and activated alumina. Cryogenic distillation is then used to remove any oxygen and nitrogen (the latter of which entered the system through the oxygen feed, which has about 1% N_2).

This purified stream of CO and H2 enters the FTR and undergoes reaction to form lighter alkanes (LPG, naphtha, and diesel), waxes, and steam. This exothermic reaction is cooled by water, generating steam to be used in the process. The products are separated through the use of a fractionator to remove waxes from the lighter products.The lighter components are separated into LPG, tail gas, methane and ethane (which are used as fuel gas) and naphtha.

The waxes are sent to the hydroisomerization unit to be refined into paraffins, diesel, and additional naphtha. This unit also requires an input of fuel gas and oxygen for burning. Oxygen used in the process is purchased from a supplier. Cooling water circulates throughout many of the units to maintain appropriate temperatures, and returns to the cooling tower to reduce its temperature before going through the process units again.

Flue gas generated in the process and used steam are sent through a condenser. The water is removed and recycled to the cooling tower. Some of the carbon dioxide is recycled to the syngas unit to achieve the desired equilibrium, while the rest is vented to the atmosphere.

Process Flow Diagrams

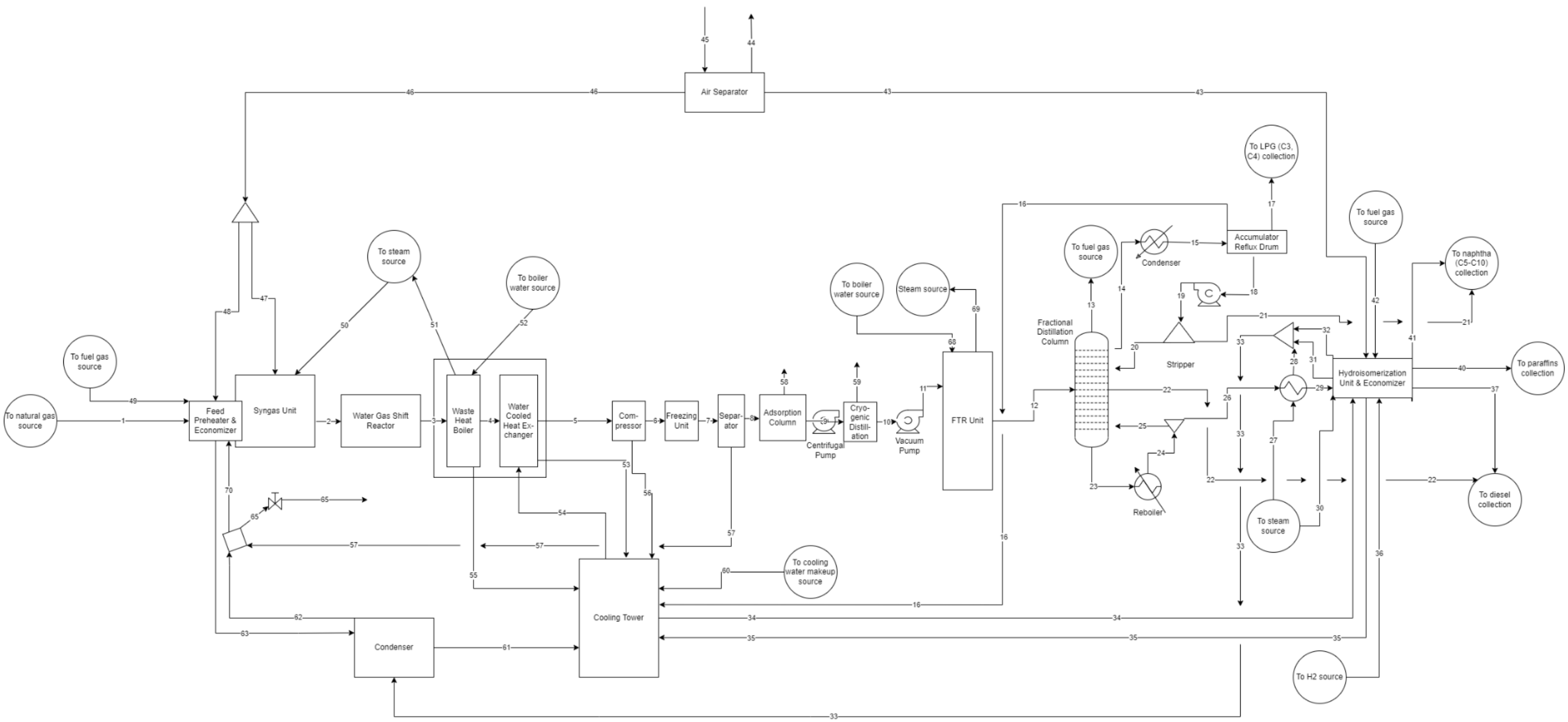


Figure 1: PFD

Heat and Material Balances

Below is a summary of the major streams in the overall process flow of the plant:

Overall								
Stream	01	17	21	22	27	30	33	36
Temperature (F)	100	60	60	60	353	353	212	60
Pressure (psig)	500	0	0	0	125	125	0	0
Mass flow (lb/day)								
H2O	0	0	0	0	51910	51910	103800	0
O2	0	0	0	0	0	0	0	0
CO2	0	0	0	0	0	0	0	0
H2	0	0	0	0	0	0	0	16290
N2	0	0	0	0	0	0	0	0
CH4	22820000	0	0	0	0	0	0	0
C2	0	0	0	0	0	0	0	0
C3	0	125800	0	0	0	0	0	0
C4	0	165800	0	0	0	0	0	0
C5-C10 (Naphtha)	0	0	1562000	0	0	0	0	0
C11-C19 (Diesel)	0	0	0	2204000	0	0	0	0

Figure 2: Material Balance 1 of 6

Overall								
Stream	37	40	41	42	44	45	49	50
Temperature (F)	60	60	60	60	75	75	60	353
Pressure (psig)	0	0	0	0	500	500	0	125
Mass flow (lb/day)								
H2O	0	0	0	0	0	0	0	7268000
O2	0	0	0	0	0	23330000	0	0
CO2	0	0	0	0	0	0	0	330700000
H2	0	0	0	0	0	0	0	0
N2	0	0	0	0	76600000	76800000	0	0
CH4	0	29420	0	32510	0	0	493000	0
C2	0	14710	0	2438	0	0	36960	0
C3	0	103000	0	0	0	0	0	0
C4	0	103000	0	0	0	0	0	0
C5-C10 (Naphtha)	0	0	333600000	0	0	0	0	0
C11-C19 (Diesel)	1956000	0	0	0	0	0	0	0

Figure 3: Material Balance 2 of 6

Overall								
Stream	51	52	57	58	59	65	68	69
Temperature (F)	260	77	-328	-328	-328	60	77	499
Pressure (psig)	20	0	600	600	600	0	0	0
Mass flow (lb/day)								
H2O	27560000	27560000	0	7064000	0	0	127000000	127000000
O2	0	0	0	0	9524000	0	0	0
CO2	0	0	291000	0	0	1460000	0	0
H2	0	0	0	0	0	0	0	0
N2	0	0	0	0	187100	0	0	0
CH4	0	0	0	917100	0	0	0	0
C2	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0
C4	0	0	0	0	0	0	0	0
C5-C10 (Naphtha)	0	0	0	0	0	0	0	0
C11-C19 (Diesel)	0	0	0	0	0	0	0	0

Figure 4: Material Balance 3 of 6

Here is a summary of the heat and material balance of the designed portion of the plant featuring the FTR reactor and the separator unit:

Stream	05	06	07	08	10	11	12	13
Temperature (F)	1800	1800	-200	-200	440	440	440	350
Pressure (psig)	0	798	798	798	600	600	0	0
Mass flow (lb/day)								
H2O	7064000	7064000	7064000	7064000	0	0	13710000	13710000
O2	9524000	9524000	9524000	9524000	0	0	0	0
CO2	291000	291000	291000	0	0	0	0	0
CO	21300000	21300000	21300000	21300000	21300000	21300000	0	0
H2	3044000	3044000	3044000	3044000	3044000	3044000	0	0
N2	187100	187100	187100	187100	0	0	0	0
CH4	917100	917100	917100	917100	0	0	1143000	0
C2	0	0	0	0	0	0	85760	0
C3	0	0	0	0	0	0	125800	0
C4	0	0	0	0	0	0	165800	0
C5-C10 (Naphtha)	0	0	0	0	0	0	1562000	0
C11-C19 (Diesel)	0	0	0	0	0	0	2204000	0
C20- C25	0	0	0	0	0	0	1043000	0
C26- C29	0	0	0	0	0	0	511800	0
C30-C35	0	0	0	0	0	0	549000	0
C36- C47	0	0	0	0	0	0	578500	0
C48+	0	0	0	0	0	0	259700	0

Figure 5: Material Balance 4 of 6

Stream	**15**	**16**	**17**	**18**	**21**	**22**	**24**	**25**	**26**
Temperature (F)	-42	-42	-42	-42	60	60	350	350	350
Pressure (psig)	0	0	0	0	0	0	5	5	5
Mass flow (lb/day)									
H2O	0	13710000	0	0	0	0	0	0	0
O2	0	0	0	0	0	0	0	0	0
CO2	0	0	0	0	0	0	0	0	0
CO	0	0	0	0	0	0	0	0	0
H2	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0
CH4	0	0	0	0	0	0	0	0	0
C2	0	0	0	0	0	0	0	0	0
C3	2641000	0	125800	2516000	0	0	0	0	0
C4	3482000	0	165800	3316000	1562000	0	0	0	0
C5-C10 (Naphtha)	0	0	0	0	0	0	0	0	0
C11-C19 (Diesel)	0	0	0	0	0	2204000	0	0	0
C20- C25	0	0	0	0	0	0	21890000	20850000	1043000
C26- C29	0	0	0	0	0	0	10750000	10240000	511800
C30-C35	0	0	0	0	0	0	11530000	10980000	549000
C36- C47	0	0	0	0	0	0	12150000	11570000	578500
C48+	0	0	0	0	0	0	5453000	5194000	259700

Figure 6: Material Balance 5 of 6

Stream	**27**	**30**	**33**	**57**	**58**	**59**	**68**	**69**
Temperature (F)	353	353	353	-328	-328	-328	77	499
Pressure (psig)	125	125	100	0	600	600	0	0
Mass flow (lb/day)								
H2O	51910	51910	103800	0	7064000	0	127000000	127000000
O2	0	0	0	0	0	9524000	0	0
CO2	0	0	0	291000	0	0	0	0
CO	0	0	0	0	0	0	0	0
H2	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	187100	0	0
CH4	0	0	0	0	917100	0	0	0
C2	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0
C4	0	0	0	0	0	0	0	0
C5-C10 (Naphtha)	0	0	0	0	0	0	0	0
C11-C19 (Diesel)	0	0	0	0	0	0	0	0
C20- C25	0	0	0	0	0	0	0	0
C26- C29	0	0	0	0	0	0	0	0
C30-C35	0	0	0	0	0	0	0	0
C36- C47	0	0	0	0	0	0	0	0
C48+	0	0	0	0	0	0	0	0

Figure 7: Material Balance 6 of 6

Safety/ Environmental Summary

Critical Hazard: Overheating FTR Unit (Runaway Reaction)

Causes: This situation can be caused by a reduction in the flow of cooling water, an increase in the inlet temperature of the cooling water, or an increase in the rate of entry of the fuel stream.
Risks: Overheating the FTR will result in deactivation of the catalyst and production of methane rather than higher molecular weight hydrocarbons. Furthermore, the reaction will continue releasing heat, resulting in rampant temperature increase and possibly an explosion.
Mitigation:
The FTR has a high temperature transmitter to stop or reduce the flow of reactants if the temperature gets too high. If it fails, the emergency shutdown button can be pressed to stop the flow of reactants to the unit.

Critical Hazard: Gas Leak

Causes: Broken piping or pipe connections, flawed connections, broken subsystems or gas sources, system blockage (such as by cooled waxes), sabotage, or uncontrolled pressure spikes.
Risks: Carbon monoxide poisoning and possible death without warning odors, asphyxiation by displacement of O2 by other gasses, scalding by steam or other hot gasses, fire, explosion with projectiles, sustained flow of dangerous gasses and vapors, shortage of reactants, loss of valuable material.
Mitigation:
Beveled edge pipes and ball valves are in place to reduce leaks caused by connections. Pipes should be inspected at least weekly for damage.

Critical Hazard: Product Fuel Ignition

Causes: Excessive heat (such as from a fire), loss of containment (see causes of gas leaks) and formation of flammable vapor mixtures
Risks: Fire, explosions, injuries, death, equipment damage, valuable material losses.
Mitigation: Sensors, alarms, grounding

Critical Hazard: Wax Solidification

Causes: If the FTR unit is overcooled and the reaction stops, flow could halt, and waxes in the system , flash vessel, or nearby piping could cool down and solidify, plugging the system. Overcooling could be caused by a reduction of feed (and therefore reaction heat output) or too much cooling water at too cold a temperature (perhaps coupled with a cold snap and bad insulation).
Risks: A plug would not be dangerous in itself, but it could back up the system, causing all manner of malfunctions. If pressure backs up, flow could be reversed. Additionally, increasing pressure could cause a leak.

Mitigation:
The FTR unit has a temperature transmitter to tell the valve feeding the reactants to open if the temperature gets too low. Pipes leaving the FTR should be insulated.

Critical Hazard: Pressurized Liquid LPG Escape and Evaporation

Causes: Breach in LPG containment (facility or trucks), sabotage, faulty or broken transfer piping.
Risks: Boiling liquid expanding vapor explosion, frostbite, suffocation, chemical explosion.
Mitigation:
The fractional distillation column and reflux drum have two vacuum and pressure relief valves per unit to vent excess pressure. Enclosed areas will be ventilated to remove hazardous gasses.

Equipment Description

Equipment	ID	Unit Description
Centrifugal Compressor	CMP	The centrifugal compressor compresses the incoming gas feed of carbon monoxide, methane, water, and carbon dioxide by increasing pressure to 55 bar. This increase in pressure allows the water to condense out.
Freezing Unit	FZU	The compressed feed stream is sent to the freezing unit where it is cooled -200 degrees Celsius. This allows the carbon dioxide to sublime and the other gas components to be liquefied allowing them to be purified and processed through the cryogenic distillation unit.
Separator	SP	The filter removes the sublimed carbon dioxide from the gas stream since the sublimed carbon dioxide particles can damage the cryogenic distillation unit damaging equipment and leading to a less effective distillation of gas components.
Adsorption Column	MSC	The gas components are sent to an adsorption column filled with molecular sieve 3A which removes any additional water and carbon dioxide as well as methane.
Centrifugal Pump	P-1	The pump is placed after the adsorption column to account for the pressure loss as the gas stream passes through the

		column.
Cryogenic Distillation Tower	CD	The cryogenic distillation unit separates the following gas components: oxygen, nitrogen, carbon monoxide, hydrogen gas. The oxygen is collected as a bottoms product as a liquid. The nitrogen is collected as an overhead product.
Vacuum Pump	VP	The vacuum pump changes the pressure to create near vacuum conditions and is part of the control system aimed at regulating the pressure of the gas as it leaves the cryogenic distillation unit.
Fractional Distillation Column	FDC	The fractional distillation column is heated up to 350 F allowing the FTR products to be separated.
Condenser	C	The condenser allows the water to condense out.
Reflux Drum	RD	Naphtha leaves the reflux drum to be reflux back to the distillation unit. The reflux ratio is 20:1.
Centrifugal Pump	P-2	A centrifugal pump pumps the Naptha from the reflux drum to a splitter where approximately 30% of the Naptha stream is sent back to the fractional distillation column.
Reboiler	R	The reboiler heats the bottoms product of C19+ hydrocarbons and a portion of the reboil vapor is sent back to the distillation unit to allow for more collection of diesel

		and the overhead products of naphtha and LPG.
Cooling Tower	HE	The function of the cooling tower is to remove the waste heat from the process using water.
FTR Reactor	FTR	The FTR reactor is a microchannel reactor made up of three modules. Each of the modules contain 19000 channels. The dimensions of the reaction microchannels are as follows: 0.037 in x 0.70 in x 4.6 ft. The dimensions of the cooling channels are as follows: 0.037 in x 0.12 in x 4.6 ft. Each individual reaction microchannel is cooled by two cooling channels on top and bottom. The function of the reactor is the conversion of carbon monoxide and hydrogen gas into liquid alkanes and water.

Figure 8: Equipment Descriptions

Equipment Specifications

Equipment Specification Date Estimated: 4/25/2022

Modular Fischer Tropsch Gas to Liquids Synthesis

Capacity: 500 MSCF/day of Natural Gas

Equipment	ID	Capacity/ Size Specifications	Material	Temper-ature	Pressure (Gauge)	Bare Module Cost
Centrifugal Compressor	CMP	27,000 m^3/hr	SS 316	440 F	55 bar	$6,813,400
Freezing Unit	FZU	The dimensions are as follows: 15 ft x 15 ftx 8ft	SS 316	-392 F	55 bar	$16,000,000
Separator	SP	The area of the filter that is used is 3000 m	SS 316	-392 F	55 bar	$344,472
Molecular Sieve Adsorption Column	MSC	Column Diameter 2 m Column Height: 60 m	SS 316	-392 F	55 bar	$35,000,000
Centrifugal Pump	P-1	Shaft Power: 20 kW	SS 316	60 F	55 bar	$350,000
Cryogenic Distillation Tower	CD	Column Diameter: 1.5m Column Height: 7 m	SS 304	-392 F	55 bar	$1,744,000
Vacuum Pump	VP	Shaft Power: 7 kW	Hastelloy	60 F	48 bar	$550,000
Fractional Distillation Column	FDC	Column Diameter: 3 m Column Height: 50m	Hastelloy	350 F	55 bar	$33,578,000

Condenser	C	Maximum Operating Pressure Shell Side: 8.62 bar Maximum Operating Tube Side: 3.45 bar Heat Transfer Area: 5000 m^2	Hastelloy	-70 F	3 bar	$12,388,000
Reflux Drum	RD	Capacity: 50000 m^3	Hastelloy	350 F	55 bar	$13,000,000
Centrifugal Pump	P-2	Shaft Power: 7 kW	Hastelloy	350 F	48 bar	$253,093
Reboiler	R	Maximum Operating Pressure Shell Side: 10.3 bar Maximum Operating Tube Side: 8.3 bar Heat Transfer Area: 5000 m^2	Hastelloy	350 F	48 bar	$16,388,000
Cooling Tower	HE	150 ft Tall 250 ft Long Hyperboloid structure	Stainless Steel	353 F	9 bar	$326,000
FTR Reactor	FTR	Module Dimension: 1.5 m x 1m x 1m No. of Modules Required: 3	Hastelloy	440 F	25 bar	$5,000,000

Figure 9: Equipment Specifications

Piping and Instrumentation Diagram

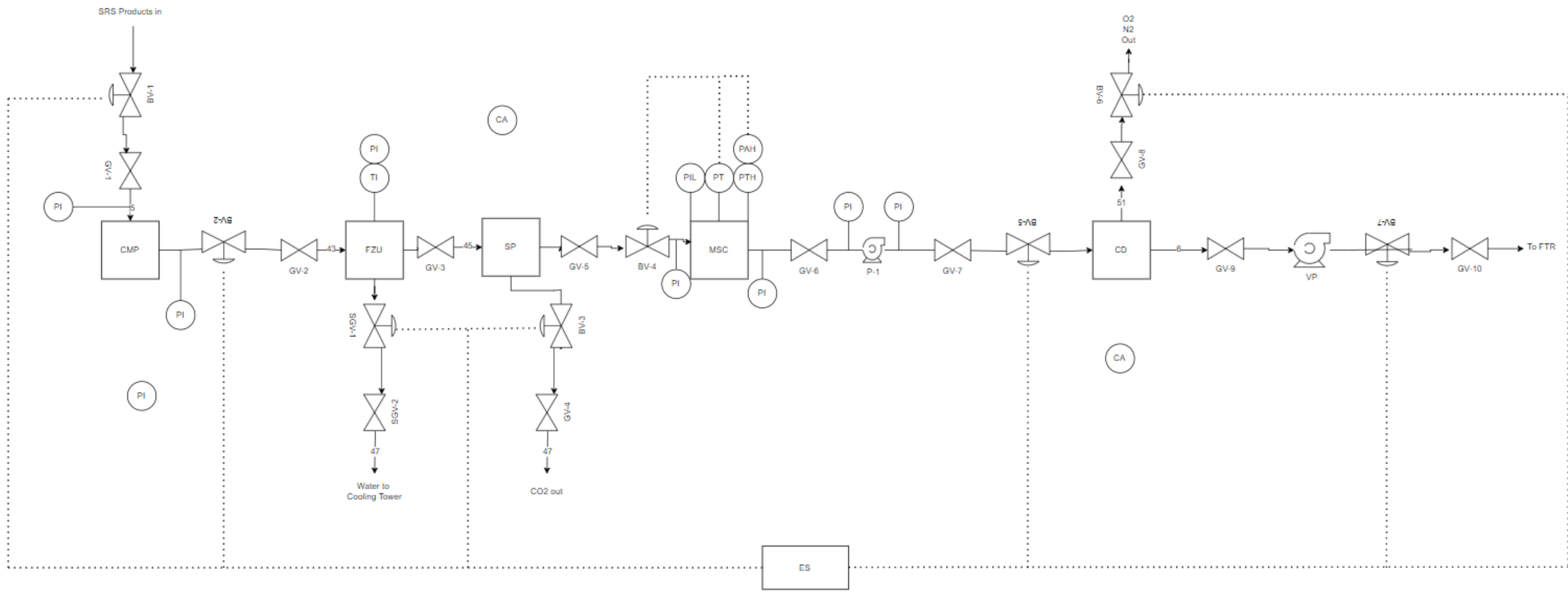


Figure 10: Cryogenic Distillation P&ID

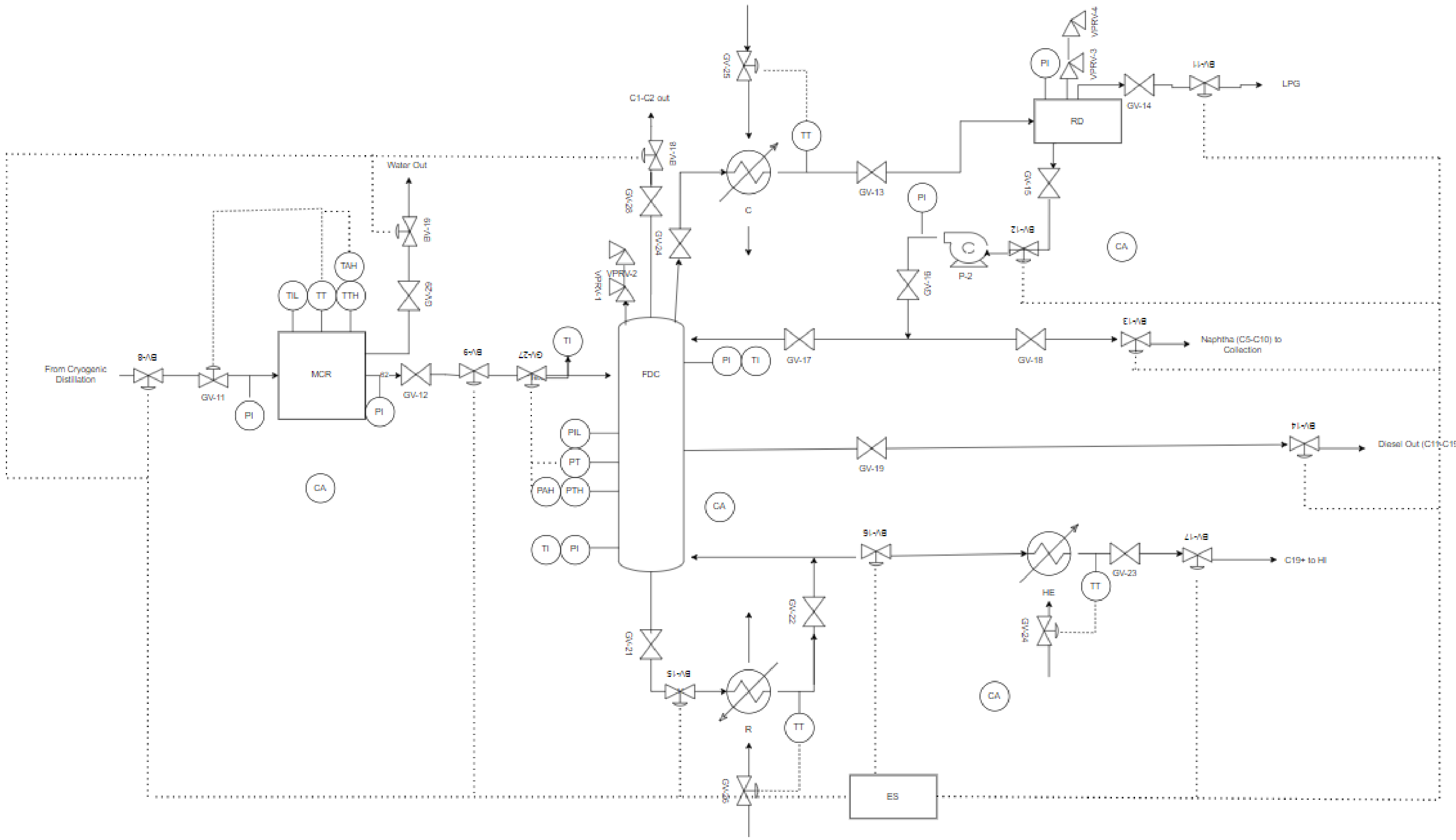


Figure 11: Separation P&ID

BV-X	Ball Valve	PIL	Pressure Indicator Low
C	Condenser	PT	Pressure Transmitter
CMP	Compressor	PTH	Pressure Transmitter High
CD	Cryogenic Distillation	R	Reboiler
ES	Emergency Shutoff Button	RD	Reflux Drum
FDC	Fractional Distillation Column	SGV-X	Slide Gate Valve
FZU	Freezing Unit	SP	Separator
GV-X	Globe Valve	TI	Temperature Indicator
HE	Heat Exchanger	TIL	Temperature Indicator Low
MCR	Micro Channel Reactor	TT	Temperature Transmitter
MSC	Molecular Sieve Column	TTH	Temperature Transmitter High
P	Pump	VP	Vacuum Pump
PI	Pressure Indicator	VPRV	Vacuum and Pressure Relief Valve
CA	Carbon Monoxide Detector	TAH	Temperature Alarm High
PAH	Pressure Alarm High		

Figure 12: Key Sheet for P&IDs

Equipment Information Summary

Material Selection

Chemical compatibility charts were used to choose materials for the process equipment. 316L Stainless Steel has complete resistance to all materials except pentane. Hastelloy C has complete resistance to all chemicals, but is more expensive than stainless steel. Hastelloy C is used when streams or equipment contain pentane.

Pipe Specifications

Pipes were sized using rules of thumb for velocity. The rules were 100 ft/s for gasses and 10 ft/s for liquids

Pipe	Service	Material	Inner Diameter (in)	Nominal Diameter (in)	Ends/Connections	Number of Pipes Needed
SRS Products to Compressor	H2 CO CH4 H2O CO2	316L Stainless Steel	34.5	36	Beveled	5
CMP to FZU	H2 CO CH4 H2O CO2	316L Stainless Steel	34.5	36	Beveled	5
FZU to SP	H2 CO CH4 CO2	316L Stainless Steel	34.5	36	Beveled	5
SP outlet	CO2	316L Stainless Steel	4.026	4	Beveled	1
SP to MSC	H2 CH4	316L Stainless Steel	19	20	Beveled	1
MSC to P-1	H2 CH4	316L Stainless Steel	34.5	36	Beveled	5
P-1 to CD	H2 CH4	316L Stainless Steel	34.5	36	Beveled	5
CD to VP	H2 CH4	316L Stainless Steel	34.5	36	Beveled	5

Figure 13: Pipe Specifications 1 of 3

Pipe	Service	Material	Inner Diameter (in)	Nominal Diameter (in)	Ends/Connections	Number of Pipes Needed
VP to MCR	H2 CH4	316L Stainless Steel	34.5	36	Beveled	5
HE C19+ Out	C20-C63	316L Stainless Steel	34.5	36	Beveled	3
MCR H2O Out	H2O	316L Stainless STeel	8.071	8	Beveled	1
MCR to FDC	C1-C63	Hastelloy C	20.25	22	Beveled	1
FDC to C	C3-C10	Hastelloy C	23.5	24	Beveled	4
C to RD	C3-C10	Hastelloy C	29.5	24	Beveled	1
LPG out	C3-C4	316L Stainless Steel	34.5	36	Beveled	1
RD to P-2	C5-C10	Hastelloy C	29.5	30	Beveled	1
P-2/Reflux	C5-C10	Hastelloy C	29.5	30	Beveled	1
FDC C11-C19 out	C11-C19	316L Stainless Steel	34.5	36	Beveled	2
FDC to R	C20-C63	316L Stainless Steel	5.501	6	Beveled	1

Figure 14: Pipe Specifications 2 of 3

Pipe	Service	Material	Inner Diameter (in)	Nominal Diameter (in)	Ends/Connections	Number of Pipes Needed
R out/Reboil	C20-C63	316L Stainless Steel	34.5	36	Beveled	3
HE C19+ Out	C20-C63	316L Stainless Steel	34.5	36	Beveled	3
FDC C1-C2 Out	C1 C2	316L Stainless Steel	25.25	26	Beveled	1

Figure 15: Pipe Specifications 3 of 3

Valve Specifications

Globe valves were used for flow control since they are designed to be partially opened.

Globe Valves 1-11	Pipe	Inner Diameter (in)	Material	Service
1	SRS Products to Compressor	34.5	316L Stainless Steel	H2 CO CH4 H2O CO2
2	C to FZU	34.5	316L Stainless Steel	H2 CO CH4 H2O CO2
3	FZU to SP	34.5	316L Stainless Steel	H2 CO CH4 CO2
4	SP outlet	4.026	316L Stainless Steel	CO2
5	SP outlet	4.026	316L Stainless Steel	CO2
6	MSC to P-1	34.5	316L Stainless Steel	H2 CH4
7	P-1 to CD	34.5	316L Stainless Steel	H2 CH4
9	CD to VP	34.5	316L Stainless Steel	H2 CH4
10	VP to MCR	34.5	316L Stainless Steel	H2 CH4
11	VP to MCR	34.5	316L Stainless Steel	H2 CH4

Table 16: Valve Specifications for Globe Valves 1-10

Globe Valves 11-19	Pipe	Inner Diameter (in)	Material	Service
12	MCR to FDC	20.25	Hastelloy C	C1-C63
13	C to RD	29.5	Hastelloy C	C3-C10
14	LPG out	34.5	316L Stainless Steel	C1-C4
15	RD to P-2	29.5	Hastelloy C	C5-C10
16	P-2/Reflux	29.5	Hastelloy C	C5-C10
17	P-2/Reflux	29.5	Hastelloy C	C5-C10
18	P-2/Reflux	29.5	Hastelloy C	C5-C10
19	FDC C11-C19 out	34.5	316L Stainless Steel	C11-C19

Table 17: Valve Specifications for Globe Valves 11-20

Globe Valves 21-29	Pipe	Inner Diameter (in)	Material	Service
21	FDC to R	5.501	316L Stainless Steel	C20-C63
22	R/Reboil	34.5	316L Stainless Steel	C20-C63
23	HE 19+ out	34.5	316L Stainless Steel	C20-C63
24	FDC to C	7.625	Hastelloy C	C1-C10
27	MCR to FDC	20.25	Hastelloy C	C1-C63
28	C1-C2 out from FDC	25.25	316L Stainless Steel	C1 C2
29	MCR Water out	8.071	316L Stainless Steel	H2O

Table 18: Valve Specifications for Globe Valves 21-27

Ball valves were used as shutoff valves since they can be closed quickly, work at higher pressures, and are not prone to leaking.

Ball Valves 1-9	Pipe	Diameter	Material	Service
1	SRS Products to C	34.5	316L Stainless Steel	H_2 CO CH_4 H_2O CO_2
2	CMP to FZU	34.5	316L Stainless Steel	H_2 CO CH_4 H_2O CO_2
3	SP outlet	4.026	316L Stainless Steel	CO_2
4	SP to MSC	19	316L Stainless Steel	H_2 CH_4
5	P-1 to CD	34.5	316L Stainless Steel	H_2 CH_4
7	VP to MCR	34.5	316L Stainless Steel	H_2 CH_4
8	VP to MCR	34.5	316L Stainless Steel	H_2 CH_4
9	MCR to FDC	20.25	Hastelloy C	C1-C63

Table 19: Valve Specifications for Ball Valves 1-9

Ball Valves 11-19	Pipe	Diameter	Material	Service
11	LPG out	34.5	316L Stainless Steel	C1-C4
12	RD to P-2	29.5	Hastelloy C	C5-C10
13	P-2/Reflux	29.5	Hastelloy C	C5-C10
14	FDC C11-C19 Out	34.5	316L Stainless Steel	C11-C19
15	FDC to R	5.501	316L Stainless Steel	C20-C63
16	R/Reboiler	34.5	316L Stainless Steel	C20-C63
17	HE C19+ out	34.5	316L Stainless Steel	C20-C63
18	FDC C1-C2 Out	25.25	316L Stainless Steel	C1 C2
19	MCR Water Out	8.071	316L Stainless Steel	H2O

Table 20: Valve Specifications for Ball Valves 11-17

Slide gate valves are used to control the flow of solids in the dry ice separator.

Slide Gate Valves	Inner Diameter (in)	Material	Service
1	4.026	316L Stainless Steel	H2O (s)
2	4.026	316L Stainless Steel	H2O (s)

Table 21: Valve Specifications for Slide Gate Valves

Vacuum and pressure relief valves are used as a safety measure for the fractional distillation column and reflux drum.

Vacuum and Pressure Relief Valves	Unit	Material	Service
1	FDC	Hastelloy C	C1-C63
2	FDC	Hastelloy C	C1-C63
3	RD	Hastelloy C	C3-C10
4	RD	Hastelloy C	C3-C10

Table 22: Valve Specifications for Vacuum and Pressure Relief Valves

Process Control and Instrumentation

Name	Description
Temperature Transmitter	Sends temperature data to globe valves for flow control
Temperature Indicator Low	Indicates when temperature is below the range of the temperature transmitter
Temperature Transmitter High	Sends temperature data to globe valves when the temperature is above the range of the temperature transmitter
Ball Valve	Quick closing valves that closes when the emergency shutoff button is pressed
Vacuum and Pressure Relief Valve	Valve that opens when the pressure is too high or when a vacuum is generated in the unit
Globe Valve	Valve that opens or closes partially to control flow rates
Pressure Transmitter	Sends pressure data to globe valves to adjust the flow rate
Pressure Indicator Low	Indicates when pressure is below the range of the pressure transmitter
Pressure Transmitter High	Sends pressure data to globe valves when the pressure is above the range of the pressure transmitter
Emergency Shutoff Button	Closes all ball valves during an emergency
Carbon Monoxide Detector	Detects carbon monoxide in the plant

Figure 23: Instrument Descriptions

Economics

All operating costs were calculated using prices as listed in the problem statement. Additional Operating expenses were estimated as 3% of the capital investment to account for yearly operating expenses beyond process materials and utility costs.

Operating Costs	
Material	Price ($/yr)
Purified oxygen	341100000
SU steam feed	8491000
Cooling water after SU	482300
Cooling water for FTR	2237000
FTR catalyst	18930000
HIU steam	121300
HIU hydrogen	285300
HIU cooling water	454700
Additional Operating expenses	42690000
Electricity for Air sep	136400000
Electricity for HIU	303100
Total	551500000

Figure 24: Operating Costs

Below is a summary of the equipment costs including equipment included as part of the design of the FTR and the separator unit and previously designed units. The total equipment investment was estimated as 4.8 times the equipment costs.

Capital costs	
	Price ($)
Existing units	
SU	94370000
HIU	34930000
Equipment	
Centrifugal pump	412400
Condenser	12390000
Compressor	6183000
Cryogenic Distillation	1744000
FTR Reactor	5000000
Centrifugal pump	300000
Vacuum pump	896500
Reboiler	16630000
Freezing unit	16000000
Rotary drum filter	344500
Fractional distillation unit	33580000
Molecular sieve	35000000
Contigencies (15%)	38670000
Total Capital Investment	1423000000

Figure 25: Capital Costs

The price of valuable products was calculated using prices given in the problem statement and the yearly return expected are summarized below:

Yearly Product Revenue	
Material	Revenue ($/yr)
Naphtha	199500000
Diesel	172800000
LPG	43650000
Fuel gas	9261000
Diesel from sep	194700000
Cooling water recovered	212500
Steam recovered	293900000
Total	913900000

Figure 26: Yearly Revenue

An economic analysis was conducted year-by-year over the 20-year project life. A 3% yearly inflation was applied on the expenses and revenue calculated. A 8% discount rate was applied on the cash flow for each year with a tax rate of 20%. Depreciation was employed as a 7-year straight line calculation write off before taxes. Depreciation values were calculated with an assumption of a salvage value of 10% of the initial expense plus $24000. The NPV was calculated as a net value less the initial investment. A plot of the total NPV over each year in

20-year life span is shown below:

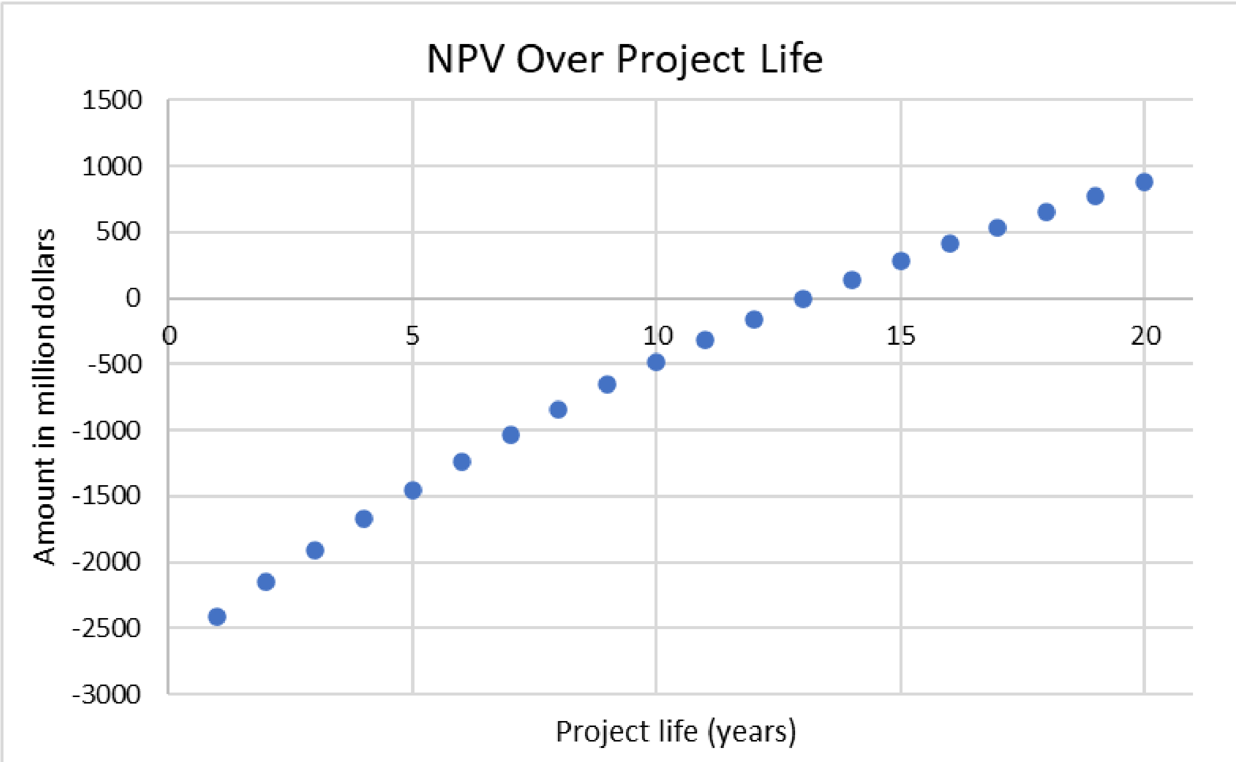


Figure 28: NPV over Project Life

This results in a payback period of thirteen(13) years.

Logistics and Mobilization of Modular Units

Wellhead Deployment

Vast quantities of inconveniently located natural gas is wasted each year in the pursuit of oil, which is far easier to transport. As the oil is harvested, the gas is released and hopefully flared, contributing to carbon emissions without producing any beneficial products or energy. Gasses are simply much more difficult to transport economically than liquids.

Fischer Tropsch technology allows syngas to be converted into liquid fuels. Natural gas can be converted into syngas through the water gas shift reaction. An obstacle to utilizing these processes in remote locations is the difficulty and cost of building a stick built plant in such an inconvenient area. This can be remediated by using modular manufacturing, producing the major process equipment as transportable modules which can be shipped to and assembled on the site of interest with relative ease. Modular manufacturing also provides the benefit of cheaper equipment if the models are mass produced.

Wellhead	Deployment Time (years from project start)
A1	12
B1	6
C1	4
D1	6
E1	10
F1	0
G1	8
H1	10
A2	16
B2	0
C2	3
D2	14
E2	18
F2	0
G2	14
H2	12

Figure 29: Wellhead Deployment

Plot Layout

<u>Floor Plan</u>

Labels on the floor plan correspond to the equipment IDs:

Figure 29: Floor Plan

Sensitivity Analysis

One parameter that had a significant change in the NPV and capital costs of the plant is changing the Lang factor to 1.7. The current economic analysis is based on the Lang factor for a stick built plant at 4.8. If the capital costs were calculated based on the Lang factor for a prefabricated modular plant at 1.7, the capital costs decrease by 65% from $1,422,878,926 to $503,936,286.30. The total costs correspondingly decreased from $1,974,377,793 to $1,027,866,875. Furthermore, the NPV increased significantly. The payback period drops from 13 years to 4 years as shown by the graph below. Due to the significant economics savings predicted from using a prefabricated modular plant, switching over to that option from the current option of using a stick-built model is highly recommended.

Figure X

Capital costs	
Existing units	
	Amount ($)
SU	94367919.82
HIU	34927229.55
Equipment	
Centrifugal pump	412400
Condenser	12388000
Compressor	6183400
Cryogenic Distillation	1744000
FTR Reactor	5000000
Centrifugal pump	300000
Vacuum pump	896500
Reboiler	16626000
Freezing unit	16000000
Rotary drum filter	344472
Fractional distillation unit	33578000
Molecular sieve	35000000
Total Capital Investment	1422878926

Figure 30: Capital Costs for Sensitivity Analysis

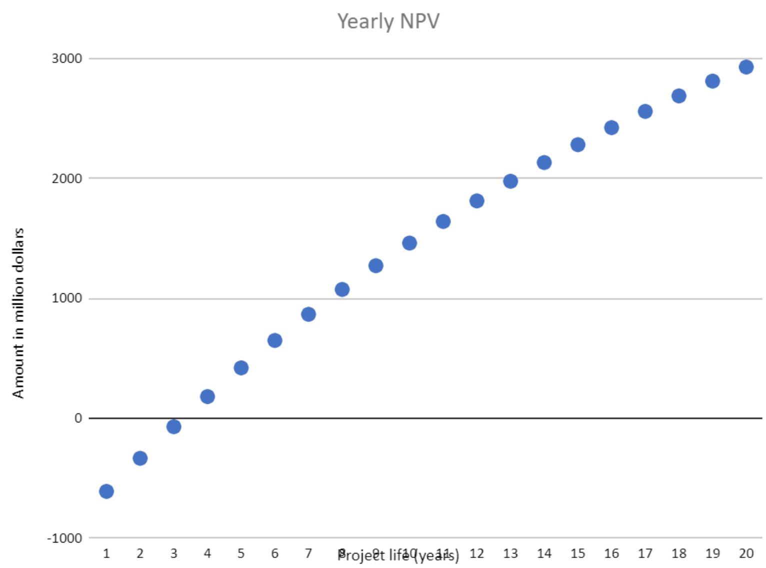


Figure 31: Yearly NPV for Sensitivity Analysis

The sale of liquid oxygen extracted from the cryogenic distillation process will yield an additional $476, 800. As a result, the revenue will decrease by 0.0052% from -$9,150,432,987 to -$9149956190. As demonstrated by the graph below, the savings from the sale of oxygen were not significant enough to make up for the large negative revenue.

Yearly product gain	
Material	Revenue ($/yr)
Naphtha	199450961.5
Diesel	172767187.2
LPG	43650573.4
Fuel gas	9261332.162
Diesel from sep	194661402.1
Cooling water recovered	212544.8631
Steam recovered	2.94E+08
Oxygen Sold	476800
SUM	914342028.5
Profit	-9149956187

Figure 32: Yearly Product Revenue for Sensitivity Analysis

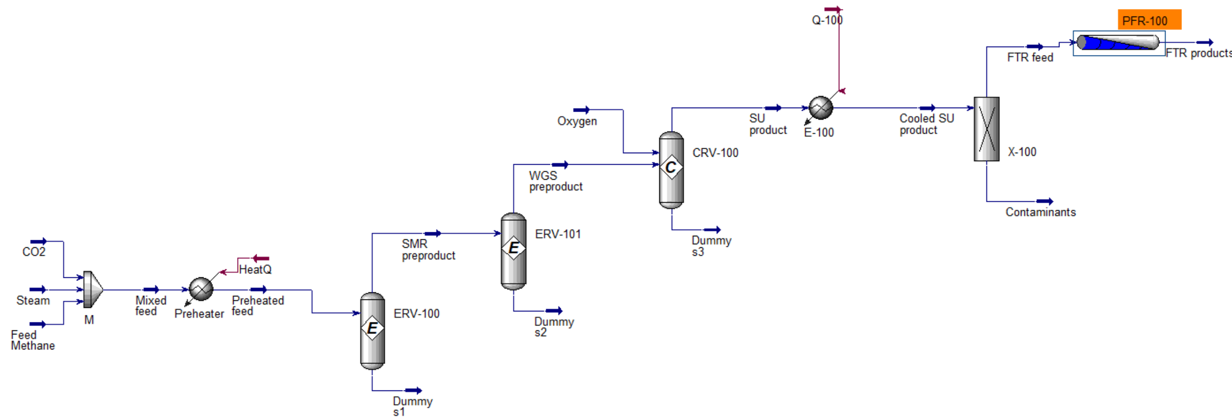
Conclusion

We compiled a preliminary design package to successfully convert a pure methane feed to an array of valuable liquid paraffins products. The liquid products as well as recovered utilities can be sold to produce revenue with an estimated payback period of 13 years. The economic analysis shows a net profit of about one trillion dollars at the end of the project life as economic justification for the project. Additional (environmental)justification is that the project presents an alternative to flaring of natural gas which contributes to accumulation of CO_2 in the atmosphere.

Appendix

A.1 Engineering Calculations and Simulation Outputs

ASPEN Simulations



Preliminary process simulations were run on Aspen. The feed streams were mixed then preheated. The Syngas unit was simulated using two equilibrium reactors and one conversion reactor. The preheated stream (at 1000F) was fed into the 1st equilibrium reactor set to simulate the steam methane reforming reaction. The 2nd equilibrium reactor simulates the water shift gas reaction and the conversion reactor attempts to simulate the partial oxidation of methane. The products were then cooled by utility type cooling water then fed into the FTR unit. The FTR unit was simulated by a Plug Flow reactor. More in depth calculations were carried out using Excel and MATLAB.

Reaction Calculations

Syngas Unit

The SU is designed to convert methane to synthesis gas in the ratio desired for the FTR unit, H2:CO - 2:1 molar ratio. The three primary reactions are:

SMR: $$CH_4 + H_2O \leftrightarrow CO + 3H_2$$

WGS: $$CO + H_2O \leftrightarrow CO_2 + H_2$$

PO: $$CH_4 + \frac{3}{2}O_2 \rightarrow CO + 2H_2O$$

Equilibrium information was referenced from a case study on chemical reactor design by Howard Rase. The equilibrium equations used for the Steam Methane Reforming (SMR) reaction are :

$$K_{eq} = exp(30.53 - \frac{4.8486\times10^4}{T} + \frac{2.421748\times10^6}{T^2} + \frac{2.49\times10^9}{T^3})$$

$$Q = \frac{(n_{H_2})^2(n_{CO})P^2}{(n_{CH_4})(n_{H_2O})(n_{Total})^2}$$

The equilibrium equations used for the Water Gas shift reaction are:

$$K_{eq} = exp(-\ 2.930632 + \frac{3606.211}{T} + \frac{5.02424\times10^{6}}{T^{2}} - \frac{1.815388\times10^{9}}{T^{3}})$$

$$Q = \frac{(n_{H_2})\ (n_{CO_2})}{(n_{CO})(n_{H_2O})}$$

Energy balance:

	ni (mol/day)	Hi (kJ/mol)	niHi	no (mol/day)	Ho (kJ/mol)	noHo (kJ/day)
CH4	3.6600E+08	-28.12338494	-1.0293E+10	26000000	-2.601525316	-67639658.21
CO2	8.0000E+06	-351.6409318	-2.8131E+09	3.0000E+06	-322.2050268	-966615080.5
H2O	1.8300E+08	-210.2869292	-3.8483E+10	178000000	-186.0807177	-33122367746
O2	3.0000E+08	27.1582881	8.1475E+09	1.3500E+08	31.25344291	4219214792
N2	3.0303E+06	25.55591954	7.7442E+07	3.0303E+06	42.62449606	129165139.6
CO		-84.61637241	0.0000E+00	345000000	-67.34876297	-23235323226
H2		24.04606456	0.0000E+00	685000000	39.19411619	26847969592

FTR Unit

The products of the FTR were calculated using the reaction rate equation and selectivity equations given in the problem statement. Calculations were conducted in MATLAB and Excel. The amounts produced are summarized in the table below:

	Selectivity	**Weight fraction**	**Mole fraction**	**Amount (mol/day)**
H2O				345000000
n (in CnH2n+2)				
1	0.093957864	0	0	32415463.2
2	0.003758315	0	0	1296618.528
3	0.003758315	0	0	1296618.528
4	0.003758315	0	0	1296618.528
5	0	0.030859078	0.064177349	1456236.94
6	0	0.033469702	0.058005533	1316193.359
7	0	0.035292813	0.05242725	1189617.506
8	0	0.036455737	0.047385419	1075214.217
9	0	0.037068589	0.042828452	971812.8775
10	0	0.037226413	0.03870972	878355.4516

11	0	0.037011061	0.034987079	793885.6514
12	0	0.036492847	0.031622437	717539.1538
13	0	0.035732015	0.028581366	648534.7561
14	0	0.034780021	0.02583275	586166.3821
15	0	0.033680669	0.023348462	529795.858
16	0	0.032471106	0.021103085	478846.3817
17	0	0.031182697	0.01907364	432796.6212
18	0	0.029841793	0.017239364	391175.38
19	0	0.028470406	0.015581487	353556.7757
20	0	0.0270868	0.014083044	319555.8822
21	0	0.025706009	0.012728704	288824.7909
22	0	0.024340287	0.011504609	261049.0512
23	0	0.022999506	0.010398232	235944.4525
24	0	0.021691499	0.009398253	213254.116
25	0	0.020422362	0.008494441	192745.8667
26	0	0.019196717	0.007677546	174209.8574
27	0	0.018017936	0.006939211	157456.4214
28	0	0.01688834	0.00627188	142314.132
29	0	0.01580937	0.005668725	128628.0482
30	0	0.014781737	0.005123575	116258.1295
31	0	0.013805545	0.00463085	105077.8027
32	0	0.012880405	0.00418551	94972.66705
33	0	0.012005524	0.003782997	85839.32338
34	0	0.011179793	0.003419193	77584.31627
35	0	0.010401849	0.003090376	70123.17775
36	0	0.009670137	0.00279318	63379.56296
37	0	0.008982961	0.002524565	57284.46899
38	0	0.008338521	0.002281783	51775.5288
39	0	0.007734953	0.002062348	46796.37308
40	0	0.007170356	0.001864016	42296.05345
41	0	0.006642816	0.001684757	38228.52113

42	0	0.006150428	0.001522737	34552.15579
43	0	0.005691309	0.001376298	31229.33962
44	0	0.005263614	0.001243942	28226.07247
45	0	0.004865545	0.001124315	25511.62389
46	0	0.00449536	0.001016191	23058.21876
47	0	0.004151377	0.000918466	20840.75301
48	0	0.00383198	0.000830139	18836.53679
49	0	0.003535621	0.000750306	17025.0623
50	0	0.003260823	0.000678151	15387.79391
51	0	0.003006181	0.000612934	13907.97857
52	0	0.002770358	0.000553989	12570.47429
53	0	0.002552091	0.000500713	11361.5953
54	0	0.002350183	0.000452561	10268.97194
55	0	0.002163506	0.000409039	9281.424125
56	0	0.001991	0.000369702	8388.846935
57	0	0.001831663	0.000334149	7582.107222
58	0	0.00168456	0.000302014	6852.950159
59	0	0.00154881	0.00027297	6193.914765
60	0	0.00142359	0.000246719	5598.257572
61	0	0.001308131	0.000222992	5059.883617
62	0	0.001201713	0.000201548	4573.284078
63	0	0.001103665	0.000182165	4133.479906

(All heat of combustion, heat of Formation and specific heat capacity values were referenced from the NIST webbook)

A.2 Economic Analysis Calculations

Years	Expenses	Income	Cash flow (EBITDA)	Discounted cash flow	Tax	Earnings	NPV	NPV-II
1	1974377793	913865228.5	-1060512565	-981956078.7	0	-981956078.7	-981956078.7	-2404835005
2	568043833.5	941281185.4	373237351.8	319990870.9	63656472.57	256334398.3	-725621680.3	-2148500606
3	585085148.5	969519620.9	384434472.4	305176478.7	60693594.13	244482884.6	-481138795.7	-1904017722
4	602637703	998605209.5	395967506.5	291047938.1	57867886	233180052.1	-247958743.7	-1670837670
5	620716834.1	1028563366	407846531.7	277573496.5	55172997.68	222400498.8	-25558244.89	-1448437171
6	639338339.1	1059420267	420081927.7	264722871.6	52602872.71	212119998.9	186561754	-1236317172
7	658518489.3	1091202875	432684385.5	252467183.1	50151735.01	202315448.1	388877202.2	-1034001724
8	678274044	1123938961	445664917.1	240778887.6	48155777.52	192623110.1	581500312.3	-841378614
9	698622265.3	1157657130	459034864.6	229631716.9	45926343.38	183705373.5	765205685.8	-657673240
10	719580933.2	1192386844	472805910.5	219000618.9	43800123.78	175200495.1	940406180.9	-482472745
11	741168361.2	1228158449	486990087.9	208861701.4	41772340.27	167089361.1	1107495542	-315383384
12	763403412.1	1265003203	501599790.5	199192178.1	39838435.63	159353742.5	1266849284	-156029641
13	786305514.4	1302953299	516647784.2	189970318	37994063.61	151976254.4	1418825539	-4053387.05
14	809894679.9	1342041898	532147217.7	181175395.9	36235079.18	144940316.7	1563765856	140886930
15	834191520.3	1382303155	548111634.3	172787646.1	34557529.22	138230116.9	1701995973	279117047

16	859217265.9	1423772249	564554983.3	164788218	32957643.61	131830574.4	1833826547	410947621
17	884993783.8	1466485417	581491632.8	157159133.9	31431826.77	125727307.1	1959553854	536674928
18	911543597.4	1510479979	598936381.8	149883248	29976649.61	119906598.4	2079460452	656581527
19	938889905.3	1555794379	616904473.2	142944208.8	28588841.76	114355367	2193815820	770936894
20	967056602.4	1602468210	635411607.4	136326421.3	27265284.27	109061137.1	2302876957	879998031

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