

American Institute of Chemical Engineers

AIChE[®]

**2009 National Student Design
Competition**

If there are any questions about the Design Competition, student chapter advisors and design course instructors are asked to contact:

Professor Richard L. Long

**New Mexico State University
Chemical Engineering Department
Las Cruces, NM 88003**

Phone: (505) 646-2503

Fax: (505) 646-7706

Email: rilong@nmsu.edu

**Please read the rules on the following pages carefully
before submitting a solution to AIChE.**

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October 2008

Dear Chemical Engineering Department Heads and Student Chapter Advisors,

I am pleased to send you the 2009 AIChE National Student Design Competition statement. Please forward it to those faculty teaching design courses. Following is this year's challenge:

“ABE Fermentation.”

As always, the names of the sponsoring organization and the authors are being withheld to ensure confidentiality. Both will be announced after the deadline, June 5, 2009.

An entry form – required for each participant -- is available as a separate attachment, and must be submitted along with the completed solution.

We welcome participation by individuals and teams of up to three students. Please indicate the names of all team members on each entry form, and be advised that each team member is required to submit a separate entry form.

Because the National Student Design Competition is a benefit of AIChE student membership, entrants must be AIChE national student members. Any non-member submissions will not be considered. To join, students can download a membership application form at <http://www.aiche.org/students/>.

Please take time to review the rules, found on the following pages. It is important that all solutions strictly adhere to the Final Report Format.

All submissions must be submitted in an electronic format – and submitted via postal mail on a cd.

Submissions must be no more than two documents --totaling 100 or fewer pages of main text, with an allowable 100 pages of supplementary materials – in one of the following formats: PDF or MS-Word. The requested format is a single PDF file—the Adobe Acrobat program can be used to combine pages from different sources into one document.

Student Chapter Advisors are asked to select the best solution or solutions, not to exceed two from each category (individual and team).

Solutions must be submitted **on a diskette** by postal mail or ground delivery -- postmarked no later than Friday, June 5, 2009. Please maintain a copy for your files. To order additional copies of the Student Design Competition statement, email studentchapters@aiiche.org or call AIChE at 1-800-AIChemE (242-4363).

If I can be of assistance, please contact me at (646) 495-1348 or via email at studentchapters@aiiche.org. Questions relating to the substance of the design problem should be directed to Professor Richard L. Long, New Mexico State University, at (505) 646-2503 or rilong@nmsu.edu.

Thank you for your support of this important student competition.

Sincerely,

Gordon Ellis
AIChE / CEP Magazine

AIChE National Student Design Competition

2009

Rules of the Contest

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. Accuracy of computations is intended to mean primarily freedom from mistakes; extreme precision is not necessary.

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 textbooks, handbooks, journal articles, and lecture notes is permitted.

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.

The 2009 National 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 three students working together. Solutions will be judged in two categories: individual and team. There are, however, other academically sound approaches to using the problem, and it is expected that some Advisors will use the problem as classroom material. The following confidentiality rules therefore apply:

1. For individual students or teams whose solutions may be considered for the contest: The problem may not be discussed with anyone (students, faculty, or others, in or out of class) before or during the period allowed for solutions. Discussion with faculty and students at that college or university is permitted only after complete final reports have been submitted to the Chapter Advisor.

2. For students whose solutions are not intended for the contest: Discussion with faculty and with other students at that college or university who are not participating in the contest is permitted.

3. For all students: The problem may not be discussed with students or faculty from other colleges and universities, or with individuals in the same institution who are still working on the problem for the contest, until after June 5, 2009. This is particularly important in cases where neighboring institutions may be using different schedules.

Submission of a solution for the competition implies strict adherence to the following conditions: **(Failure to comply will result in solutions being returned to the appropriate Faculty Advisor for revision. Revised submissions must meet the original deadline.)**

ELIGIBILITY

- ONLY AIChE NATIONAL STUDENT MEMBERS MAY SUBMIT A SOLUTION. Non-member entries will not be considered. If you would like to become a National Student member, we must receive your membership application prior to submitting your solution. Application forms are found at <http://www.aiche.org/students/>.
- Entries must be submitted either by individuals or by teams of no more than three students. Each team member must meet all eligibility requirements.
- Each Faculty Advisor should select the best solution or solutions, not to exceed two from each category (individual and team), from his or her chapter and submit them per the instructions below.

TIMELINE FOR COMPLETING THE SOLUTION

- A period of no more than thirty (30) days is allowed for completion of the solution. This period may be selected at the discretion of the individual advisor, but in order to be eligible for an award, a solution must be postmarked no later than midnight June 5, 2009.
- The finished report should be submitted to the faculty advisor within the 30-day period.

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.
- The solution itself must bear no reference to the students' names and institution by which it might be identified. Please expunge all such references to the degree possible.
- **Final submission of solutions to AIChE must be in electronic format (PDF or MS-Word).** The main text must be 100 pages or less, and an additional 100 page or less is allowable for supplementary material. The final submission to AIChE must consist of 1 or 2 electronic files.

SENDING THE SOLUTION TO AIChE

- There should not be any variation in form or content between the solution submitted to the Faculty Advisor and that sent to AIChE National. The Student Chapter Advisor, or Faculty Advisor, sponsoring the student(s), is asked to maintain the original manuscript(s).
- **Copy the electronic file (PDF or MS-Word) to a cd, accompanied by its corresponding entry form, and mail the diskette to Awards Administrator, AIChE, 3 Park Avenue, 19th Floor, New York, NY 10016**

- **DEADLINE: Entries must be emailed no later than midnight June 5, 2009.**

2008 National Student Design Competition: ABE Fermentation

The purpose of this work is to synthesize a process, size, cost and optimize a plant to produce butanol by fermentation, for use as a biofuel. The end product of this work is a full process description, material and energy balance, list of equipment with sizes and costs, utility consumption, economic analysis, optimization and safety health and environmental analysis. You must be specifically concerned with the energy consumption of the plant, as the product is, ultimately, energy. Water consumption is also critical, as the plant is located in an area where water is scarce.

Introduction

Prior to the advent of the petrochemical industry, which made the process uneconomic, acetone, butanol and ethanol were produced together by fermentation, using one of several *Clostridia* strains in what was called the ABE process (see attached block diagram, last page of document). With the growth in interest of biofuels and the increase in price of petroleum and petrochemicals, this fermentation route is being revisited by several parties. The alcohols are excellent biofuels, and acetone is a versatile industrial solvent and chemical. Butanol has several advantages over the more conventional biofuel ethanol in blending with gasoline:

- Lower vapor pressure
- Higher flash point
- Higher energy content (miles per gallon)
- Less susceptible to separation in the presence of water
- Potential for blending at the oil refinery and pipeline transportation
- Potential for blending to higher levels than ethanol without engine modifications

Your company is interested in commercializing butanol as a biofuel. Your assignment is to develop the most economical conceptual design using corn as a feedstock. Because over 100 plants in the United States use corn to make fuel ethanol, significant learnings from the corn dry grind industry should apply to ABE fermentation. Your plant will be located in the U.S. Corn Belt and should produce 50 million U.S. gallons per year of fuel grade butanol, along with the corresponding amounts of other products.

Biological Background

The historic ABE fermentation by *Clostridium acetobutylicum* is one of the oldest known industrial fermentations. In a typical ABE process, butyric, propionic and acetic acids are first produced by *C. acetobutylicum*. The culture then undergoes a metabolic shift

and solvents (butanol, acetone and ethanol) are formed from the acids. Increasing butyric acid concentration to above 2 g/L and decreasing the pH to below 5 are required for the metabolic shift from acidogenesis to solventogenesis. Furthermore, the production of butanol is limited by product inhibition. Butanol at a concentration of 10 g/L can significantly inhibit the cell growth and the fermentation.

Over the years, there have been numerous attempts to improve butanol production in the ABE process, such as cell recycle and cell immobilization to improve cell density and reactor production. Extractive fermentation has also been studied to minimize product inhibition.

Your organization's research labs have isolated an improved bacterial strain that produces ABE in the (molar) ratio 3:6:1 to a maximum titer of 33 g/L total solvents. The unexpected finding is that this strain produces only these compounds as liquid products – no other coproducts are produced.

The organism is a naturally occurring strain and thus is less stringently regulated than if it were genetically modified. Nonetheless, it would be prudent to design facilities to physically contain the live organism. Prior to removal from containment, the organism must be deactivated or killed and then disposed of properly. A reasonable kill procedure is 5 minutes at 212 deg F or higher. Likewise, operating vents and spills that could contain live organism are to be contained and treated. The operating vent could be treated with a scrubber using a low concentration of bleach or caustic. Spills could be sent to a tank and heated to sterilization temperature prior to discharge.

General Process Description

A conceptual block flow diagram is shown in the attached figure, to accompany this process description. It is anticipated that the most economical process will have many similarities to the corn to ethanol process, but some key differences. Note that you may deviate from this block flow diagram, but you should justify that decision in your report.

Feed Preparation

Shelled corn will be purchased by the proposed plant as the feedstock. The corn will be ground in hammer mills, mixed with water and cooked to sterilize any adventitious organisms in the corn. For this first generation project, no fractionation of the corn solids should be considered – the whole corn kernels are fed to the cooking process.

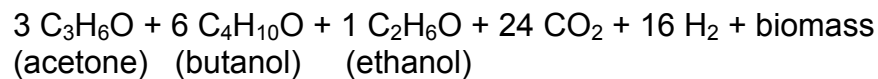
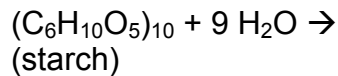
The corn mash must be cooked at 250 deg F for 1 hour. This can be done in a plug flow reactor, a batch reactor or a series of three stirred-tank reactors to simulate plug flow.

Fermentation

After cooling, the corn mash is fed to the anaerobic batch fermenters. Your *Clostridium* can ferment the corn starch as is, without needing a separate saccharification step to convert the starch to sugar. Fermentation takes 24 hours once the tank is full. As the only batch step in the process, your design must consider how to best match up fermentation with the presumably continuous front end and back end of the plant. A Gantt chart may be helpful to illustrate the filling, fermentation, emptying and cleaning process for however many production and seed fermenters your design employs.

The organism can derive most of the nutrients it needs from the corn mash. The only added nutrient is 1 lb of NH₃ per 1000 lb of corn. Sulfuric acid, 2 lb per 1000 lb of corn, is expected to be needed for pH adjustment. Lime is also used for pH adjustment, and the expected consumption is 1 lb per 1000 lb of corn

The overall chemistry can be written as:



Conversion of starch in the fermenter is 99%.

Fermentation off-gas will, unlike in ethanol plants, contain a significant amount of hydrogen, as shown in the stoichiometry above. Your design needs to handle this stream in a safe, environmentally acceptable and economical manner before discharge to the atmosphere. You may assume a slight positive pressure on the fermenters, say 5 inches of water gauge, which will help keep the fermentation anaerobic.

You will need to estimate the heat of reaction to determine fermentation cooling requirements. The fermenter must be maintained at 90 deg F year round for maximum biological productivity.

Seed Fermentation

Also fed to the fermenters is your *Clostridium* inoculum, which you produce in a separate seed fermentation train. The biochemistry of the organism is outside the scope of this project. It is known to be complex (see Lenz and Morelra, for example). Fortunately, your research organization has developed a simple scenario for your use. The organism will come from 1 ml vials stored in a freezer on site. It will be grown in successive stages each 20 times the size of the prior stage, each stage taking 24 hours. After 24 hours, it is put in the next larger vessel along with water and a sugar source. If you use less than a 20 X factor for any stage of fermentation, you must still allow 24 hours for that stage of fermentation to take place. Ten (10) liters is the largest stage that

can be grown in the lab before transferring to the first seed fermenter in the plant. Lab scale fermentations will use clean sugar and other nutrients, the cost of which can be ignored for this evaluation, along with the cost of the initial vial of organism. (Note, however, that the vials do have a cost, and you can not use millions of vials per production fermenter batch in order to avoid the cost of seed fermenters. Only use one vial per production fermenter batch.) Once the laboratory-produced seed is taken to the plant seed fermentation train, each stage of seed fermentation will be fed with plant water and enough corn mash to produce the maximum titer of 33 g/L total product before transfer to the next larger seed fermenter, or ultimately the production fermenter(s). Your material and energy balance should include the amount of water and mash fed to the plant seed train.

Product Recovery

After fermentation, the broth needs to be separated into acetone, butanol and ethanol products. Distillation is the obvious candidate, but you may consider any other technologies for which you can find sufficient, reliable data with which to design the process.

Because the product titer is relatively low, you may wish to consider alternatives to brute force distillation of the fermentation broth. Various ISPR (in situ product removal) techniques have been published for ABE as well as other fermentations, and your process may use any of them for which you can find adequate data. Justify your decision as to separation technique based on economics and technical uncertainty.

Solids Separation

The non-starch components of the corn need to be removed from the process downstream of fermentation by centrifugation. You may do this either before or after separation of the ABE products. The solids stream from the centrifuge will be 30% solids with the remainder being the mother liquor.

Evaporation

The remaining fermentation broth contains dead organism, salts and other dissolved solids. The water must be evaporated and condensed before it can be reused, leaving behind a syrup stream containing 55% total solids.

You may use whatever technology you wish to evaporate and condense the water from the fermentation broth. Typically multiple effect evaporators are used to save energy. However, mechanical vapor recompression would reduce thermal energy consumption even further, at the expense of additional capital and electricity.

DDGS Drying

Drawing a parallel from the ethanol industry, the syrup from evaporation, which contains all the salts added to the process, can be mixed with the centrifuge solids, dried to 9% moisture, and sold as animal feed. This coproduct is called DDGS (distiller's dried grains with solubles).

If the solids are removed before the ABE products are removed, then the solids will also contain ABE. A water wash of the solids would reduce the ABE in the solids going to the dryer. Should your design go this route, you must determine the fate of the volatiles in the dryer, as well as the yield implications. Most new plants send the dryer vent to a thermal oxidizer.

Design Considerations

Your design should be for a new green field plant. The site is level, clear and ready for construction. Roads and rail to the plant gate are adequate for shipping raw material and product. You will need to include capital to make your own steam, a cooling tower, electrical substation, and any other utilities needed. The plant is surrounded by corn farms for as far as the eye can see. Conveniently, a natural gas pipeline, electrical lines, city water and sewer run right past the front gate of the plant site.

Biofuels processes are subject to contamination by unwanted microorganisms. Suitable measures must be taken to ensure that no adventitious organisms enter the process, eating feedstock and generating undesired products. Everything entering the fermenter must be sterile, except of course the inoculum. However, it is known that biofuels processes can not be held to the same level of cleanliness and sterility as pharmaceutical plants, due to cost. Your design should consider the impact of an occasional (say once per year) contaminated fermentation batch whereby the main products are ethanol and lactic and acetic acid.

Between fermentation batches, the fermenter is cleaned and sterilized to begin another batch. Your design may include multiple production fermenters, in addition to the required seed fermenters. After draining, the fermenter is rinsed with plant water. Then, cleaning is normally done with a dilute caustic solution. This solution normally begins at 4% caustic. After cleaning one production fermenter, the solution can be assumed to have dropped to 2% caustic. It can be boosted with concentrated caustic back to 4% up to 3 times before it must be discarded. The caustic both kills adventitious organisms and helps remove materials that adhere to the walls of the vessels. Rotating spray nozzles are normally used inside any vessels that need this clean-in-place (CIP) procedure. After CIP, the fermenter is rinsed with plant water. Then the fermenter should be pasteurized with atmospheric pressure steam to a temperature approaching 212 deg F between batches to kill any remaining organism before being placed into service again. A similar procedure is followed for each plant seed fermenter. Your design needs to

include sufficient time for this procedure, as well as including the streams in the material and energy balance.

Since your product is intended for transportation fuel use, it is imperative that the process be as energy efficient as possible. The current benchmark for energy use in a fuel ethanol plant is about 35,000 BTU/gallon of product. (This is calculated as the amount of heat and electricity needed by the process, not the amount of fuel consumed in the boiler.) Although butanol has a higher fuel value than ethanol, you should strive to meet this target. You should also calculate the amount of fossil fuel consumed plus electricity required to run the plant per gallon of product.

As in much of the Corn Belt, water is a big concern at your proposed plant site. The plant will need to be a zero-discharge plant, meaning that all process water is recycled within the plant. The only liquid discharge allowed is the small amount of boiler and cooling tower blowdown required to purge salts. You need to design the ABE process to use the minimum amount of water and purify and recycle essentially all of it. There is no river to which you can discharge effluents. The current benchmark for total water use in a fuel ethanol plant is about 3 gal/gal of product, and you should strive to meet or exceed that benchmark. (Hint – if your water usage is dramatically below the benchmark, you have likely overlooked a major water user on the plant.) You may ignore the small amount of domestic water used on the plant.

If your company is successful at capturing a large share of the transportation fuel market and building many plants, you will produce significantly more acetone than the market can absorb. Rather than depress world acetone prices, you should burn the acetone in your boiler to generate steam, displacing natural gas from your boiler.

Ethanol may be produced for sale or similarly burned in the boiler, whichever is more economic to do. If it is sold, it must be denatured on site with 2-5% by volume of unleaded gasoline, to conform to the Bureau of Alcohol, Tobacco and Firearms regulations (preventing human consumption of untaxed alcohol).

You may recycle some water before evaporation back to the cooking step. The ethanol industry calls this backset. It is difficult to know *a priori* how much backset can be tolerated by the organism, since it brings along ions and trace impurities which may inhibit biological activity. Assume that you may employ backset up to the point where the level of dissolved solids in fermentation has increased by 20% over the level that would exist in fermentation if backset were not used. All other water must be evaporated before reuse.

Solids recycle is not commonly used in corn ethanol plants. Although it may be an effective way to build cell mass in a process that feeds clean sugars, there is no known economical method to separate cells from corn mash. Your design may employ solids recycle, recognizing of course that it should be conducted before any heating of the fermentation broth, which would deactivate the organism.

The plant must be designed to be robust and safe to operate. Typically, ethanol plant operators do not have the level of experience or expertise of traditional chemical plant operators. It is reasonable to expect that ABE plant operators will similarly have neither chemical nor biological training beyond high school. A key tenet of the design will be the KISS principle (see Wikipedia).

Because the fuel industry is under the sustainability microscope, the plant design should be as environmentally friendly and energy efficient as possible. Recover and recycle process materials to the maximum economic extent. Remember that you will be there for the start-up and will have to live with whatever design decisions you have made.

Gallons are normally measured at 68 deg F.

Design Specifications

The only requirement from this plant is to make 50MM U.S. gallons of biobutanol, either pure or contained in a mixed biofuel. All liquid products are stored on site before being shipped by truck or rail.

Specs for the fuel products are given below. A mixed transportation fuel product containing both alcohols is also a possibility. There is currently no spec for such a product, but you may reasonably extrapolate that it must meet the same specs as pure biofuels, as shown below.

If you choose to burn your ethanol rather than selling it, it must be at most 10% water. The same applies for the acetone fuel product. Be sure to account for any water in the boiler feed stream when calculating the amount of heat of combustion liberated in the boiler.

Butanol product – 99.5% purity, max 0.5% water, max 0.01% ketones and aldehydes

Ethanol product – optional product with the same purity specs as butanol. The maximum amount that can be produced is determined by the stoichiometry. Denatured with 2-5% (by volume) gasoline.

Acetone product – burned in the boiler. Max 10% water. The maximum amount that can be produced is determined by the stoichiometry.

Mixed fuel product – optional product with any mixture of butanol and ethanol. Max 0.5% water, max 0.01% ketones and aldehydes. Denaturing is not required.

DDGS product – solid product, stored in a building before being shipped by truck or rail. Max 9% water, 10 ppm ABE max.

Design Data

The composition of corn may be taken as:

Water	15%
Starch	59.5%
Hemicellulose	4.4%
Cellulose	2.6%
Protein	8.3%
Oil	3.4%
Non-fermentable dissolved solids	6.8%

Approximately 40% of the proteins are soluble. The rest of the solids are insoluble and inert in the system. The oil remains with the insoluble solids as part of the DDGS animal feed product.

A good source of physical property data for some of the non-traditional compounds in the process is Wooley and Putsche.

Fuel ethanol plants normally run 350 days per year. To be competitive, the ABE plant will need to have similar uptime.

Data for binary mixtures of acetone, butanol, ethanol and water are well known in the literature and incorporated in most process simulation packages. Aspen Plus is one simulator with adequate thermodynamic methods and data. Ensure that your modeling of the process uses thermodynamic models that can predict the non-ideal VLE in the system (acetone-water tangent pinch, butanol-water azeotrope, etc.). If you use an alternative process for ISPR, ensure that your model adequately predicts all known and reported phase behavior.

Should you wish to use the fuel ethanol industry process standard for drying ethanol from near the azeotrope to 99.5% purity, molecular sieves, you need to know that regeneration of the molecular sieves requires recycling 20% of the dry ethanol product back to the sieves. This regeneration stream, which on average contains 37% water after leaving the mole sieves, must then be recycled back to your separation process. The composition of the regeneration stream varies with time, so your design should take that into consideration. A brief, but informative, discussion of the ethanol molecular sieve process is contained in Aden et. al.

Corrosion and cleanliness dictate that most process equipment be fabricated from 304 stainless steel. This holds for any equipment that contains water. Exceptions include corn silos, product storage tanks, and any distillation or other separation systems that contain less than 1% water, which may use carbon steel.

Undoubtedly, you will need additional data beyond what is given here. Cite any literature data used. If need be, make reasonable assumptions, state what they are,

and whether your design or economics are sensitive to the assumptions you have made.

Cost Data

Corn price = \$4.00/bushel (56 lbs) at 15% moisture

Natural Gas = \$8.00/million BTU

Electricity = \$0.05/kWhr

Water = \$3.00/thousand gallons (treated to be of adequate quality for the plant)

Unleaded gasoline = \$2.50/gallon (wholesale)

Ethanol (denatured) = \$2.50/gallon (market forecast)

Butanol = \$3.25/gallon (market forecast)

DDGS = \$150/ton

Sewer = \$5.00/thousand gallons (limit 10 ppm organics – boiler and cooling tower blowdown only)

Caustic (as a 50% solution, cost on a 100% basis) = \$0.125/lb

Lime = \$0.05/lb

Sulfuric acid (100% basis) = \$0.06/lb

Ammonia = \$0.16/lb

All prices are delivered to your site, in the quantities needed, expressed in 2009 dollars.

If you produce a mixed transportation fuel, you may assume a price that is the volume-based average of the butanol and ethanol in the fuel. You must then discount the effective price by 1% to allow for additional marketing and promotional costs for this new product.

Although corn prices have been quite volatile in recent times, reaching up to and beyond \$7/bushel, your best market intelligence indicates a long-term equilibrium price of \$4/bushel delivered to your plant location, surrounded by corn farms. Obviously, you will want to test the sensitivity of your economics to the assumed prices of feedstock and products.

Calculate the NPV (at a 10% discount rate) and IRR for the project.

If the economics are not favorable based on your design, you should recommend courses of action for your company to take to make the process suitably economical to justify investment. This may include research objectives.

Capital Cost Data

You may use any suitable reference for equipment costs, such as Seider Seader and Lewin; Peters Timmerhaus and West; Turton et. al., and/or appropriate software. You should be cautious about mixing cost data from different sources. The costs of some of the equipment required for this project may not be very readily available. You may use

the following purchased (bare) equipment costs if your source of choice does not include costs for that type of equipment.

Hammer mill - \$160,000 to process 100,000 lb/hr of corn. Scale the cost with a 0.7 exponent to different capacities. Includes 400 HP motor.

Centrifuge - \$500,000 to process 70,000 lb/hr of fermentation broth with solids. Scale the cost down with a 0.7 exponent to different capacities. Scale the cost up by adding multiple units no larger than this size. Electricity consumption is 75 HP.

DDGS dryer - \$1.7 million to evaporate 40,000 lb/hr of water from wet grain. Scale the cost with a 0.7 exponent to different capacities. This is a direct fired natural gas dryer, and has a 71% thermal efficiency. Electricity consumption is 400 HP.

A packaged unit for drying ethanol with molecular sieves costs \$2.5 million to process 34,000 lb/hr on a pure ethanol basis. The feed is saturated vapor at 1 atm, 92% ethanol, 8% water by weight. The products are saturated liquid at 1 atm. Scale the cost with a 0.6 exponent. Electrical usage is 0.002 kWhr/lb of product. Steam usage is 0.04 lb/lb of product for additional heating. Cooling water usage is 3 gal/lb of product. Since this is a packaged unit, it includes local piping, instrumentation, etc. and thus should have different installation factors than most other purchased equipment.

If you choose to use mechanical vapor recompression to evaporate water, a packaged unit to evaporate 135,000 lb/hr of water costs \$2.5 million. This includes the fan and the heat exchangers, local piping, instrumentation, etc. Scale the cost with a 0.6 exponent to different capacities. It uses 3,000 lb/hr of low pressure steam in normal operation, making it very energy efficient. Electricity consumption is 300 kW. Both the feed and products from this unit are saturated liquid at 1 atm.

Report Requirements

Use English units (lb, BTU, hour, deg F).

The report should follow the outline suggested in Seider Seader and Lewin. Further details on what should be included in the design report can be found in that text. Write the document from the point of view of the organization's engineer making a report and recommendation to the organization's 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. Water Balance
10. Safety, Health and Environmental Considerations
11. Equipment List and Unit Descriptions
12. Equipment Specification Sheets
13. Equipment Cost Summary
14. Fixed Capital Investment Summary
15. Other Important Considerations
16. Operating Cost and Economic Analysis
17. Conclusions and Recommendations
18. Acknowledgements
19. Bibliography
20. Appendix

Because of the nature of biofuels products, section 8 should include a detailed energy balance, listing all energy users (both thermal and electrical) in the plant. You should also calculate the fossil energy consumption in BTU/gal of product (transportation fuel), as well as the total (including renewably-sourced energy – i.e., acetone you burn) energy consumption in BTU/gal of product. Similarly, section 9 should include a complete water balance, and show how much water is required to run the plant. Express this in gal of water per gal of product.

References

The Renewable Fuels Association web site has a good description of the fuel ethanol process and industry. <http://www.ethanolrfa.org>

A good model of much of the dry grind ethanol process is discussed on <http://www.intelligen.com/literature.shtml> which links to a paper by Kwiatkowski et al. This includes a SuperPro Designer model that will work with their evaluation version of the software. Note, however, that SuperPro does not handle VLE rigorously and thus is not suitable for designing the ABE separations. Also note that the evaluation version can not print or save files, so this is best used as a learning tool for the ethanol process, rather than a design tool.

“ABE Production from Corn: A Recent Economic Evaluation”, N. Qureshi and H.P. Blaschek, J. of Industrial Microbiology & Biotechnology (2001) 27, 292-297.

“Economic Evaluation of the Acetone-Butanol Fermentation”, T. G. Lenz and A. R. Morelra, Ind Eng Chem Prod Res Dev (1980), 19, 478-483.

“Product and Process Design Principles: Synthesis, Analysis and Evaluation”, W. D. Seider, J. D. Seader and D. R. Lewin (2003)

“Plant Design for Chemical Engineers”, M. S. Peters, K. D. Timmerhaus and R. E. West (2002)

“Analysis, Synthesis, and Design of Chemical Processes”, R. Turton, R. C. Bailie, W. B. Whiting, J. A. Shaeiwitz (2002)

“Development of an ASPEN PLUS Physical Property Database for Biofuels Components”, R. J. Wooley and V. Putsche, NREL/MP-425-20685 (1996).

“Determining the Cost of Producing Ethanol from Corn Starch and Lignocellulosic Feedstocks”, A. McAloon et. al., NREL/TP-580-28893 (2000).

“Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover”, A. Aden et. al., NREL/TP-510-32438 (2002).

Note that some of the data used in this problem statement is hypothetical and does not necessarily represent reality.

Conceptual Block Diagram of the ABE Process

