2001 AICHE NATIONAL STUDENT DESIGN COMPETITION

Economic Recovery of Edible Protein from Cheese Whey by Ultrafiltration

DEADLINE FOR MAILING

Solutions must be postmarked no later than midnight, June 4, 2001.

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 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 other 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 2001 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. Solution 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 or universities, or with individuals in the same institution who are still working on the problem for the contest, until after June 4, 2001. 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 and check when you submit your solution, if not before. Application forms can be downloaded at: https://www.aiche-mart.org/memberapps/student.asp

✄ Entries may 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 send these by registered mail, as per the below instructions, to the Institute.

TIMELINE FOR COMPLETING THE SOLUTION

✄ A period of no more than thirty 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 4, 2001.

✄ 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, typewritten or computer-generated. Tables may be written in ink. Supporting calculations and other appendix material may be in pencil.

✄ The solution itself must bear no reference to the students' names or institution by which it might be identified. In this connection, graph paper bearing the name of the institution should not be used.

SENDING THE SOLUTION TO AIChE

✄ Two copies of each of the solution(s) must be sent to the address below; original manuscript(s) must remain in the possession of the Student Chapter Advisor, or Faculty Advisor, sponsoring the student(s)

✄ There should not be any variation in form of content between the solution submitted to the Faculty Advisor and that sent to the AIChE office.

✄ Each copy must be accompanied by the enclosed ENTRY FORM giving each contestant's name, AIChE membership number, college or university, Faculty Advisor name, address, home address, home telephone number, and student chapter, lightly attached to the report. This form will be retained for identification by the executive director of the Institute.

✂ DEADLINE: Entries must be postmarked no later than midnight, June 4, 2001. As soon as the winners have been notified, original manuscripts must be forwarded to the office of the executive director as soon as possible.

SEND TO:
Awards Administrator
American Institute of Chemical Engineers
3 Park Avenue
New York, New York 10016-5991

DEADLINE: JUNE 4, 2001

AICHE DESIGN PROBLEM FOR 2001

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INTRODUCTION

A cheese plant produces cheddar cheese from whole milk and has a current whey stream of 1,000,000 lbs/day. The plant operates 7 days/week, all year. The operating day is 20 hours and plant cleaning takes place in the remaining 4 hours. The whey is currently subjected to evaporation and spray drying to produce a dry product sold as animal food. It is sold to a customer at $ 0.15 per pound who picks it up at the plant, but, considering costs, the company makes only a marginal profit on the product. The drying operation does, however, eliminate cheese whey as a waste stream from the plant. The cheese plant is one of the production facilities in a large food company. Company management has decided to investigate the possibility of using ultrafiltration to produce whey protein concentrate products to be sold as food additives for human consumption.

You are a design team in the engineering department of a company that designs and manufactures ultrafiltration membranes and systems. You have been given the task of developing a proposal to present to the food company. Your proposal must not only present the selling price for the equipment, installation supervision, and startup supervision but must also give a complete financial analysis for the process. Your client will set up the ultrafiltration unit process as a profit center that will have profit and loss responsibility. The company has determined that they will produce three dry powder products--one containing 35% protein (based on the sum of true protein, TP, and non-protein nitrogen, NPN), one containing 75% protein and one containing 85% protein. The initial year of operation will begin on January 1, 2003 and due to estimated market conditions the company will not be able to sell more than 14,000 lbs/day of the 35% product, 4000 lbs/day of the 75% product, and 400 lbs/day of the 85% product. The company has determined that for the 35% protein product a price of $0.65 per pound of dry powder can be obtained, for the 75% product a price of $1.25 per pound and for the 85% product a price of $2.50 per pound.

The existing evaporator and spray dryer can be utilized to dry the products.

At the beginning of the second year after the profit center begins production, the cheese plant will increase its cheese production by 4% per year (and 4% more per year of each of the products can be sold). The company will charge the profit center $0.05 per pound of protein (TP and NPN) for the whey feed and will allocate costs to the center for space, administration, selling and research.

The existing evaporator and spray dryer, which is now being used to produce a dry animal feed from the whey, should be utilized to dry the new protein products. (To do this their plant people realize it will need to operate on a block time basis.) This existing drying system was installed in 1990 for a Fixed Capital Investment of $1.1 million. It has a steam requirement of 0.35 lb steam/lb of water evaporated.

Using Feed Specification, Product Specifications, Economic Parameters and other information presented in the Project Premises section of this document, develop a full Project Proposal.

The outline for the Project Proposal is shown in Appendix I.

Assume that equipment transferred to the center as well as purchased equipment will have a 10-year life and no scrap value. The 7 year MACRS method will be used for depreciation. The process will produce a waste stream consisting primarily of lactose, salt and water. The cheese plant is located in Springfield, MO. For the economic analysis determine the cost of sending the waste to the city sewage plant based on the cost data given under the heading, "Waste Treatment" below. You may want to look at possible options for disposal and/or by-product recovery and recommend an alternative disposal process and develop costs for the alternative.

DESIGN CONSIDERATIONS FOR PROCESS CONTROL

The ultrafiltration system should be semi-automatic. Startup should be manually initiated but pressure control should be automatic and it should be possible to set and control an overall feed-to-bleed ratio. You will need to determine how to analyze the composition of the product and provide feedback to the controller. The system should have suitable alarms for malfunctions and should shut down for such events as high pressure, high temperature, running out of feed, etc. Cleaning should be manually initiated but all cleaning steps should be automatic. If a heat exchanger(s) is necessary, then process temperature should be automatically controlled.

PROCESSING OPTIONS FOR PRODUCING THE THREE PRODUCTS

Appendix II describes the fundamentals of the ultrafiltration process and gives the principles of process and system design using hollow fiber modules. In the case of manufacturing whey protein concentrates, ultrafiltration will increase the concentration of protein while selectively removing the low molecular weight solutes—ash (salt) and lactose. Appendix II describes both batch processes and continuous processes for ultrafiltration process design. For the 35% product and the 75% product continuous processing will be much more advantageous because spoilage will not occur because the residence time in the system is less than 4 hours. However, to manufacture the 85% product you may be limited to a carefully designed batch system. If you do use a batch system remember that the batch time can be no longer than four hours.

From practical experience with the specified type of hollow-fiber modules it has been found that there is an important constraint on process design. That constraint is that the maximum protein concentration that can be reached with straight ultrafiltration is close to 55% (on a dry solids basis). This limitation is due in large part to the retentate becoming too viscous above 55%. To reach 75% and 85% you must use diafiltration (described in Appendix II). Diafiltration is accomplished by diluting the feed with water in order to facilitate a better separation of components.

OPERATING CONDITIONS OF THE ULTRAFILTRATION SYSTEM

Your company has aided the food company in carrying out extensive pilot work to develop design parameters for the system. Pertinent details of the ultrafiltration modules are given in the section of this memo entitled "Project Premises." The optimum operating conditions are given in this section. The equation generated giving flux rate as a function of concentration factor is presented. Cleaning and sanitizing was effectively accomplished by using an acid rinse, 1.0 volume percent "CIP Acid" from Ecolab recirculated for 30 minutes, followed by a caustic rinse which is 1.0 volume percent "Ultrasil 22" from Ecolab recirculated for 30 minutes, followed by 200 ppm sodium hypochlorite recirculated for 30 minutes. More details about these cleaning solutions along with purchase prices are also included in the section of this memo entitled "Project Premises." The overall process for cleaning and sanitizing includes draining of the system (with the drained whey sent forward to the 35% product tank), a soft water rinse, draining, the acid rinse, draining, a soft water rinse, draining, the caustic rinse, draining, a soft water rinse, draining, the sodium hypochlorite rinse, draining, and a final soft water rinse which is drained before the system goes back on line. This cleaning and sanitizing is required for two reasons: (1) to remove foulants which have accumulated on the membranes during the 20-hour run and thus to maintain long-term flux rate stability and (2) to kill the microorganisms which have grown and attached to the wetted system components during the run. Also, USDA requires the daily cleaning and sanitizing procedures for dairy systems manufacturing products for human consumption.

The cleaning system must be carefully designed for automatic operation. To minimize solution volumes it will be necessary to recirculate the cleaning and sanitizing solutions from both the feed and permeate sides of the membrane system back to a cleaning tank.

USDA requires manual positive disconnects between the cleaning system and the whey processing system. In other words valves cannot be used to separate the cleaning system from the whey processing system.

DELIVERABLES TO THE FOOD COMPANY

The proposal should include a ten-year income statement for the cost center. with appropriate balance sheet items to use in calculating cash flow. You should include the rate of return based on discounted cash flow (IRR). Your client will probably use a hurdle rate of at least 12% IRR. so optimization of the design for cost effectiveness and innovation in order to achieve 12% or more is important. For completeness also include the payout time for the investment.

The plant design and the development of the income statement should be carried out using appropriate computer techniques. Manual calculations are not acceptable. You must write your own program, use a math program such as TK Solver, or use a spreadsheet program such as Excel. Do not attempt to use or adapt a module in one of the process simulator programs such as Aspen.

PROJECT PREMISES

Feed composition (weight basis):

True Protein, TP	0.6 %
Non-Protein Nitrogen, NPN	0.3 %
Lactose	4.9 %
Ash	0.8 %
Butter Fat	0.05%
Remainder is water	
Density = 8.5 lbs/gal	

Product compositions (dry basis):

TP and NPN	35.0 wt. %
TP and NPN	75.0 wt. %
TP and NPN	90.0 wt. %
Density = 8.5 lbs/gal	

Membrane rejections:

True protein	0.970
Non-protein nitrogen	0.320
Lactose	0.085
Ash	0.115
Butter fat	1.00

Membrane Cartridge (PM 10 from Koch Membrane Systems)

Cost of 26.5 sq. ft. hollow fiber cartridge	$200 each
Cost of cartridge clamps, gaskets, adapters	$15 each cartridge
Membrane life	1 year
Cartridge dimensions, 3 in. diameter x 40 in. long	
Manifold spacing	7-in. centers

Optimum Cartridge Operating Conditions:

Cartridge inlet pressure	30 psig
Crossflow pressure drop	15 psi
Permeate pressure	5 psig
Recirculation Rate/Cartridge	23 gpm

Equation for Membrane Flux Rate:

$$J = 27.9 - 5.3 \, \text{LN} \, (CF)$$

where

J = flux rate in GSFD (gallons per sq. ft. of membrane per day)
CF = concentration factor (See Appendix II for definitions)

(Note that this equation was developed from data generated by using a batch membrane system containing PM 10 hollow fiber membrane cartridges and measuring the flux rate as a function of concentration factor. The starting material was a representative sample of the cheese whey feed for the proposed process and the cartridge operating conditions were those outlined above. This equation will only apply with this feed, this type of membrane cartridge, and these operating conditions. The concentration factor, CF, to be used in the equation would be the overall concentration factor up to the place in the system where a flux rate is needed for design calculations.)

Power cost: $0.07/kwh
Steam cost: $5.00/million BTU

Financial Data:

Company allocation for Administrative Costs	4% of Sales
Allocation for Selling Expense	12% of Sales
Allocation for R&D Expense	5% of Sales
Allocation for Space (including plant overhead and general utilities but not manufacturing system utilities. This allocation also includes local taxes and insurance.)	$125,000/year

Inventory, days on hand	60 days
Accounts Receivable, days	45 days
Increase in Fixed Assets/Year (after 1st year)	2% of Sales
Book value of equipment (evaporator and spray dryer) transferred to cost center.	$300,000

Cost of Concentrates to Formulate Cleaning Solutions

CIP Acid from Ecolab	$ 9.09/gal
Ultrasil 22 from Ecolab	$11.86/gal
Sodium Hypochlorite from Wal-Mart (5.25 wt. %)	$ 0.90/gal

Margins and other information for selling price calculations:

Margin on cartridges	75 %
Margin on other costs	35 %
Engineering labor rate	$60/hour

OTHER INFORMATION:

OTHER FINANCIAL PARAMETERS

Your company will supply the equipment, cartridges, installation supervision, operator training and startup supervision. You must determine the cost of all of these items and mark them up using the margins above. The food company will perform the installation with your company's supervision. The cost of this installation will be 50 percent of the selling price of equipment and services which you (the engineering company provides). This installation cost will includes the working capital requirement and all other costs for the installation period. The total fixed capital investment is the selling price of the equipment and services plus the installation cost. Note, however, that the cartridge cost to the food company will be an operating cost, not a component of the fixed capital investment.

As part of the problem statement the "Inventory, Days on Hand" of 60 days and the "Accounts Receivable, Days" of 45 are given. These numbers are used to calculate the "Inventory" and the "Accounts Receivable" which are balance sheet items for the financial analysis.

"Days on Hand" of 60 days means at the specific date being considered, in this case at the end of the year, that there are 60 days of inventory available.

$$\text{Inventory} = \frac{(Days-on-Hand)}{365} \text{ x (Cost of Sales)}$$

"Days" of "Accounts Receivable" means that at the specific date being considered, in this case at the end of the year, that the average period of time that invoices to customers are outstanding before payment is 45 days.

$$\text{Accounts Receivable} = \frac{Days}{365} \text{ x Sales}$$

For the 10-year income statement for your design report, calculate "Inventory" and "Accounts Receivable" by these equations. You should calculate, not estimate, the working capital requirement for each of the 10 years of protein product manufacture.

Margins (in fractional terms) are used to calculate selling prices as follows:

$$\text{Selling Price} = \frac{Cost}{1 - Margin}$$

Remember that you work for the engineering company that will be selling a UF system to the food company. Your cost to design and manufacture the UF system (not including cartridges) can be estimated as follows:

Basic cost for a manual stage	$ 1,200 per cartridge position
Extra cost/stage (when part of a staged system)	10,000
Cost to automate each stage	6,000
Central control panel including PLC and motor starters	48,000
Cleaning system	55,000

The cost calculated by these guidelines will include all component costs (e.g., pumps, valves, piping, instrumentation, heat exchangers, if required, etc.). The cost of any balance tanks or product storage tanks is not included and must be estimated separately. The whey feed tank is already in place and a cost for it need not be estimated.

Your proposal should include a selling price for the system, selling price for the cartridges and a selling price for the supervision and operator training which your engineers will provide during the installation and startup period.

Your design will consist of stages with the hollow fiber cartridges in parallel. Because of the availability of system components such as valves and fittings, you are limited to using no more than 4-inch nominal stainless steel tubing for all process piping. Also, you should design the system so that the fluid velocity at any point is no more than 16 ft/sec to prevent shear stresses so high that there is a risk of protein denaturation. Piping pressure drops must be calculated to properly size the pumps.

Although the cost of pumps is included in the costing procedure above, the pumps must be sized as part of the complete documentation and so that power requirements can be determined. In the documentation show the pump model number, impeller size, and motor horsepower. Every pump as well as other components must be included on the Equipment Information Summary. For this project use pumps and other sanitary components manufactured by Tri-Clover, Inc. The Tri-Clover Catalog of Sanitary Processing Equipment can be found on Tri-Clover's web site, *http://www.triclover.com*. All equipment for this project must meet 3A standards for food processing. If there is a materials option, 316 SS must be used.

Any tanks required for the project, except for tanks in the cleaning system, must also be manufactured from 316 SS and must be of sanitary construction. The cleaning system tanks may be plastic.

Water will be needed to make up cleaning solutions and for diafiltration. The cost of soft water for cleaning is $5.00 per 1000 gallons and the cost of deionized water for diafiltration is $15.00 per 1000 gallons.

The system can be operated with one operator per shift.

Federal taxes are 34% and state taxes are 6%. For purposes of investment analysis, you may assume that the food company is profitable. This means of course, that if the profit center loses money in any year, for purposes of determining cash flow, the "net profit (loss) after tax" will be 60% of the actual loss.

Operating costs such as direct supervision, clerical labor, maintenance and repairs, operating supplies, and laboratory charges should be estimated. Clearly state your assumptions and the literature reference for the assumptions and methods.

WASTE TREATMENT

The plant is located in Springfield, MO. The liquid waste includes the permeate from the ultrafiltration system as well as spent cleaning solutions. If the waste is sent to the municipal treatment plant, the costs will be as follows.

$/1000 gallons of hydraulic load	$1.00
$/lb of BOD* above 300 mg/L	$0.12
$/lb of TSS (total suspended solids)	$0.10

- Estimate the BOD load based on BOD being 60% of the theoretical COD for the complete oxidation of organics, primarily lactose.

You may find that if you send the waste to the municipal treatment plant that the cost will be such that your customer may reject the project. As one option for disposing of the permeate you may consider concentrating the stream to 20% TDS (total dissolved solids). At this level of solids, the local farmers can use the waste as cattle feed and will arrange for tanker trucks to pick up the waste at the plant. They will not pay for the concentrated solution but will take it away from the plant at no charge to the food company. If you suggest this option to the food company, you must include capital and operating cost for concentrating the waste stream.

You may be able to find more cost effective ways of disposing of the waste and you are encouraged to do so.

Appendix I

Proposal Format

- **Title Page**
- **Table of Contents**
- **Executive Summary** – One page (maximum) condensation of report.
- **Introduction** – Orient the client to the assigned task.
- **Summary** – Summarize the results of the analysis and summarize the conclusions and recommendations. Briefly tell what options were considered and the advantages/disadvantages of each.
- **Conclusions** – Interpret your results. List your conclusions in decreasing order of significance.
- **Recommendations** – Emphasize business opportunity and potential process improvements. Address product quality.
- **Project Premises** – Itemize all pertinent process and economic premises, including (1) the overall project schedule, battery limits, etc., (2) feed and product specifications, (3) costs of raw materials, utilities, etc., (4) selling prices of all products (5) economic parameters, including depreciation schedule, taxes, project life, etc., (6) environmental requirements, (7) processing limitations, (9) extraordinary costs, (10) labor cost, (11) product quality considerations.
- **Process Flow Diagram (PFD**) – Include all items of process equipment, include and number all process streams, indicate all utilities needed per individual piece of equipment. Include all process control loops and pipe sizes.
- **Stream Attributes** – For each and every stream on the PFD include on the PFD or on a separate page a Tabulation of Stream Attributes (SA's), including Stream Number, Mass Flow of Each Component, Total Mass Flow, Temperature, Pressure and Volumetric Flow Rate (GPM for liquids & CFM for gases).
- **Process Description** – Include process conditions, equipment type and size and how the process equipment is integrated to achieve process objectives. Explain the purpose of each process equipment item. Control schemes should be included in this Process Description with primary emphasis on (1) what is controlled, (2) where is the controlled variable measured and (3) what type (e.g. flow or pressure) of controller is used.
- **Safety and Environmental** – What are the potential safety problems from an analysis of the flowsheet. Discuss any emissions and describe how they are handled to comply with environmental regulations.
- **Utility Summary** – Itemize in a table each utility by user. Give Usage per user, cost per unit of utility, yearly utility usage and total yearly costs.
- **Operating Cost Summary** – Itemize using the categories given in Peters and Timmerhaus, Fourth Edition, Tables 26 and 27, page 210 and 211.
- **Equipment Information Summary** – Itemize operating conditions and sizes of process equipment for each and every item of process equipment.

- **Capital Estimate** – Itemize the estimate per the procedures mandated in this memo. Give your companies costs (which normally the customer would not be told) and the selling prices.
- **Economic Analysis** – Include a discussion of the economic methods and analysis. Give a 10-year Income Statement, those Balance Sheet items necessary to calculate Cash Flow, any economic options which you need to present to the customer, the resulting IRR and Payout Time.
- **Innovation and Optimization** – Explain and document what was done to make the process the economic optimum. For example, plot IRR vs. key parameters such as number of stages.
- **Engineering Calculations** – Include all pertinent sample calculations and hand calculation although, as noted above, hand calculations are not acceptable for the process design of the ultrafiltration system.
- **Computer Programs** - Describe the computer programs or spreadsheet programs which are used. Include input and output files, an explanation of the model(s) used and the nomenclature. Every program must be fully documented with appropriate Nomenclature and Comments. This requires that cell formulas be included with spreadsheet programs.