AIChE The Global Home of Chemical Engineers

2021 - 2022

Student Design Competition Problem Statement & Rules

If there are any questions about the design problem, Student Chapter Advisors and Design Assignment Instructors are directed to contact studentchapters@aiche.org.

Please read the rules before preparing and submitting the solution to AIChE.

AIChE 2021 - 2022 Student Design Competition

Dear Chemical Engineering Department Heads and Student Chapter Advisors,

We are pleased to send you the 2021 - 2022 AIChE Student Design Competition statement. Please forward this problem statement to those faculty teaching design courses.

In order to maintain the integrity of this competition, all Chemical Engineering Departments are asked to familiarize themselves with these rules before assigning this problem to students. **Chemical Engineering Departments, including advisors, faculty, or any other instructors, cannot provide technical aid specifically directed at the solution of the AIChE Student Design Competition if students plan on submitting to the contest. Please inform your Chemical Engineering Department about the rules for this competition so that they do not provide technical aid that would be a violation of the competition rules.**

It is the responsibility of the Design Professor to choose the best solution or solutions, not to exceed two from each category (individual and team), from his or her University and submit them to AIChE for consideration in the contest. The Design Professor will be asked to upload the winning solution(s) using an online form. Design Professors should use the 2022 AIChE Design Competition Entry Form to collect the information needed from each student (including name, AIChE Member ID, contact information and dates of problem assignment/completion).

Please remember that active AIChE Student Membership is required in order for solutions to be considered. All student members must login and renew their membership every year to keep it active. Students can join or renew online at http://www.aiche.org/students/. Any non-member submissions will not be considered.

All solutions must be submitted no later than **11:59 pm US Eastern Time** on **Friday, June 10, 2022.**

- Team Submissions:
  https://aiche.formstack.com/forms/2022_student_design_competition_team

- Individual Submissions:
  https://aiche.formstack.com/forms/2022_student_design_competition_individual

If there are any questions, please contact AIChE at studentchapters@aiche.org. Thank you for your support of this important student competition.

Sincerely,
Harpreet Singh
AIChE Student Programs

2021 – 2022 AIChE Student Design Competition Rules

1. The 2021 - 2022 Student Design Competition is designed to be solved either by an individual chemical engineering student working entirely alone, or a group of no more than four students working together. Solutions will be judged in two categories: individual and team.
2. A period of no more than **ninety (90) days** is allowed for completion of the solution. The finished report should be submitted to the faculty advisor within the 90-day period. Students & faculty advisors should include the date assigned & the date completed along with their signature on the competition entry form.
3. It is to be assumed that the statement of the problem contains all the pertinent data except for those available in handbooks and literature references. The use of internet, textbooks, handbooks, journal articles, and lecture notes is permitted.
4. Students may use any available commercial or library computer programs in preparing their solutions. Students are warned, however, that physical property data built into such programs may differ from data given in the problem statement. In such cases, as with data from literature sources, values given in the problem statement are most applicable. Students using commercial or library computer programs or other solution aids should so state in their reports and include proper references and documentation. Judging, however, will be based on the overall suitability of the solutions, not on skills in manipulating computer programs.
5. **Chemical Engineering Departments, including advisors, faculty, or any other instructors, cannot provide technical aid specifically directed at the solution of the AIChE Student Design Competition if students plan on submitting to the contest. For example, if the problem statement asks for students to design a Hydrogen production process, faculty members should not be directly telling the students how to design this process or suggesting to them which process to use.**

   Students are permitted to ask generalized questions to faculty members and outside experts while working on this problem. For example, if students are designing a Hydrogen production process and they have 2 production methods in mind, the students may ask a Faculty Member and/or professional with expertise in Hydrogen production about their experiences working with the different methods so that they can make an informed decision on which method to choose for their design. Students are also permitted to ask for assistance on how to use process simulation software. If there are any questions about the distinction of what aid can be provided to students who are working on this problem for the contest, please contact studentchapters@aiche.org.

6. **All students working on this problem statement are asked to not share or discuss the topic of this problem statement with other students from their University or from other Universities while they are working on the problem. Students should be aware that sharing the problem statement topic with students from other Universities might be giving those other Universities an unfair advantage in this competition, as those Universities may not**

have started their 90 day time limit yet. If there are any questions about this rule, please contact studentchapters@aiche.org.

7. Solutions will be graded on (a) substantial correctness of results and soundness of conclusions, (b) ingenuity and logic employed, (c) accuracy of computations, and (d) form of presentation.
8. Accuracy of computations is intended to mean primarily freedom from mistakes; extreme precision is unnecessary.

2021 - 2022 AIChE Student Design Competition Eligibility

- Please remember that active AIChE Student Membership is required in order for solutions to be considered. All student members must login and renew their membership every year to keep it active. Students can join or renew online at http://www.aiche.org/students/. Any non-member submissions will not be considered.
- Entries must be submitted either by individuals or by teams of no more than four students.
- Each Faculty Advisor should select the best solution or solutions, not to exceed two from each category (individual and team), from his or her University and submit them per the instructions.

2021 - 2022 AIChE Student Design Competition Timeline

- A period of no more than ninety (90) days is allowed for completion of the solution.
- The finished report should be submitted to the faculty advisor within the 90-day period.
- Students & faculty advisors should include the date assigned & the date completed along with their signature on the competition entry form.

2021 - 2022 AIChE Student Design Competition Report Format

Preliminary Design Package Requirements:

A summary report should be provided which includes not only a recommendation but also identification of key assumptions, sensitivity to those key assumptions, sketches of modular internal layout, plot layout for the typical wellhead equipment and other details. This should include supporting drawings & figures, tabled data, flowsheets, equipment sizing calculations, a site material & energy balance, etc. A minimum table of contents is shown below.

1. Letter of Transmittal
2. Title Page
3. Table of Contents
4. Executive Summary (w/ specific reference to design objectives)
5. Introduction
6. Summary
7. Discussion
8. Conclusions
9. Recommendations
10. Project Premises
11. Heat and Material Balance
12. FTR Unit Process Flow Diagram
13. Simplified GTL Plant Process Flow Diagram - Illustrating heat integration and stream flows & compositions between all units in GTL plant
14. Safety/Environmental Summary
    a. Inherent Safety Evaluation
    b. Process Safety Management
        i. Process hazards
        ii. P&ID of the Major Fractionator
        iii. Uncongested Vapor Cloud Deflagration
    c. c. Safety Summary
15. Equipment Information Summary – with enough design information to cost equipment
16. Unit Control and Instrumentation Description
17. Economics - In addition to DCF, include a summary of operating costs, utility requirements and energy efficiency
18. Description of well development plan, modular unit deployment and redeployment, retiring of equipment, optimization of well production and other logistics considerations
19. Include an expected plot layout for the wellhead site system
20. Summary of project NPV and sensitivities to key assumptions
21. Engineering Calculations, Computer Simulation Outputs
22. References

- **The solution itself should not reference the students' names or University. Please expunge all such references from the solution. This is so the solutions can be anonymous to the graders when they are choosing the winners.**
- Final submission of solutions to AIChE must be in electronic format (PDF and MS-Word). The main text must be 50 pages or less, and an additional 100 page or less is allowed for supplementary material only. The final submission to AIChE must consist of no more than 2 electronic files.
- There should not be any variation in form or content between the solution submitted to the Faculty Advisor and that sent to AIChE. The Student Chapter Advisor, or Faculty Advisor, sponsoring the student(s), is asked to maintain the original manuscript(s).

2021 - 2022 AIChE Student Design Competition Submission Instructions

1. Use the accompanying word document titled "2022 AIChE Design Competition Entry Form to collect the information needed from each student (including name, AIChE Member ID, contact information and dates of problem assignment/completion).

2. Upload the solution file(s) and entry form documents online by **11:59 pm US Eastern Time** on **Friday, June 10, 2022.**
   - Team Submissions: https://aiche.formstack.com/forms/2022_student_design_competition_team

   - Individual Submissions: https://aiche.formstack.com/forms/2022_student_design_competition_individual

2021 - 2022 AIChE Student Design Competition Awards

There are two categories of awards to be given in both the individual and team categories. The first category is for the best overall design. There are additional awards available for the best application of inherent process safety principles in the design.

Below is a complete list of awards available for the 2021 - 2022 AIChE Student Design Competition:

- Team Awards, Best Overall Design
  - 1st Prize (The William Cunningham Award)-$600 *to be divided equally among team members* & Certificate

    - Honorable Mention - Certificate
- Individual Awards, Best Overall Design
    - 1st Prize (The A. McLaren White Award)-$500 & Certificate
    - 2nd Prize (The A.E. Marshall Award)-$300 & Certificate
    - 3rd Prize (The Omega Chi Epsilon Award)-$200 & Certificate
- Safety and Health Division Student Design Competition Award for Safety
    - 4 awards available (from both individual & team submissions)- $600 *to be divided equally among team members* & Certificate
    - Team Design Award (The Jack Wehman Design Award)- $300 *to be divided equally among team members* & Certificate
    - Individual Design Award (The Walter Howard Design Award)- $200 & Certificate

2021 - 2022 AIChE Student Design Competition Problem Statement

Modular Distributed Gas-to-Liquids (GTL) Synthesis

Introduction

The world today is facing some daunting global challenges including a viral pandemic, an unstable and changing climate, accumulation of synthetic plastics and growing disparity between the developed and less-developed countries. Chemical engineers are positioned to help address these challenges by thoughtful application of new technology and new design concepts. Future design constraints will include not only economics and function but also an increasing emphasis on safety and sustainability. With respect to climate change, one contributing factor is the handling of associated natural gas from stranded oil production. Stranded oil and gas are resources located too far from conventional gathering pipeline systems to be economically collected. Based on 2019 data reported by the US Energy Information Administration (EIA) approximately 430,000 oil wells produced 3.9 billion barrels of oil and 6.5 trillion cubic feet (tcf) of associated gas. Because the natural gas cannot be collected and must be produced along with the associated oil, the only alternative is to burn it using an on-site flare. Estimates report that as much as 30% of the associated natural gas is flared for disposal which amounts to perhaps 2.0 tcf, potentially producing about 111,000 metric tons of carbon dioxide per year and, therefore, contributing to the accumulation of CO_2 in the atmosphere. Because methane (CH_4) has almost 25 times the greenhouse contribution pound-for-pound compared to CO_2, the impact is amplified if CH_4 is vented to the atmosphere and not flared.

The challenge of this project is to design a modular system which could be positioned at the wellhead and would be capable of converting stranded natural gas into a liquid material; designing the system as a positive contributor to reducing greenhouse gases; and then optimizing the deployment of the equipment into the field. A liquid material can easily be collected and stored on site and periodically gathered by a service vehicle. Conceptually there are many options for the final liquid product including ammonia, methanol, and other hydrocarbon liquids. These have been studied extensively and are based on conversion of CH_4 into synthesis gas (CO/H_2 mixture) as the feedstock used for final conversion. Each conversion process is being investigated and is in various stages of pilot trials. This project focuses on conversion of CH_4 into a higher molecular weight hydrocarbon that could be used as a conventional liquid fuell. It involves making synthesis gas and then utilizing Fischer-Tropsch Liquid (FTL) technology to create higher carbon chain molecules with the addition of necessary hydrogen (H_2). The work is based on the 2011 AIChE Student Design problem which focused on a large single train Gas-To-Liquids (GTL) plant capable of processing 500 MMSCF/day of natural gas. This year's challenge is to design a *small modular system* which is scalable and capable of running as little at 500 MSCF/day or as much as 5,000 MSCF/day of natural gas feed. This will include three options for module sizes based on a feed of 500 MSCF/day (small unit), 2,500 MSCF/day (medium unit) and 5,000 MSCF/day (large unit). In addition, beyond the equipment design, the problem involves consideration of the deployment strategy for the equipment both initially but also over the entire project life. The overall goal is to maximize the equipment utilization and financial return while acknowledging an overall desire to maximize sustainability. Furthermore, part of the project will be to examine the risk parameters for a changing demand profile for a single wellhead and system of wells. A key part of this analysis will be examination of the project sensitivity to size of the individual modules.

PROBLEM STATEMENT

This problem includes two parts. The first part is a more conventional process design problem involving design of the FTL and separation sections of the wellhead modular system. To limit the scope of the problem, you will be given some fundamental sizing information on the accompanying syngas unit, the hydro-isomerization unit, the oxygen separation unit, the CO_2 separation system, and the steam system. These latter systems will require sizing with a material and energy balance but will not require individual equipment designs. They can be treated as infrastructure components. The focus on this part of the problem is the design of the FTL reactor, consideration of various reactor design options, process flow and layout for modular fabrication, and the accompanying material and energy balances. Consideration must be given to the process flows but also to properly size various utilities and to manage energy consumption. Because the wellhead flow will vary over a very wide range, the problem will involve designing three different scale modules (a small, a mid-range and a large module). This will allow matching the wellhead production profile at any point by numbering up as well as preservation of capital by redeploying modules as production at any specific wellhead declines. Adoption of three 'standard' sizes takes advantage of fabrication cost learning improvement for repeat fabrication of the same capacity.

The second part of the problem involves an analysis of the supply chain and network aspect for the deployment of the modules to the wellhead in an optimum manner. This will be constrained by each well's natural gas production rate but also their rate of production decline over a 20-year planning horizon. It reflects the benefit of numbering up modules, instead of a single larger unit, and the ability to redeploy modules from declining wells to more productive ones over the course of the project. The ultimate goal is to maximize the net present value (NPV) of the total project investment via clever design and a modular approach. The problem is structured such that the central plant has limited throughput which means that only a few wells can be brought into production at any single time. Managing the specific wells that are in production at any one time as well as closing and opening other well (accompanied by redeployment of equipment) is required to maximize the overall value of the project over the 20-year life.

The unit designs should employ new modular manufacturing methods that are now becoming more common, better understood, and more accepted in the chemical process industry. Modular manufacturing is the concept where complete chemical processes, or sub-sections of chemical processes, can be prefabricated in a shop setting or simultaneously using multiple shops if desired. By comparison, many existing chemical plants are "stick built," meaning they were constructed outdoors at the plant site. Modular manufacturing can offer advantages in terms of time-to-market, quality control, construction labor productivity/safety, and economies of mass production. More details are described below in the economics and environmental permitting sections. Note that a point-of-use, distributed, modular liquids plant will be considerably smaller than conventional, stick-built, centralized plants so loss of economies of scale must also be considered. This is offset by a fabrication cost learning curve, the ability to expand and carefully control capacity by "numbering-up" the modules on site, and the flexibility to readily redeploy assets between well sites.

Please consider the following additional factors when designing the modular plant:

1. The plant may use a "numbering-up" approach that uses smaller scale unit modules that are connected in parallel to provide the total required throughput.
2. As either feedstock availability or product demand changes, this parallel approach offers flexibility to redeploy process units to more productive locations.
3. You may assume that the plant will run continuously, year-round operation at 80% utilization to account for maintenance and equipment/process upsets. Product will be stored on site or possibly some portion consumed on site to meet local energy needs.
4. Where possible in the design, process intensification (PI) concepts should be used to increase efficiency and keep total equipment costs low. This might include novel reactor or separator designs, advanced energetics, or similar design concepts.
5. The process must have as small a carbon footprint as possible. Please make recommendations on how this can be achieved.
6. Safety, financial/technical risk, and environmental aspects should be considered in decisions and recommendations.
7. For the purposes of your economic analysis assume the system will have a 20-year useful plant life, and a Minimum Acceptable Rate of Return (discount rate) of 8%.

Upstream Process

The goal of the upstream process is to produce syngas, CO and H_2. Assuming that stranded natural gas (e.g., methane and other light gaseous hydrocarbons) is the feedstock, the most common process for producing syngas is by steam methane reforming (SMR). The natural gas may require pre-treatment to remove sulfur compounds (e.g., H_2S) before being fed to an SMR reactor but for the purpose of this study assume that the natural gas is pure methane (CH_4). SMR is highly endothermic, and heat must be supplied to the reaction, usually by burning additional natural gas. The SMR reaction (Rxn 1) combines steam (H_2O) with methane (CH_4) to produce carbon monoxide (CO) and H_2. For the syngas to be used in downstream FTL processes, additional H_2 may be required. H_2 yield may be increased by feeding the output of the SMR reactor to a water-gas shift (WGS) reactor (Rxn 2). The stream exiting the WGS reactor must be cleaned up to remove CO_2 and other byproducts to produce a high-purity H_2 stream for further downstream reaction. Various methods may be appropriate for purifying the SMR effluent such as pressure swing adsorption (PSA), chilling/condensation, liquid scrubbing, or others for example.

$$C_nH_m + nH2O \leftrightarrow (n+m/2)H_2 + CO \qquad \text{(Rxn 1)}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \text{(Rxn 2)}$$

An alternative method of producing supplemental H_2 is through the electrolysis of water. Electrolysis is an electrochemical reaction that uses electricity to split water into H_2 and O_2. High-purity H_2 is produced at the cathode and high-purity O_2 is produced at the anode, eliminating the need for downstream separations. If the electricity used to drive the electrolysis is from renewable sources (e.g., stranded wind or solar photovoltaics) the H_2 produced is carbon free. Alternatively, one could use a portion of the fuel at the wellhead to generate electricity for electrolysis or to sell to the local power grid. Electrolysis stacks are formed by packing individual cells which make electrolysis inherently modular. Common electrolysis units are either alkaline or proton exchange membrane (PEM). Electrolysis systems can be relatively expensive, for example PEM electrolysis systems use precious metal catalysts, and capital cost will need to be carefully considered in addition to utility costs and raw material costs. Some information on hydrogen production via electrolysis can be found in the references.

Downstream Process

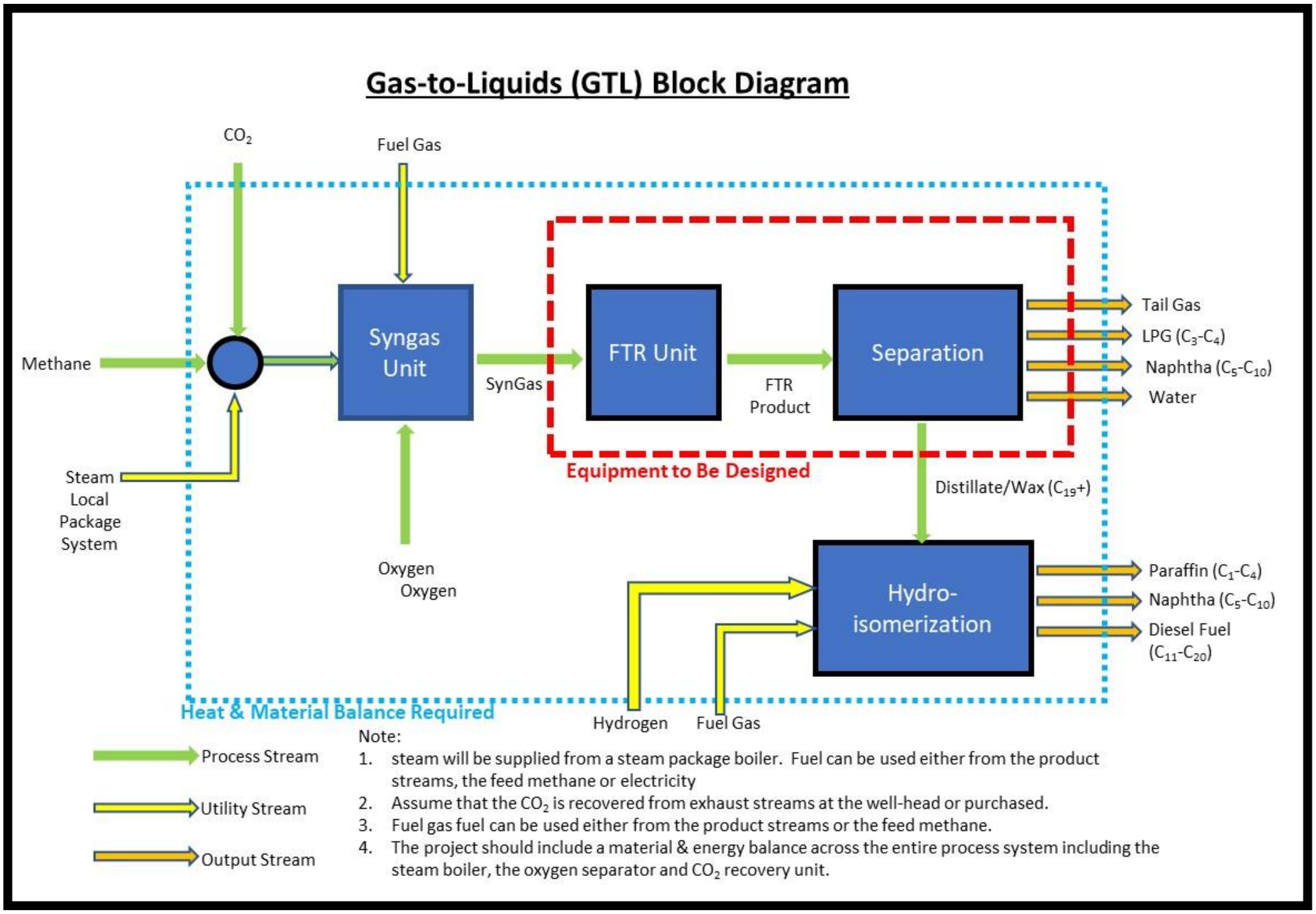
The conversion of syngas (CO/H_2 mixture) to hydrocarbons using Fischer-Tropsch (FT) synthesis is a proven method for the production of liquid fuels. Industrial fuel production using syngas and FT synthesis has been a viable option since the early 20th century, especially when petroleum reserves were unavailable or natural gas and/or coal reserves were abundant. Generation of syngas is possible from an array of carbon sources - coal, biomass, methane, etc. There are operating GTL processing facilities worldwide that convert methane from natural gas to liquid fuel via syngas generation and FT synthesis (3).

As a Process Design Engineer, you have been instructed by your company to provide the preliminary design package for a modular grass-roots Fischer-Tropsch Reaction unit (FTR), including reactor effluent and separation facilities, as part of a planned GTL network. Your company has specifically requested that you design a safe, environmentally clean, thermally integrated FTR with efficient capital and operating cost utilization. In addition, your company expects the FTR to effectively integrate with the other required units within the GTL plant to allow for the economically optimum mixture of naphtha (hydrocarbons C5-C10), a feedstock for gasoline and chemicals, and distillate range hydrocarbons (C11-C20), a feedstock for diesel production. The expectation is that the FT unit will be modular and scalable to allow deployment at several wellhead sites surrounding, but at a distance, the collection center.

Project Background

Your company is considering a GTL plant as an effective option to bring to market newly discovered gas deposits in a remote location. The company has the completed designs for a modular Syngas Unit (SU) and modular Hydro-Isomerization Unit (HI). Although your company is not asking you to design any equipment for the SU and HI, they envision your design for the FTR as an opportunity to improve on the energy efficiency and operating expenses for the GTL plant as a whole.

A simplified diagram of the GTL processes your company is planning is shown in the figure. A key characteristic of the company's strategy involves designing a compact processing system built around modular design concepts. A central refining complex will collect the liquid materials from multiple GTL systems located at various wellheads that are owned by the company but are not yet in production. The liquids will be stored at the wellhead and collected periodically in conventional tank trailers (assume 5,000 gallons capacity) using company contracted equipment and drivers. The modular unit is enclosed in the dotted blue line in the figure.


Gas-to-Liquids (GTL) Block Diagram

Note:

1. steam will be supplied from a steam package boiler. Fuel can be used either from the product streams, the feed methane or electricity
2. Assume that the CO_2 is recovered from exhaust streams at the well-head or purchased.
3. Fuel gas fuel can be used either from the product streams or the feed methane.
4. The project should include a material & energy balance across the entire process system including the steam boiler, the oxygen separator and CO_2 recovery unit.

Design Objectives

You must address and adhere to these specific objectives in the design package:

1) Safety/Environmental – Design must not pose any environmental, health or safety hazards that should have been mitigated with better equipment, instrumentation, or control. Additionally, no non-emergency (continuous) flaring/venting of hydrocarbons is permitted in the design – if necessary, hydrocarbons can be reused in the process.

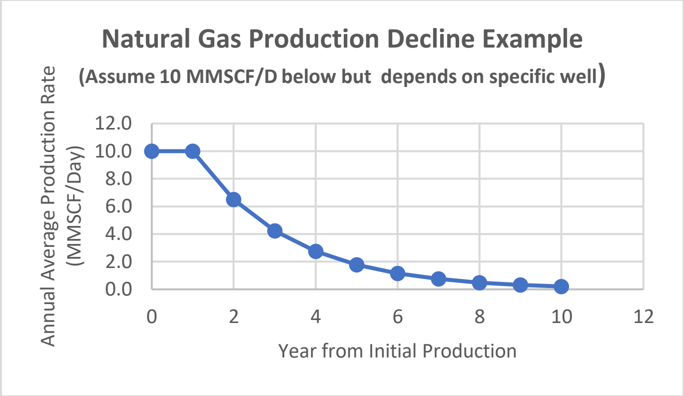
2) Modular Chemical Process Intensification (MCPI) - The design will follow basic tenets for MCPI of small, shop fabricated standalone process units that will allow fast and flexible deployment to multiple locations in the field. It is expected that the technology and design may vary from what is conventionally chosen.

3) Energy Efficiency & Lowest Environmental Impact – Defined as: (mass of carbon in finished products/mass of carbon in methane feed) x 100%. Finished products = Liquefied Petroleum Gas (LPG) + Naphtha + Distillate. Other than safety and environmental performance, energy efficiency is the next most important attribute that will determine acceptance of your design by your company.

4) Optimum Finished Liquid Fuel Production – Appropriate cost/benefit balance is achieved.

5) Economic Analysis (Discounted Cash Flow Rate of Return) - Economic analysis should reflect not only the designed equipment capital investment and expense costs, but also the expense costs of the Syngas, Air Separation Plant and Hydro-Isomerization Unit. In addition, specified capital recovery costs for both the Syngas and Hydro-Isomerization units (see below) will need to be added to the estimated total yearly expense costs. For economic calculations assume:

a) Project Life of 20 years
b) 7-year Straight Line Depreciation from day of start-up
c) 20% Tax Rate
d) Projected 3% yearly inflation
e) Total capital investment can be estimated by multiplying the equipment cost by 4.8. Multiplier will account for all associated direct costs, indirect costs and working capital.
f) Total yearly operating expenses above and beyond utilities can be estimated using 3% of the total capital investment. This estimate will cover fixed charges such as plant overhead costs, administrative costs, distribution & marketing, and research & development
g) The FTL Unit will have a 1-month turnaround every three (3) years to coincide w/ catalyst replacement
h) Variable feedstock source – assume that a given well's natural gas production will be steady for 2 years and then decline sharply by 35% each following year. For ease of analysis assume that the units are being installed on new wells.



i) You may use equipment cost data from textbooks and other public sources indexed as necessary to present the project economics in current dollars.
j) Feasible Design – Even though you are not providing the final design, your preliminary design should be viable as specified.
k) Realistic and Adequate Process Control – Control valves, instrumentation, analyzers, etc. on required equipment to provide safety and minimize personnel. It is not necessary to specify each component in detail; simply identify what they are and where in the process they are required.

Designed/Available Facilities

Syngas Unit (SU)

The SU will be immediately upstream of the FTR. The SU is being designed to convert the natural gas feedstock (actual conditions: 500 psig, 100°F) of clean methane to syngas. The heat required to drive the endothermic reforming reaction as autothermal is supplied in-situ by partial oxidation of methane. Steam and CO2 are required as feedstocks to drive the reforming reaction to the desired molar ratio of H2/CO products. In the SU, three primary reactions occur (1):

1) Steam Reforming: $CH_4 + H_2O \leftrightarrow CO + 3H_2$
2) Partial Oxidation: $CH_4 + 3/2O_2 \rightarrow CO + 2H_2O$
3) Shift Reaction: $CO + H_2O \leftrightarrow CO_2 + H_2$

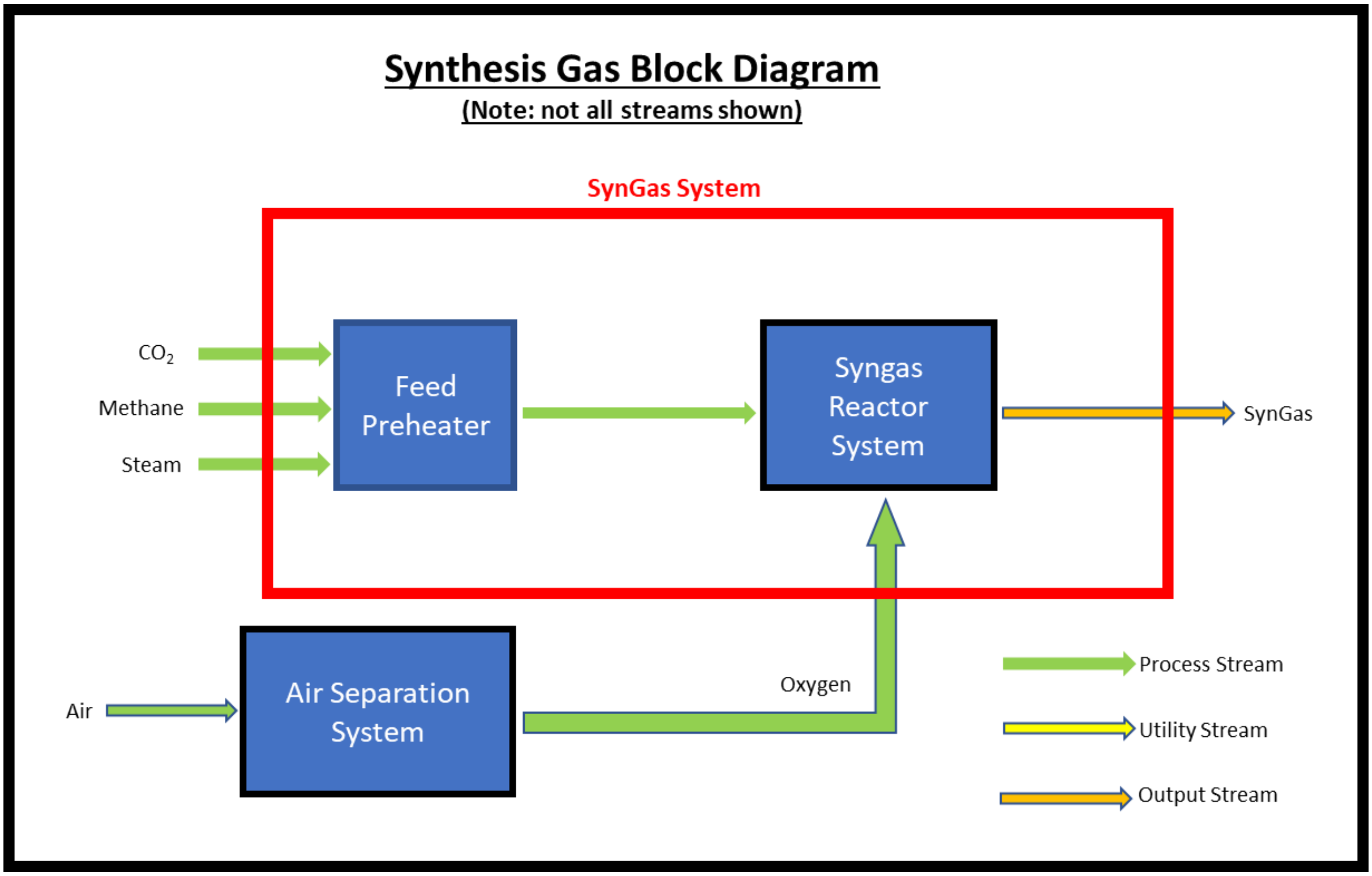
The partial oxidation reaction runs to completion; the other two reactions run to equilibrium. The heat balance determines the amount of oxygen to be supplied. You may assume zero heat losses for the reactor.

These reactions in combination determine the composition of the product gas from the reformer. Operating pressure, temperature, and feed composition will set the overall composition of the synthesis gas. You should consider the following ranges for reformer operating conditions:

- Temperature: 1600 - 1950°F
- Pressure: 300 - 500 psig
- Steam/CH4 in Feed: 0.5 mol/mol minimum to prevent coking in feed preheater

You should target to make syngas at a H2/CO molar ratio equal to the consumption ratio in the FTR (2:1). You will likely find that this requires supplemental CO2 in the feed. There will be a feed preheat furnace available expected to perform at 85% efficiency (efficiency = theoretical heat required / actual heat required). The maximum feed preheat temperature is 1000°F to guarantee metallurgical integrity. 80% of the total variable energy costs for the SU are projected to be from actual preheat furnace firing duty, with the balance to be equally divided between 125 psig steam and electricity.

A basic flowsheet for the SU is:



Air Separation Plant

You are able to purchase oxygen from a third-party packaged (that is, process system as well as gas storage) oxygen plant. The oxygen, feed to the syngas system, is supplied as 99% pure, with 1 mol% nitrogen. The Air Separation Plant owner has offered the following contractual terms:

- Oxygen (500 psig, 99 % purity, 75°F): $100/short ton contained oxygen.
- Energy for oxygen plant pumps and compressors to be provided by the customer as follows:
  - Electricity Option: 1,000 kWh/short ton contained oxygen
  - 600 psig Steam Option: 10,000 lb/short ton contained oxygen

The Air Separation Plant is designed so that the choice of electricity or steam shall be determined by the customer. Cooling water requirement is to be provided by the customer at 400 gpm per short ton/day of oxygen.

Hydro-Isomerization Unit (HIU)

The HI unit for the GTL process is to be downstream of the FTR. After initial separation of products from the FTR, the distillate and heavier boiling fractions (material with greater than 350°F boiling point) are fed to a catalytic hydro-isomerization reactor, where the paraffins are isomerized and wax is converted to lighter products. The process converts 100% of the >700°F boiling point (b.p.) material to <700°F b.p. material, with an overall selectivity of 1.0 wt% methane, 0.5 wt% ethane, 3.5 wt% propane, 3.5 wt% butane, 25 wt% naphtha, and the balance diesel.

Yields are expressed as overall reactor products, based on the amount of >700°F in the feed as shown in the example in the table.

Feed	**Basis**	**Product**
C_1		70*1%
C_2		70*0.5%
C_3		70*3.5%
C_4		70*3.5%
Naphtha		70*25%
Diesel	30	balance
700+°F	70	zero

The HIU catalyst selected for this unit is very selective to >700°F b.p. material. You are to assume that any <700°F b.p. material in the feed to the HIU will essentially pass through the HIU and remain unconverted. The catalyst is sensitive to H2O and CO; therefore, the liquid feed to the hydro-isomerization reactor must not have any free water above the solubility limit and the makeup gas should have a CO content no greater than 0.1 mol%.

The utility and make-up hydrogen requirements for the HI Unit are:

- Fuel gas: 0.08 MBTU/bbl of feed
- Hydrogen: 300 SCF/bbl of feed
- Steam (125 psig): 10 lbs/bbl of feed
- Electricity: 2.5 kWh/bbl of feed
- Cooling Water: 300 gal/bbl of feed

FTR Unit/GTL Fischer-Tropsch Reaction

Reaction

In the FTR, the syngas is converted to hydrocarbons and water by reactions with the following generic format:

$$xH_2 + CO \Rightarrow H_2O + (CH_2)_nH_2$$

CO Conversion Kinetics

Your company has developed an ultra-stable Cobalt-based FTR catalyst that you are evaluating for a proposed commercial plant. In lab tests it was determined that the overall rate equation is best fit by a Langmuir-Hinshelwood form with parameters as follows (7):

$$-r_{CO} = \frac{k * T_1 * P_{H2} * P_{CO}}{(1 + k_2 * T_2 * P_{CO})^2}$$

T_1 = Exp[-4492 * (1/T - 1/473)], T in K

T_2 = Exp[8237 * (1/T - 1/473)], T in K

k = 0.0173 gmol CO / hr·cm^3 cat·atm^2
(catalyst bulk density = 0.8 g/cm^3)

k_2 = 4.512 atm^{-1}

P_{H2}, P_{CO} = partial pressures in vapor phase, atm

T = Reactor operating temperature

For estimation of vapor phase components in the kinetics, you may assume that the vapor phase contains 100% of the H_2, CO, H_2O, CH_4, N_2 components, and 0.7 moles of C_2+ hydrocarbons for every mol of CH_4 made.

The reaction temperature will be determined by the feed temperature, the heat of reaction and heat transfer out of the tube and may vary along the length of the reactor. Information on heat transfer characteristics is provided below.

Product Selectivity

You can assume the products of the hydrocarbon synthesis reaction are all alkanes. The distribution of C_5+ products is characterized by the Anderson-Schulz-Flory (ASF) probability distribution as follows:

$$W_n/n = [(1-\alpha)^2/ \alpha]\, \alpha^{n}$$

or,

$$M_n = (1- \alpha)\, \alpha^{n-1}$$

α = ASF chain growth parameter

W_n = relative weight fraction of carbon number n

M_n = relative mol fraction of carbon number n

The selectivity of methane does not follow the ASF distribution, but instead is dependent upon temperature over the range of 390-450°F as follows:

$$S_{CH4} = rCH_4/-rCO = (0.03)T_3 \text{ (mol/mol)}$$

$$T_3 = \exp[-10000(1/T - 1/473)], \text{ T in K}$$

The ASF parameter is slightly temperature dependent and varies with the average reactor temperature as follows:

$$\alpha = (0.93)T_4$$

$$T_4 = \exp[250(1/T - 1/473)],\ T \text{ in K}$$

The selectivity of C_2-C_4 alkanes are linked to CH_4 selectivity as follows:

$$SC_n = (0.04)*SCH_4 \ \ \text{mol/mol} \qquad n=2,3,4$$

You have found that, typical for cobalt-based catalysts, CO_2 selectivity is negligible.

Catalyst

The catalyst you will be using has been formulated into 1/16-inch diameter extrudates, with a packed bulk density of 0.8 g/cm^3 and a void fraction of 0.4. Equivalent diameter is 0.08 inches. Cost is $10/lb. Assume replacement every 3 years. If desired the catalyst can be provided as particles having an average diameter of 25 to 250 microns. The catalyst can also be suspended in a 'washcoat' to be applied to catalyst surfaces for different reactor design configurations. If using a washcoat the catalyst will require replacement/refresh every 2 years.

The catalyst is an ultra-stable formulation - with low deactivation rates - and the activity (as set by the kinetic equation) can be taken as the average activity for the life of the catalyst.

Reactor Engineering

Because the reaction is highly exothermic, a tubular fixed bed reactor cooled by boiling water is often used in large scale 'stick-built' plants. A practical limit for the size of these reactors is 20 ft. in diameter and 60 ft. in length (tangent to tangent). However, this size is too large for a single modular unit. Consideration of the number of modules per system as well as the reactor type and configuration are part of the problem. You need to determine the number of reactors needed per module and the optimum arrangement of the reactors (number of stages in series and number or reactors per stage). You may also consider alternative reactor designs using such as fluidized beds, micro-channels, or others.

Reactor Heat Transfer

The reaction is highly exothermic, with a heat of reaction of 70,200 BTU/lb-mol CO converted. Temperature can be controlled by adjusting boiling water pressure on the shell side of a reactor, by air cooling, or some other method of heat removal. Normal operating conditions for both process and shell sides should be optimized to maximize process performance and minimize investment costs. You may assume, for this problem that the shell side operates isothermally.

If boiling water is used, then the heat transfer coefficient is controlled by process side conditions and found that an empirical relationship exists for the overall coefficient as follows:

$$U_0 = 0.385*G^{0.8}/D^{0.2}$$

U_0 = Overall heat transfer coefficient, BTU/hr·F·ft^2

G = Inlet gas mass velocity, g/h/cm^2

D = Tube diameter, cm

If a shell & tube exchanger is employed, then you may consider tube diameters no larger than 2 in.

Reactor Pressure Drop

Bed pressure drop should be calculated, and pressure loss should be accounted for in the kinetics. Assume fluid properties are constant through the reactor and are equal to the properties at the inlet, neglecting the reaction. To account for the contribution of the liquid on overall pressure drop, assume total pressure drop is 1.5 times the gas phase pressure drop. Maximum allowable pressure drop per reactor is 50 psi.

Mass Transfer

You have found that due to the particular formulation of your catalyst that mass transfer effects are small and can be ignored.

Feed Temperature Control

The temperature of the syngas from the SU must be lowered before being fed to the FTR reactor(s). It is recommended that this is accomplished using a waste heat boiler (steam generator) in series with an air- or water-cooled heat exchanger.

Product Separation

You will need to design the facilities to separate the desired products in the reactor effluent from unconverted feed and water. Distillate and heavier boiling (>350°F) fractions are solid at room temperature and must be kept above 250°F prior to isomerization to prevent wax crystallization. Naphtha and lighter components can be collected for direct shipment without temperature concern. Water should be separated for disposal and/or reuse.

Utilities

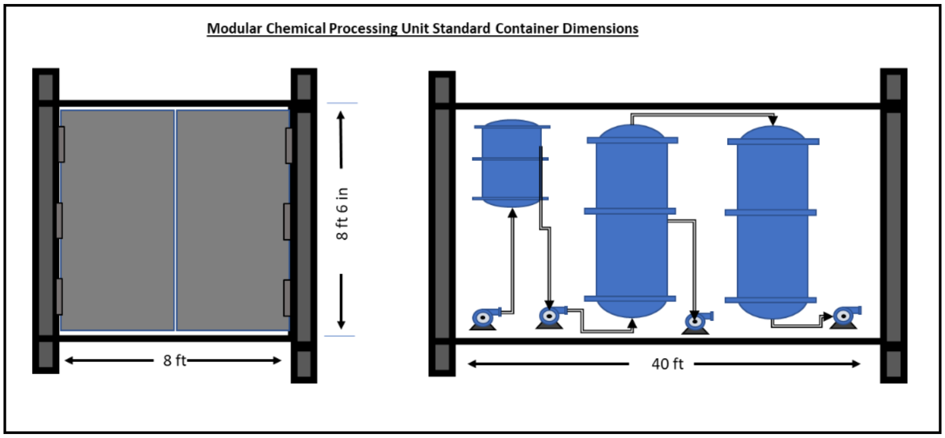
The SU, HIU, Air Separation Plant and FTR unit will all have full access to your company's utility grid, which can provide and (in some cases) accept any utilities generated during the process, provided that specific conditions are met. If multiple hydrocarbon streams produced in the process are used as fuel gas, then each hydrocarbon stream will be valued at its respective BTU/lb heating value. Typical cooling water make-up rate is 0.025-gallon make-up per gallon of water circulating. The boiler feed water blowdown rate is 3% of total mass of steam produced. Boiler feed water blowdown cannot be reused for boiler/steam, but can be used as cooling water makeup. Carbon dioxide may not be returned for credit.

Modular Plant Economic Considerations

Estimation of plant capital costs can be performed using heuristic methods (incorporated in process design software or printed charts and tables), by requesting vendor quotes, or a combination of methods. For expediency, heuristic methods are preferred during early stages of the front-end engineering design process. There are several challenges present when estimating the capital costs of small modular plants. First, heuristic approaches often use power law scaling equations (e.g., the "six-tenths" rule) to scale the capital cost based on capacity, but many of these correlations were made for conventional, large process equipment. Extrapolation of these correlations to smaller sizes may incur additional uncertainty, and this should be noted and addressed in your report. A good way to address uncertainty in your assumptions is through a sensitivity study. Second, the correction factors (e.g., Lang factors, Guthrie factors, or similar) used to go from purchased equipment costs to installed costs in most texts are tailored to the stick-built rather than modular-manufactured construction methods. As such, the individual contributions to installation factors should be examined critically to assess whether they apply to modular manufacturing. When in doubt, the factor should be included to be conservative. Nevertheless, construction and engineering costs are expected to be lower for a modular plant compared to a stick-built plant. For example, Weber and Snowden-Swan [14] used a Lang factor of 1.7 for a prefabricated modular plant installed at an existing site, while Lang factors for stick-built plants are usually in the 3–5 range.

For the purposes of this design project, you may consider two types of modular manufacturing, which we refer to as "*unitary modular manufacturing*" and "*parallel modular manufacturing*". The concept of *unitary modular manufacturing* is that plants can be broken down into smaller modules (e.g., air separation module, reactor module, utility module, etc.) that are factory-built with final installation/assembly done in the field. The design process of breaking down the flowsheet into modules is called "cubing" the project and is often driven by shipping constraints and complexity of the interconnections. This approach to modularity has advantages mentioned previously (e.g., better control over the manufacturing process) and can reduce the project timeline as discussed in the EHS section below. The *unitary modular manufacturing* concept of modularity is a fairly new concept, but it has become somewhat well established. If this approach is taken, the design report should define the module boundaries and discuss how they were chosen.

The *parallel modular manufacturing* paradigm is less well established but may well be the future of the chemical process industry in certain cases. In this concept of modularity, the designer first chooses a *unit scale* for the process (e.g., 500 MSCFD) and then the desired throughput is obtained by running these units in parallel (i.e., "numbering up" rather than



scaling up). For example, 10,000 MSCFD required throughput could be provided by four 2,500-MSCFD modules, or two 5,000-MSCFD modules. This parallel approach to modularity offers additional benefits in terms of flexibility to relocate assets and lower initial capital outlay (and therefore lower financial risk) by adding modules incrementally over time. The choice of *unit scale* is driven by several factors and constraints (e.g., shipping the modules). For the purposes of this analysis, you can assume that the maximum size of a module is defined by those of a conventional intermodal shipping container (8 feet wide x 8 ft 6 inches tall x 40 ft long) to facilitate existing shipping equipment (i.e., over-road vehicles, rail car and sea mounted container vessels). More complexity can be added by using multiple modules.

An additional factor that may be considered when costing the *parallel modular manufacturing* concept is that module manufacturing costs decrease for additional units produced after the pioneer first-of-a-kind (FOAK) unit. This cost reduction is referred to as the economy of mass production and it can compensate for the loss of economy of scale incurred while going to the small, modular, parallel approach. The effect of declining cost with the number of units produced has been observed in many industries and is commonly formulated in terms of a learning curve (or experience curve), which states that the unit cost decreases by a factor ‘p’ every time the number of units produced doubles. Often the cost reduction is expressed as a learning rate defined as (1 – p). For module manufacturing, the learning rate is approximately 20% (i.e., the unit module cost reduces by 20% every time the production quantity doubles), resulting in p = 0.8. By comparison, the learning rate for stick-built plants is less, closer to 10%. The cost of the nth module, k_n, can be estimated as,

$$k_n = k_1 * n^{log_2 * p}$$

Where k_1 is the cost of the FOAK plant. The total cost K(N) of a modular, numbered-up, parallel plant made of N unit-scale modules is then,

$$K(N) = \sum_{1}^{N} k_n$$

Environment, Health and Safety:

Environment, Health and Safety (EHS) aspects are critical to the economic viability, sustainability, and social responsibility of chemical sector investment and operations. These aspects must be carefully considered during design to ensure that the process minimizes energy and raw material consumption, safely contains process materials, and effectively treats potentially harmful discharges prior to release to the environment.

These aspects are especially important when processes employ or produce toxic and flammable materials. Your design will be judged in part on your recognition of the potential environment, health and safety hazards inherent in the process, as well as on the mitigation steps you incorporate to mitigate these potential hazards.

1. **Minimizing Environmental Impacts**

Your design must identify the composition and quantity of gaseous, liquid, and solid waste generated by the process. This information will be required in order to obtain construction and operating permits from the regulatory authorities. You should assume that the regulatory authorities require the application of *Best Available Control Technology (BACT)* to treat waste prior to discharge to the environment. Failure to meet this requirement will result in denial of your permit application, which will result in considerable project delays.

As you lay out your project schedule, you must accommodate the environmental permitting process. You should assume that it takes at least 6 months from the submission of your permit request, including the completed design basis, site characteristics and all expected environmental discharges, to obtain a construction permit. As a point of reference, 'stick-built' plants typically take 36−40 months for engineering and construction, whereas modular plants typically take 6−12 months. You should assume that the regulators:

a) <u>Do not allow</u> field construction to begin until a construction permit is issued.

b) <u>Do allow</u> the purchase of equipment prior to construction permit issuance, including modular pre-assembled units, which may provide a schedule advantage, at your own financial risk. This equipment cannot be installed on the construction site until the construction permit is granted.

Note that off-site waste treatment may be an economically attractive option, however, you must incorporate the estimated off-site waste treatment cost, including transportation, in your economic model.

<u>Your design must include a list of gaseous, liquid and solid waste streams generated from the process and the BACT you have incorporated to manage treat these prior to discharge.</u>

2. **Assessing and Mitigating Potential Health Impacts**

Your design must recognize the hazards associated with potential human exposure, both on-site and off-site, to process materials, including raw material, intermediate and finished products, by-products and wastes, catalysts, chemicals, and utilities (such as steam, nitrogen, cooling water, etc.). It should also consider such items as thermal exposure to hot surfaces, creation of confined spaces and the hazards of working on tall equipment.

A good way to screen for health risks is to assemble a list of all materials present in your process, and then review the relevant *Safety Data Sheets* (SDS, formerly known as MSDS). Screening for potential health risks is an important element of process safety.

The SDS for common materials are readily available on-line and provide a wealth of useful information on the health hazards associated with materials. This information can inform key mitigations, including the design of containment and control systems, leak detection (toxics and flammables) and suppression, selection and provision of personnel protective equipment, personnel training and emergency response procedures.

Your design must include a table with the key health risks and steps taken to mitigate these.

3. **Safety – Learning from Experience**

Chemical Process Safety is defined by the Center for Chemical Process Safety (CCPS) as a "*disciplined framework for managing the integrity of operating systems and processes handling hazardous substances by applying good design principles, engineering and operating practices.*"

In designing any chemical process, safety is the concern above all else. This involves fundamental efforts to reduce hazards at every step from the selection of the least hazardous materials that will still meet the process needs up to proper consideration of fabrication, assembly, and operation of the process through the implementing proper process hazard review standards. So important point to consider include:

A. Inherent Safety

There are four key principles of Inherently Safer Design (ISD): (CSB video may be helpful, too: https://www.youtube.com/watch?v=h4ZgvD4FjJ8&feature=youtu.be)

(1) Substitution (e.g., less hazardous chemical)
(2) Minimization (reduce the amount of chemical stored, reduce concentration of toxic or reactive component in a mixture)
(3) Moderation (cooler temperatures, lower pressures)
(4) Simplification (reduce unnecessary complexity so it is less prone to fail)

You must explain how you considered ISD in your design and specific examples *unique to your design*. Please do not re-summarize what is written here.

B. Process Safety Management Considerations:

Inherent Safety is related to, but not the same as, Process Safety Management (PSM). PSM is the use of multiple management systems to "keep chemical energy in the pipe" – prevent rare but catastrophic events that result in fires, explosions, and toxic releases. This includes, but is not limited to, understanding the hazards of the process; conducting risk assessment (process hazard analysis and explosion impact/facility siting analysis); installing mitigation (engineering and administrative controls such as alarms, interlocks, explosion and relief systems); and establishing management systems to ensure changes are managed, systems are maintained, and people know and follow procedures.

Good engineers recognize that there are 1,000's of pages of details involved in process design, but it is our job to highlight the most critical pieces of information that can result in a catastrophic event and communicate that information concisely and clearly to our team: Operators, Maintenance Workers, Leaders, and Technical staff. The Judges expect the design solution to summarize the critical hazards (how bad can it be?); mitigation (what prevents bad things from happening?); and unique aspects of the design that will prevent catastrophe. We do not want 100's of pages that is left to us to interpret what to do.

For further information please refer to the AIChE Center for Chemical Process safety website for resources and information.

https://www.aiche.org/ccps/resources/publications/books/guidelines-risk-based-process-safetyccps/documents/overview

Your design should consider relevant lessons learned from the industry, and a summary of how these have been incorporated in the design.

Additional Information:

1) Standard conditions are 60°F and 14.7psia.
2) Your company uses US Customary Units of Measure (see utility costs).
3) Unless otherwise indicated: G = 10^9, MMSCF = 10^6 ft^3, MSCF = 10^3 ft^3, K=10^3
4) Short ton = 2000 lb; metric ton = 1,000 kg; bbl = barrel of liquid at standard conditions = 42 gal
5) Ambient: 75°F (avg), Min/Max Dry Bulb Temp = 20/90°F, Avg. Windspeed = 10mph.

Feed Costs:

- Methane Feed: assume zero value at wellhead

Capital Basis for External Units:

- Syngas unit: Base CapEx = $21.62 MM, Base capacity = 12.2 kg/s, scaling factor = 0.67
- Hydro-Isomerization Unit (HIU): Base CapEx = $8.29 MM, Base capacity = 1.13 kg/s, scaling factor = 0.55
- Steam plant: Assume 80% fuel efficiency and capital cost is $350/Hp of steam supplied if burner based; if electric driven assume 90% efficiency and capital cost of $300/Hp
- CO2 recovery system: $5.3 MM, Base capacity = 8.54 kg/s, scaling factor = 0.55
- Salvage value of any equipment at end of life is 10% of the initial capital expense plus $25,000 removal cost

Utility Values:

- 600#, 490F HP Steam: Cost: $5/klb consumed, Credit: $4/klb produced
- 125#, 353F MP Steam: Cost: $4/klb consumed, Credit: $3/klb produced
- 20#, 260F LP Steam: Cost: $3.5/klb consumed Credit: $2.5/klb produced
- Electricity: Cost: $0.04/kWh consumed, Credit: $0.03/kWh produced
- Fuel Gas: Cost: $3/MBTU consumed, Credit: $2/MBTU produced
- Hydrogen: Cost: $0.06/lb consumed
- Carbon Dioxide: 100% pure (500psig & 100°F): Cost: $400/MSCF consumed
- Steam Condensate (at least 99.9% v/v pure): Credit: $2/klb produced
- Process/Cooling Tower Water (at least 95% v/v pure): Cost: $0.5/kgal consumed, Credit: $0.35/kgal produced
- Waste Water Treatment (at least 75% v/v pure): Cost: $6/kgal produced

Hint: Steady-state design may not require all utilities. You may ignore transient start-up requirements for preliminary design.

Product Prices:

Product is to be stored in on-site wellhead storage tanks and then periodically collect in 5,000-gallon truck trailers for transport (pressured rated for LPG or conventional for petroleum liquids). The planned price structure and standard liquid densities for finished products are:

- LPG (C3, C4) – regardless of composition: $0.30/lb
- Naphtha (C5 - C10); 45 lb/ft^3: $75/bbl
- Diesel (C11 – C20); 53 lb/ft^3: $90/bbl

Pseudocomponents:

For simulation purposes, you may consider lumping some of the product species together as pseudocomponents. The following properties are provided for suggested lumped species:

Pseudocomponents Properties					
Carbon Range	C21-C25	C26-C29	C30-C35	C36-C47	C48+
MW	322.6	386.5	454.9	572.2	861.7
SG @ 60F	0.801	0.810	0.818	0.827	0.839
NBP, F	714.3	799.6	876.7	982.5	1155.2

Part 2 – Network Design and Optimization

Consider the overall system architecture as illustrated below. There is a central process plant which has the ability to receive the output from the wellhead FTL units and blend them into finished fuels. This plant is surrounded by a number of new wellheads. These wellheads have varying production levels of associated natural gas and are located at various distances from the plant. The objective is to determine the most economic set of wells to be fitted with a certain number of modular FTL units that can be of different sizes. The wells will experience a sharp decline once put into production (as described elsewhere) so it will make sense to move modules to new well production as others decline. Product will be collected by truck on a periodic basis, but the truck trailers are limited to 5,000 gallons of liquid on each trip. The cost of truck transportation is $1.25/mile driven for vehicle and driver (these are supplied on 5-year contract to the company) so consider how many trucks should be on contract and when they should be contracted. The central plant can process material equal to 30,000 MSCF of natural gas feed equivalent from the wells irrespective of the product form. Managing the total number of trucks on contract is part of the economic analysis.

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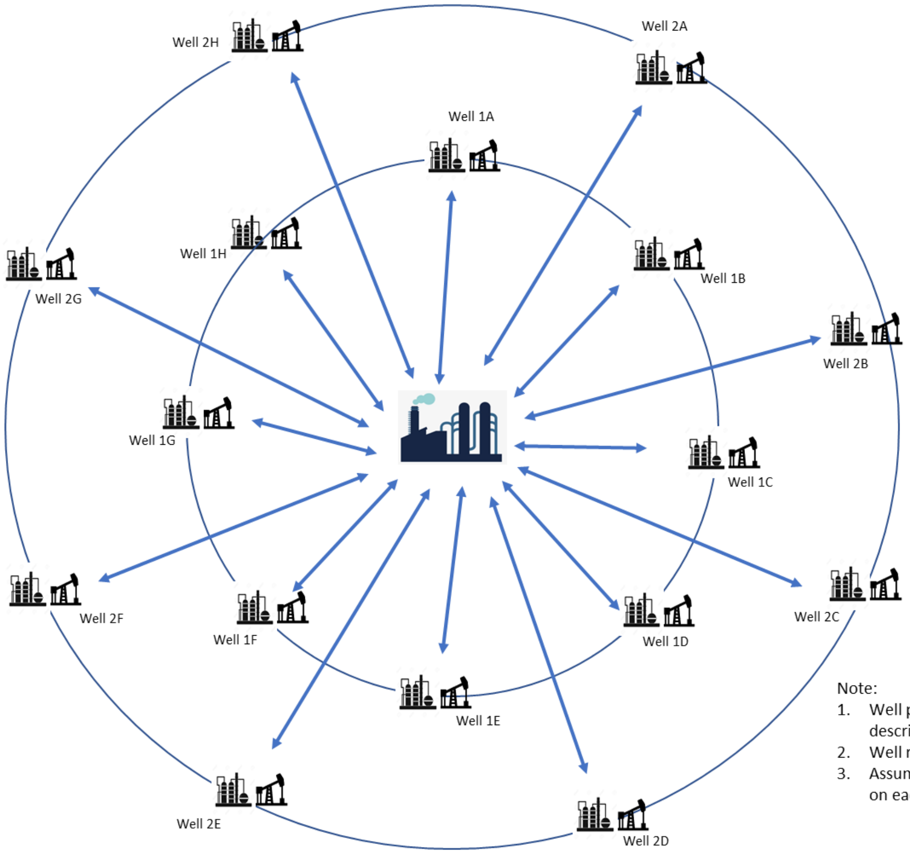
Modular Network Optimization for AICHE 2021 Student Design Problem



Associated Gas Well ID	Initial Associated Gas Production MSCF/day	Distance from Central Plant Miles
1A	4,494	62.0
1B	2,989	21.0
1C	8,365	17.0
1D	7,447	73.4
1E	3,290	6.2
1F	14,737	91.0
1G	11,155	59.0
1H	7,081	89.3
2A	9,182	85.8
2B	12,258	84.7
2C	8,742	2.4
2D	3,840	42.0
2E	7,939	98.8
2F	2,874	13.0
2G	6,076	87.0
2H	6,468	36.0

Note:

1. Well production follows a decline rate described in the text.
2. Well rates are assigned per the table
3. Assume that the plants separated equally on each ring at 45° angle.

The point of this part of the problem is to maximize the entire project net present value over the 20-year planning horizon using modular process design skills for part one and then optimizing the deployment of the equipment to the field locations in part two. The highest production wells are also the ones that will experience the sharpest decline over time. Maximum return will require managing the timing on bringing wells into production, timing for building the right number and right size modular FTL units and deploying plus redeploying the FTL units to maintain the highest level of production that is possible. The cost of redeploying any module will be $3.00 per MCF capacity per mile transported. And it will take the unit out of service for one (1) month. So, for example, moving a 500 MCFD unit for 50 miles will cost $75,000 and it will involve one month (30 days) of lost production during removal, movement, and reinstallation. The distance between any two wells can be simply calculated given the distance from the center and the respective angle. Overall, the thoughtful use of the modular assets may suggest a strategy of maintaining one or more spare units to shorten the redeployment time and manage the movement cost.

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