AIChE The Global Home of Chemical Engineers

2019-2020
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 2019-2020 Student Design Competition

Dear Chemical Engineering Department Heads and Student Chapter Advisors,

I am pleased to send you the 2019-2020 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 2020 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 **Friday, June 12, 2020.**

- Team Submissions: https://chenected.wufoo.com/forms/2020-student-design-competition-team/

- Individual Submissions: https://chenected.wufoo.com/forms/2020-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,
Sarah Ewing
AIChE Student Programs

2019- 2020 AIChE Student Design Competition Rules

1. The 2019-2020 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 **sixty (60) days** is allowed for completion of the solution. The finished report should be submitted to the faculty advisor within the 60-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 student may ask a Faculty Member with experience 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 the 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 60 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 not necessary.

2019- 2020 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.

2019 – 2020 AIChE Student Design Competition Timeline

- A period of no more than sixty (60) days is allowed for completion of the solution.
- The finished report should be submitted to the faculty advisor within the 60-day period.
- Students & faculty advisors should include the date assigned & the date completed along with their signature on the competition entry form.

2019 – 2020 AIChE Student Design Competition Report Format

The body of the report must be suitable for reproduction, that is, computer-generated and in a printable format. Tables, supporting calculations and other appendix material may be handwritten. This report should include the following components. Write the document from the point of view of the organization's engineer making a report and recommendation to the organizations management.

1. Letter of Transmittal
2. Cover Page
3. Table of Contents
4. Abstract
5. Introduction
6. Process Flow Diagram and Material Balances
7. Process Description
8. Energy Balance and Utility Requirements
9. Equipment List and Unit Descriptions
10. Equipment Specification Sheets
11. Equipment Cost Summary
12. Fixed Capital Investment Summary
13. Safety, Health, and Environmental Considerations
14. Process Safety Considerations
    a. List of waste streams and BACT to treat waste prior to discharge.
    b. Table with the key health risks and steps taken to mitigate these.
    c. Relevant lessons learned from the industry and a summary of how these have been incorporated in the design.
15. Other Important Considerations
16. Manufacturing/Operation Costs (exclusive of Capital Requirements)
17. Economic Analysis
18. Conclusions and Recommendations
19. Acknowledgements
20. Bibliography
21. Appendix

- **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 125 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).

2019 – 2020 AIChE Student Design Competition Submission Instructions

1. Use the accompanying word document titled "2020 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 **Friday June 12, 2020**.

- Team Submissions: https://chenected.wufoo.com/forms/2020-student-design-competition-team/

- Individual Submissions: https://chenected.wufoo.com/forms/2020-student-design-competition-individual/

2019 – 2020 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 2019-2020 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
- SAChE Student Design Competition for Safety in Design
  - 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

2019 – 2020 AIChE Student Design Competition Problem Statement

Modular Distributed Ammonia Synthesis

Business Objective:

Ammonia is sustaining the food supply for half the world's population. Ammonia manufacturing accounts for 1–3% of the world's energy consumption, 5% of natural gas consumption, and a significant portion (*ca.* 3%) of greenhouse gas emissions. In the US, ammonia is primarily produced through the Haber-Bosch process along the Gulf Coast due to the availability of cheap, abundant natural gas. A majority of this ammonia (>85%) is used for fertilizer, and therefore shipped by truck or rail from the Gulf Coast to agricultural regions, such as the Corn Belt in the Midwest. Because ammonia is a toxic gas at ambient conditions, shipping is expensive and hazardous with high associated insurance costs.

Senior management at your organization is seeking recommendations from the engineering department for potential alternatives to the current ammonia production supply chain. Your recommendation should include an analysis of technical, economic, health and safety aspects of the project.

The plant should be able to produce 50 metric tonnes per day (mtpd) of commercial-grade anhydrous ammonia. The plant should be located near the point-of-use in the US Corn Belt to minimize transportation costs. More details on plant location are given below. Commercial-grade anhydrous ammonia has a purity of at least 99.5% (by mass) and is produced and stored as a liquid at high pressure.

Ammonia is produced from nitrogen and hydrogen intermediates, which in turn must be produced from other upstream feedstocks at the plant. The choice of those upstream feed materials is open to consideration. Anhydrous ammonia, one type of nitrogen fertilizer, is used directly by injecting the liquid under the ground using standard farm equipment. When injected into the soil, the liquid ammonia expands into a gas and is readily absorbed in the soil moisture. Therefore no additional downstream processing is required to convert the anhydrous ammonia into a form usable for agriculture.

The design should employ new modular manufacturing methods becoming more common in the chemical process industry. Modular manufacturing is the concept that complete chemical processes or sub-sections of chemical processes can be prefabricated in a factory setting. 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 the 50 mtpd point-of-use, distributed, modular ammonia plant is considerably smaller than conventional, stick-built, centralized ammonia plants, which are often >1000 mtpd, so loss of economies of scale must also be considered.

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

1. The plant may use a "numbering-up" approach that uses smaller *unit scale* modules that are stacked in parallel to provide the required 50 mtpd throughput.
2. You may assume the 50 mtpd scale is right-sized for continuous, year-round operation and seasonal variation in fertilizer demand can be leveled out through various off-take agreements (e.g., sales to a neighboring facility that converts ammonia to other, storage-friendly forms of fixed nitrogen outside of the growing season).
3. Where possible in the design, process intensification (PI) concepts should be used to keep equipment costs low.
4. The process must have as small a carbon footprint as possible. Please make recommendations on how this can be achieved.
5. Innovative designs are desired to minimize the amount of background intellectual property (IP) that must be licensed.
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%.

Technical Objectives and Data:

Anhydrous ammonia for agricultural use should be a clear, colorless liquid or gas, free from visible impurities. It has a minimum purity specification of 99.5% on a mass basis; the remaining 0.5% being composed of remaining water and oil.

The produced ammonia should be stored as a pressurized liquid in appropriately sized and designed tanks. Anhydrous ammonia storage tanks are regulated by the U.S. Dept. of Labor and must conform to the requirements of 29CFR1910.111. It is customary to store anhydrous liquid ammonia at approximately 200 psia and occupying 85% of the tanks usable capacity (the remaining 15% as vapor space necessary to allow for expansion) . The storage tanks are built according to the ASME Boiler and Pressure Vessel Code and are rated for 250 psig.

Process Description:

Today ammonia is primarily made using the Haber-Bosch process, which was first performed at the industrial scale in 1910. The process converts atmospheric nitrogen (N_2) to ammonia (NH_3) by a reaction with hydrogen (H_2) using a metal catalyst under high temperatures and pressures. Here we describe separately the upstream process for production of the H_2 and N_2 and the downstream conversion to NH_3 and subsequent clean-up and compression.

You may choose to use any process you wish, and the following information should be considered as only one possible starting point. Clearly explain the rationale for the process you have selected.

Upstream Process

N_2 can be produced by separation from atmospheric air. The most appropriate process technology for air separation depends strongly on the scale. Examples of air separation processes include cryogenic distillation, membranes, and pressure-swing adsorption (PSA).

H_2 can also be produced in a several ways. In existing ammonia plants, H_2 is produced by steam methane reforming (SMR) using natural gas as the feedstock. The natural gas may require pre-treatment to remove sulfur compounds (e.g., H_2S) before being fed to the SMR reactor. 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. To further increase the H_2 yield, the output of the SMR reactor is fed 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 the downstream Haber-Bosch reaction. Various methods may be appropriate for purifying the SMR effluent including PSA.

$$C_nH_m + nH_2O \leftrightarrow (n+m/2)H_2 + CO \text{ (Rxn 1)}$$

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

An alternative method of producing 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 electrolyzer is from renewable sources (e.g., stranded wind or solar) the H_2 produced is carbon free. Electrolyzer stacks are formed by stacking individual cells making electrolyzers inherently modular. Common electrolylzers are either alkaline or proton exchange membrane (PEM). Electrolyzers can be relatively expensive, for example PEM electrolyzers 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.

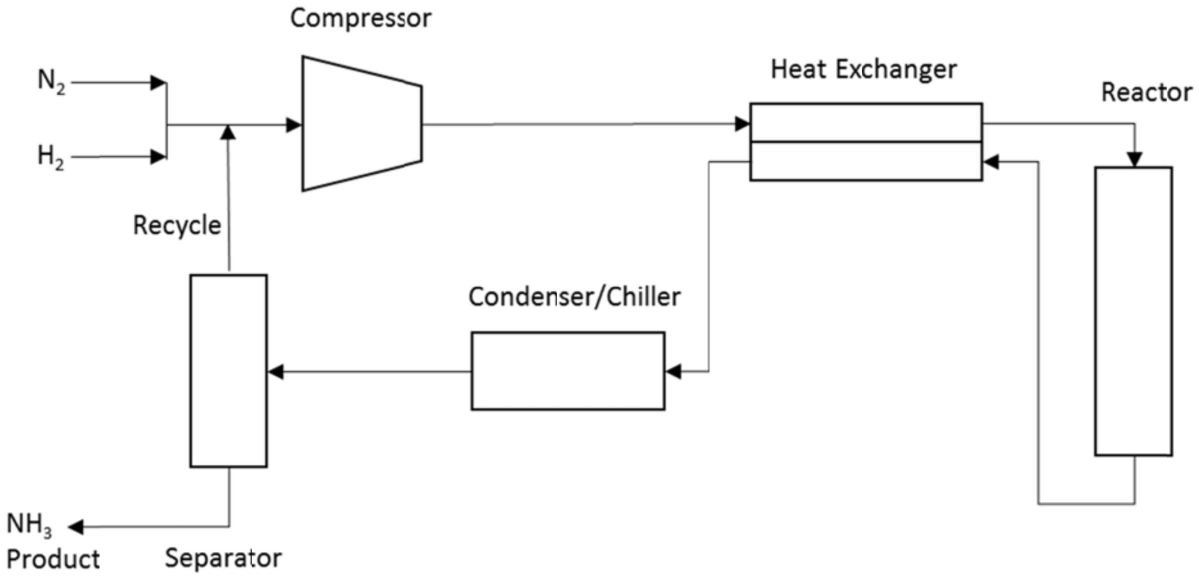
Downstream Process

The traditional route to ammonia production is via the "ammonia synthesis loop” or Haber-Bosch process [2] [3] that reacts highly purified hydrogen and nitrogen 3:1 molar ratio.

$$N_2 + 3H_2 \leftrightarrow 2NH_3 \text{ (Rxn 3)}$$

The catalyst (typically iron-based) used for this reaction is particularly affected by the presence of any oxygenated compounds so the feed gas should be clean of CO, CO_2 and H_2O, as well as

O_2 from air. The ammonia synthesis reaction is highly sensitive to temperature and pressure, and needs to be run at high pressure, 60 to 180 bar, to achieve commercially viable conversions. Even at those conditions, the reaction only achieves single-pass conversions of less than 20% thus necessitating high recycle rates. The split between ammonia product and unreacted feed gases is not a difficult one, but it is rather energy intensive, and can be accomplished using a single stage phase separator ("flash") after condensing the ammonia product using a chiller.



There is quite active research into alternatives to the traditional ammonia synthesis loop in order to lower the reaction conditions (temperature and pressure), increase the conversion, and simplify the flowsheet. Some interesting examples of PI applied to ammonia synthesis are:

- Researchers at the University of Minnesota have published a process [4] based on combining the synthesis reaction with ammonia absorption (using $MgCl_2$ as absorbent) – a PI concept referred to as reactive separation − to avoid the conversion limitations due to reaction thermodynamic equilibrium. They have shown results with conversions over 90% (at similar temperature and pressure conditions as the conventional ammonia synthesis loop) [12] that might be able to compensate the more complex and capital intensive process configuration.
- Use of non-thermal plasma (NTP) catalysis, made feasible by cheap and abundant renewable electricity, is capable of high ammonia conversions at atmospheric pressure [5].
- Methods to simplify the flowsheet by streamlining the water-gas shift reactor and the gas purification steps [10].

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 the 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 in to 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 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 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., 10 mtpd) and then the desired throughput is obtained by running these units in parallel (i.e., "numbering up" rather than scaling up). For example, the 50 mtpd required throughput could be provided by ten 5-mtpd modules, or five 10-mtpd 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 up to a 10-mtpd module can be transported over the road.

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,

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

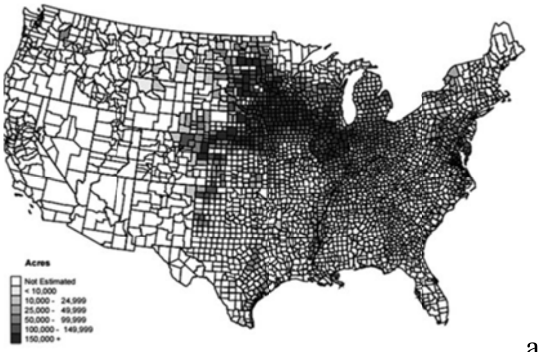
where k_1 is the cost of the FOAK plant. The total cost $K(N)$ of a modular, numbered-up, parallel plant made of N unit-scale modules is then,

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

Plant Location:

The chosen location for this ammonia production facility is the region of Western Minnesota known as the Minnesota River Valley. This region combines three important characteristics that make it especially suited to modular ammonia production: high ammonia demand for agricultural use (corn being the #1 ammonia consuming crop), high renewable electricity generation potential due to high underused wind availability (sometimes known as “stranded wind”), and availability of associated gas from neighboring states. [5]

wind distribution



ammonia consumption

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 30−34 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 materials, intermediate and

finished products, by-products and wastes, catalysts, chemicals and utilities (such as steam and nitrogen).
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 procdures.

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.*"

CCPS has created a framework of "20 Elements of Risk Based Process Safety" as a guideline for the industry to manage and minimize process safety risk, a link to this is provided in the "EHS Resources" [7] below. For the purposes of this exercise, we would like you to explore the CCPS Process Safety Pillar entitled "Learn from Experience". To help you do that, a link to a paper that documents 50 years of history in the manufacture of ammonia in included in the "EHS Resources" [7] below. A number of past incidents associated with ammonia production and handling are documented for various production routes (not all may apply to your design), providing insights into what can go wrong, and ways to mitigate these risks.

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

Resources:

[1] **RAPID Resources**

Two suggested resources (free to active AIChE Student Members) to view prior to approaching the problem includes:

1. RAPID Webinar: The Value of Process Intensification for Module Manufacturing (https://aiche.org/academy/webinars/value-process-intensification-module-manufacturing)
2. RAPID eLearning Course: The Fundamentals of Process Intensification (Particularly Module 4: Module Manufacturing) (www.aiche.org/ela300)

[2] Pattabathula, V. (2019). Ammonia. In Kirk-Othmer Encyclopedia of Chemical Technology, John Wiley & Sons, Inc (Ed.). https://onlinelibrary.wiley.com/doi/10.1002/0471238961.0113131503262116.a01.pub3

[3] Performance of a Small-Scale Haber Process. Michael Reese, Cory Marquart, Mahdi Malmali, Kevin Wagner, Eric Buchanan, Alon McCormick, and Edward L. Cussler. Industrial & Engineering Chemistry Research 2016 55 (13), 3742-3750; https://pubs.acs.org/doi/pdf/10.1021/acs.iecr.5b04909?rand=q7z3dt6h

[4] Ammonia Synthesis at Reduced Pressure via Reactive Separation. Mahdi Malmali, Yongming Wei, Alon McCormick, and Edward L. Cussler. Industrial & Engineering Chemistry Research 2016 55 (33), 8922-8932. https://pubs.acs.org/doi/abs/10.1021/acs.iecr.6b01880

[5] A review on the non-thermal plasma-assisted ammonia synthesis technologies. Peng P, Chen P, Schiappacasse C, Zhou N, Anderson E, Chen D, Liu J Cheng Y, Hatzenbeller R, Addy M, Zhang Y, Liu Y, Ruan R. Journal of Cleaner Production, 2018 vol: 177 pp: 597-609. https://www.sciencedirect.com/science/article/pii/S0959652617332195

[6] Allman, A. , Daoutidis, P. , Tiffany, D. and Kelley, S. (2017), A framework for ammonia supply chain optimization incorporating conventional and renewable generation. AIChE J., 63: 4390-4402. https://aiche.onlinelibrary.wiley.com/doi/full/10.1002/aic.15838

[7] **EHS Resources**

1. EPA database contains case-specific information on the "Best Available" air pollution technologies: https://cfpub.epa.gov/rblc/index.cfm?action=Search.BasicSearch&lang=en
2. Center for Chemical Process Safety (CCPS), 2011. Guidelines for Risk Based Process Safety. New York: Wiley. https://www.aiche.org/sites/default/files/docs/summaries/overview-of-risk-based-06-25-14.pdf

3. The AIChE Ammonia Safety Symposium, 50 Years of Shared Experiences, Venkat Pattabathula, Bhaskar Rani, and D.H. Timbres, 2005. **Note that this Resource was sent with Problem Statement.*

[8] Pattabathula V., Richardson J., Introduction to Ammonia Production. (2016). CEP Magazine. https://www.aiche.org/resources/publications/cep/2016/september/introduction-ammonia-production

[9] Special thanks to Linde for providing access this applicable presentation for educational use in the AIChE Student Design Competition: "Scaling Down Ammonia Production. Modular Solutions for Constructability" https://www.globalsyngas.org/uploads/downloads/2017-presentations/s1-3-lalou.pdf

[10] Hiwale, R., Kandziora, B., & Lalou, C. (2019). Breaking from Convention. *World Fertilizer Magazine*, (July/August 2017), 35-39. **Note that this Resource was sent with Problem Statement.*

[11] McCormick, A. (2015). Potential Strategies for Distributed Sustainable Ammonia Production. Presentation, NH3 Fuel Conference. https://nh3fuelassociation.org/wp-content/uploads/2016/08/mccormick-nh3-fuel-conference-21sep2015.pdf

[12] Himstedt, H. H., Huberty, M. S., McCormick, A. V., Schmidt, L. D. and Cussler, E. L. (2015), Ammonia synthesis enhanced by magnesium chloride absorption. AIChE J., 61: 1364-1371. https://aiche.onlinelibrary.wiley.com/doi/abs/10.1002/aic.14733

[13] Eric Dahlgren, Caner Göçmen, Klaus Lackner & Garrett van Ryzin (2013) Small Modular Infrastructure, The Engineering Economist, 58:4, 231-264. https://www.tandfonline.com/doi/abs/10.1080/0013791X.2013.825038
*Note: if you cannot access this resource, see [14]

[14] Weber and Snowden-Swan, The economics of numbering up a chemical process enterprise, JAMP, DOI: https://aiche.onlinelibrary.wiley.com/doi/abs/10.1002/amp2.10011

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http://Solarhydrogensystem.com

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