

Implementation of Educational Modules in a Biotechnology Course: A Challenge Based Education Approach

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Abstract

Biotechnology is one of the active domains in the NSF funded Engineering Research Center VaNTH (Vanderbilt, Northwestern, University of Texas, and Harvard/MIT) where an educational mosaic is currently being developed. This mosaic covers a collection of challenges designed around bioreactors, mass/momentum transfer issues, microbial kinetics, and downstream processing, which are among core biotechnology topics. Aspects of this mosaic have been tested by students at Vanderbilt University and have proven to be useful. Based on the results from these studies, the challenges relating to bioreactors and mass/momentum transfer are currently being refined. At Northwestern, Birol and coworkers have developed challenge-based educational materials that focus on microbial kinetics and downstream processing. The combination of the work developed at Vanderbilt with the new challenge topics at Northwestern form the basis of the 'mosaic' for a course on biotechnology. The aim of this study was to design a new biotechnology course centered on challenge-based education and to implement the new educational tools. This paper focuses on the implementation of the mosaic at Northwestern in the new Bioprocess Technology Course (BME 395). We also focus on how the new biotechnology course at Northwestern builds on the work from Vanderbilt and discuss issues relating to the implementation of innovative course materials.

Introduction

During the 1998-99 academic year, Northwestern's Biomedical Engineering Department became part of the Vanderbilt-Northwestern, Texas-Harvard/MIT (VaNTH) Engineering Research Center in Bioengineering Educational Technologies funded by NSF. In this center, faculty (as domain experts) are currently working with learning scientists, learning technologists, assessment experts and students to develop educational modules and tools for bioengineering education. Learning science, learning technology and assessment are continuously being integrated into these modules (1-3).

As part of this educational endeavor, new courses are being developed and integrated with new educational modules to offer students a better learning environment. This paper describes the development and successful implementation of a unique undergraduate Bioprocess Technology course open to both undergraduate and graduate students. The Biomedical Engineering Department of Northwestern University (NU) offers a biotechnology specialization program and this course is a special topics course, which was designed to introduce biotechnology to bioengineering students. Bioengineering lies within the intersection of biology with engineering, the physical/chemical sciences and mathematics. The topics of this course were chosen in such a way to provide students with an in-depth description of biosynthesis and properties and biomedical applications of biotech processes.

Course Description

The primary learning goals of the Bioprocess Technology course were to provide students with basic principles in cellular and molecular biology of microbial and mammalian cells, give them a working knowledge of bioreactor operations and microbial kinetics and their industrial applications, and introduce product recovery processes of pharmaceuticals. In this course, we also aimed to promote and help students develop lifelong skills such as adaptive expertise, presentation and communication skills in an active learning environment. Furthermore, integrating the new educational modules developed at Vanderbilt into class material of a course at NU was the first attempt and required strategic planning. At the beginning of the course design process, the topics to be covered in the course were prioritized and learning objectives related to each topic were identified (Table 1). Stemming from the fact that the ideal teaching and learning strategy depends on the goals of the instructor, the level of knowledge and skills of the students, and the particular materials being taught, this course was designed based on the How People Learn framework (4,5).

Northwestern has a quarter system and each quarter is about 9 ½ to 10 ½ weeks long. The 10-week course consisted of two class meetings of 80 minutes/class per week. Table 2 shows the distribution of class time on the specific topics covered during the Fall 2001 quarter. Students were informed that they would be extensively working on challenges and were expected to participate in all in/out class activities and would be assessed regularly throughout the quarter. The grading policy consisted of two take-home exams (20% each), homework (30%), final team project (20%) and class participation and/or quizzes (10%). In addition, a course web site through Blackboard system was developed and maintained by the instructor served as a resource (all educational material distributed electronically) as well as an effective means of communication. A course diary was also maintained to keep track of daily activities.

Implementation

The Biomedical Engineering Department offered the new Bioprocess Technology course during Fall 2001 quarter. Eleven students enrolled for this course: nine seniors, one sophomore and one junior. Among these students, nine of them including the junior and the sophomore were in the biotechnology specialization area and two seniors were in the transport specialization area.

There were three educational modules that were integrated into class material: the first two (M1 and M2, see Table 1) covered bioreactor operations and were originally developed by T. D. Giorgio and S. Brophy at Vanderbilt. The first one (M1) focused primarily on bioreactor choice and the second one (M2) focused on mass and momentum transfer issues in bioreactors. The third one (M3) was a module on microbial kinetics that is under development by G. Birol and A. McKenna at Northwestern. The topics covered during this course are summarized in Table 2, which also shows how the educational modules were embedded into class material.

How People Learn Framework

Research on expertise and learning suggests designs for learning environments should consider four primary elements. First, education research suggests that learning environments be ‘learner-centered’. That is, the environment and class activities should take into account the knowledge, skills, preconceptions and learning styles of the learners. Second, a learning environment should be ‘knowledge-centered’ in the sense that it helps students learn with understanding by thinking qualitatively, and organizing their knowledge around key concepts. Third, learning environments should be ‘assessment-centered’ such that it provides frequent opportunities for students to make their thinking visible so that their understanding can be refined as needed. Finally the learning environment should be ‘community-centered’ in the sense that it fosters norms that encourage students to learn from one another, plus encourages faculty to do likewise (4,5).

Educational Modules

Each of the modules were designed and constructed by a team composed of one or more Domain Experts, Learning Scientists, Learning Technologists and Assessment Experts. Each module included a Challenge, methods to stimulate Idea Generation, presentations of Multiple Perspectives, questions and materials to support Research and Revision, opportunities to Test Your Mettle and methods to Go Public (Figure 1). The underlined activities represent the core of the STAR. Legacy method that was adopted as the template for module development (6,7). Details and contents of M1 and M2 are documented elsewhere. Challenge statements of the modules are presented in Table 3.

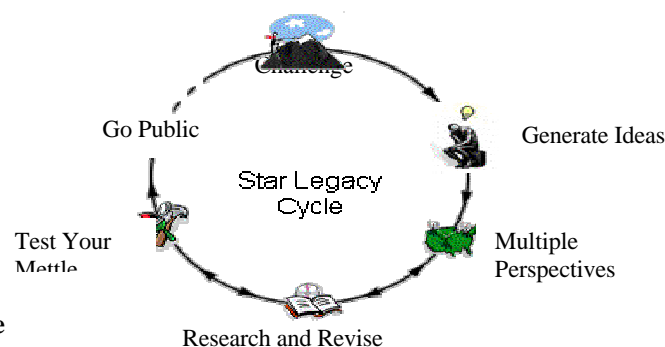


Figure 1. Star. Legacy Cycle

Overview of Class Sessions

The first 1 ½ week of class time was spent on general introduction and biology topics in a rather classical lecture format followed by a small discussion on the topic. During the second week topics on bioreactors were introduced. This included different modes of operation and corresponding mass balance equations, a typical bioreactor configuration, and specific issues related to bioreactor operations. After introducing the bioreactor topics, the first challenge statement (Table 3) was introduced to students in class and students were asked to write down their initial thoughts about the challenge for about 10 minutes. After this period, they were encouraged to make partners and share their ideas. All the generated ideas were collected by the instructor and posted anonymously on the course web site at the end of the lecture period. Students were asked to review the posted ideas and generate any new ideas based on their review of others' comments.

In the next class meeting, which took place in a PC lab, the first half of the class (approx. 45 min.) was spent discussing different bioreactor configurations, including some examples over the Internet, and some instrumentation and their applications (e.g baffles, spargers, impellers, etc.) in a classical lecture format. In the second half of the class time, students were divided into 4 groups (three groups of three and one group of two students). A small discussion on the ideas generated was held in order to address possible mis/pre-conceptions and highlight important issues that should be addressed in the remainder of the quarter. Then, the groups were assigned one expert from the software module to listen to and summarize what he/she said. (The expert and activity is contained in the Multiple Perspectives section of M1.) This activity took about 15 minutes and at the end of the activity, each group reported out the important issues raised by the expert, including their own thinking about the process. During the reporting out process, the instructor raised questions about the topic to facilitate discussion. Research and Revise activities were assigned as homework and were due next class meeting.

Research and revise activities were composed primarily of questions for discussion, and elements contained in the web-based bioreactor module. This was the formal mechanism of formative assessment. During the following class meeting, the instructor continued and finished bioreactor configurations and introduced mass transfer in a single phase. At the end of the class period, Test Your Mettle questions of the module (M1) were assigned as homework. In the next class meeting, the instructor reviewed the homework solutions and continued with mass transfer issues and correlations and also introduced power requirements in stirred tank bioreactors in a classical lecture format. Students also engaged in a 'share and pair' activity during the class. At the end of the class, Go Public questions of the module (M1) were assigned as a new homework set.

In order to promote synthesizing and applying the lecture plus module material, to critically evaluate their thinking, and to help them gain self-confidence on the bioreactors topic, Go Public questions (homework question 1) were administered as an on-line debate. Students were asked to post their solutions (these were multiple choice questions) by the end of the day with a clear explanation and reasoning about their choice. Then, they were expected to review each others'

answers and debate about their answers with a sound justification through the course web site. And at the end of the debate, they were expected to post their final answers with some explanation and reasoning if their answers were different from their initial answers. After the debate, when the class met again, the instructor went over these solutions. The second module (M2) was implemented in a very similar way to the first module. The topics covered (Table 1) were basically momentum and mass transfer in bioreactors and it took about two weeks to complete the module. In the meanwhile, the instructor also covered scaling up of bioreactors topic. At the end of each module and the class material on bioreactors, a series of assessment techniques were carried out and will be discussed in Assessment part of this paper.

The in-class activities turned out to be very fruitful in motivating students' interest towards the topics covered. Since it is very common in a 80 min. class period, after 45 min. or so, to see students' interest decline. These activities helped bring students back in focus. Assigning a weight to class participation (10% of the total grade) also promoted in-class questions and participation in class discussions and activities.

Note that the material covered in class was not the same material covered through the modules (M1, M2 and M3) but was carefully chosen to compliment each other. In this sense the instructor could cover a wider range of material than she would cover if she did not use the module. Most of the time, examples presented in class were based on microbial cell cultures while the modules (M1 and M2) were based on mammalian cell cultures. The topic choices also challenged the students to think beyond the course material and apply their knowledge to new situations, which was among the course objectives.

The implementation of the third module that was under development at NU was slightly different than the first two modules. There were several goals in this first implementation of the kinetics module. First we wanted to document students' mis/pre-conceptions about the topic of microbial kinetics. In addition, based on student input, we can adjust the level of complexity of the module and revise any technical problems for future implementations. All the activities were designed based on the how people learn framework. The details of the module development are described elsewhere (8). The module was introduced after one lecture on microbial kinetics: Cell population kinetics, modeling, parameter estimation, and different models in biotechnology with varying complexities. Since one of the learning goals of this class was to promote and help students develop lifelong skills such as presentation and communication skills, it was critical that the structure of the course promoted group interactions throughout the quarter in many activities. Thus, the homework assignments for the third module were designed to necessitate group work. For the rest of the quarter, the students worked with the same group members of their choice. There were four three-student groups and one two-student group. In order to make sure a fair distribution, the junior and the sophomore students were encouraged to form a group that had at least a senior student in the group. Each assignment was followed by a presentation and a class discussion and the students handed in a report. After every assignment (total of three), the instructor went over the report and provided immediate feedback since the next report would consist of a revised version of the previous one with additional requirements of that particular assignment. At the end of three assignments, the students formed one single, formal report. All

the presentations were videotaped and a graduate student took notes during the discussion. Documenting these events will help inform the module development process. This module was completed within a three-week time span and during this period, the instructor introduced related course material (refer to Table 1) in a classical lecture format including extensive discussions with students. Two lectures were spent on presentations (ca. 12 min-15 per group). At the end of the module, a series of assessment techniques were implemented and will be discussed in the following section.

Students contacted the instructor via e-mail or in person. Whenever a student raised a question on a lecture topic or the homework, the instructor either sent an e-mail to the whole class or addressed that issue in class, whichever came first. In some cases she posted the questions on the course web site. Furthermore, all the solutions (e.g. homework, exam, other assignments etc) were posted right after students handed those in on the web site. This allowed maintaining a good level of communication and continuity.

Assessment

In order to assess the achievement of the learning objectives of the Bioprocess Technology course, a series of assessment methods were applied. Table 2 summarizes the specific assessment methods and when they were administered. A team of domain experts, learning scientists and assessment experts is currently working on analyzing the extensive data obtained through these assessment methods. The data will be reported as they become available.

Basically, there were three levels of assessment: (i) course as a whole which was achieved by pre/post tests and concept mapping activities, (ii) module specific assessment which included surveys, muddiest points (9) and reflection activities, (iii) assessment of learning objectives which included homework, two take home examinations and class participation.

Pre and post-tests were administered at the beginning and at the end of the quarter (Table 4). The tests consisted of three parts, the first part was designed to capture general, 'adaptable' problem solving skills (e.g. students' abilities to design a plan and identify necessary resources), the second and third parts were designed to gauge understanding of concepts covered in Bioreactor (M1 and M2) and Microbial Kinetics (M3) modules. It was also aimed to compare student responses across campuses (i.e. Vanderbilt and Northwestern) and to capture learning and potential 'value-added' of modules. Currently, a rubric to code the responses is being developed.

Concept mapping is the representation of the major semantic relationships among a set of conceptual terms (10). Two questions were designed to capture students' understanding of biotechnology and microbial kinetics concepts. The first question was "What is *Biotechnology*? And how does it relate to Biomedical Engineering?" The second one was "What are the factors affecting *cell growth rate*? What are the factors affecting *product formation rate*? How are they related?"

Surveys were targeted to obtain information about the effectiveness of the modules as an educational tool and were in the form of questionnaires completed at the end of each module. The muddiest points about the modules were also asked at the end of each module and targeted to uncover the ineffective parts of the module (e.g. a technical difficulty, lack of information, muddiest points about the presentation of questions etc.).

The reflection activity assignments encouraged students to reflect on what they wrote down earlier on their pre-test solutions and revise their answers accordingly. This served both as an assessment of their ability to notice and change their thinking and an instructional device to help them keep sight on their learning goals. Table 5 shows this activity. Homework and exam questions formed the formative assessment of this course.

Summary

A new Bioprocess Technology course was designed and implemented. Three educational modules based on the how people learn framework were effectively integrated into class material facilitating the achievement of the learning objectives of the course. An extensive assessment plan was developed and a team of domain experts, learning scientists and assessment experts, is currently analyzing the data generated, which will be reported as they become available.

Some preliminary conclusions drawn from this work are:

- The timing of the introduction of the challenge turned out to be critically important in order to be useful to the students. Introducing the challenge earlier was found to be more practical than introducing it later since the latter might have created redundancy if the material covered in the module would have already been introduced to the students in the lecture. Furthermore, introducing the challenge earlier in the course helped to create interest in the topics and to focus students on the learning goals.
- The course material to be covered in the class as a lecture by the instructor and by the modules needs to be adjusted in such a way to avoid repetition yet to compliment each other.
- Student involvement was very high.
- Integration of educational modules helped the instructor cover more course material than would have covered in a classical lecture format.
- The assessment plan developed will be refined and used in other courses as well as in the refinement of the modules (M1 and M2) and in the design of the new module (M3).

Table 1. A Summary of Priorities of Topics, Learning Objectives and Educational Modules Used in Bioprocess Technology Course, M1 and M2: Bioreactor Operation Module, M3: Microbial Kinetics Module

Bioprocess Technology (Priority Levels, F:Familiar, I:Important,E: Essential)	Module	Learning Objective
1. Biology (I) 1.1. Cellular Biology (I) 1.2. Molecular Biology (F)		<ul style="list-style-type: none"> • Identify specific classifications of cells such as microbial, plant and animal, • Notice (or recognize) the importance of cells in biotechnology, and be aware of cells' capabilities, • Learn about their physiology, morphology, reproduction characteristics, • Define their growth environments and conditions • Be aware of the benefits of the recombinant DNA technology and techniques and of gene manipulation
2. Bioreactors (E) 2.1. Cell Cultivation (E) 2.2. Operation and Analysis (E) 2.3. Momentum and Mass Transfer Issues (I)	M1 M2	<ul style="list-style-type: none"> • Classify bioreactor types, • Explain the major differences among various bioreactor types, and recognize the constraints of bioreactors, • Learn the different types of cultivations, • Recognize the constraints for cultivation of different cell types • Be able to choose the right bioreactor configuration for a given cell culture conditions, • Learn about the operation and analysis of bioreactors, • Learn about the mass transfer limitations in bioreactors, • Explain the effects of manipulated variables (e.g. agitation rate, aeration rate etc) on cell growth and product formation,
3. Microbial Kinetics (E) 3.1. Stoichiometry of Growth and Product Formation (E) 3.2. Biomass Formation (E) 3.3. Product Formation (E) 3.4. Substrate Utilization (E)	M3	<ul style="list-style-type: none"> • Know how to make use of stoichiometric information, • Learn to perform elemental material balances, and to estimate yield coefficients, • Explain how and why cell, product and substrate concentrations changes in batch cultures, • Learn what the specific growth rate, specific product formation rate are, • Define rate expression for cell growth, for product formation given the growth conditions, • Explain the differences in rate expressions for cell growth and for product formation • Recognize the limitations of growth, of product formation • Demonstrate the ability to write down a rate expression for a given data set and to solve it, • Compute the specific growth rate, the specific product formation rate, • Demonstrate the ability to combine cell growth and product formation data to find substrate utilization, • Learn how to apply yield coefficient information to define substrate utilization,
4. Product Recovery (F) 4.2. Separation of Insolubles (F) 4.4. Primary Purification (F) 4.5. Final Purification (F)		<ul style="list-style-type: none"> • Identify the major steps in product recovery for a given product and recognize the different purification methods, • Explain the differences between different levels of purification

Table 2. Class time distribution and the corresponding methods of assessment on the topics covered.

<u>Week 1-2</u>	
Assessment: Pre Test Concept mapping activity	
Introduction 1. Biology 1.1. Cellular Biology 1.2. Molecular Biology	
<u>Week 3-7</u> 2. Bioreactors 2.1. Cell Cultivation 2.2. Operation and Analysis 2.3. Momentum and Mass Transfer Issues	<p>M 1 – Bioreactor operation (adopted from Giorgio's module) <i>Assessment:</i> <i>Survey on Module</i> <i>Muddiest Points</i> <i>Reflection Activity</i></p> <p>M 2 – Bioreactor operation (adopted from Giorgio's module) <i>Assessment:</i> <i>Survey on Module</i> <i>Muddiest Points</i> <i>Reflection Activity</i></p>
Assessment: Post Test 1 (as part of Midterm Exam 1)	
<u>Week 8-10</u> 3. Microbial Kinetics 3.1. Stoichiometry of Growth and Product Formation 3.2. Biomass Formation 3.3. Product Formation 3.4. Substrate Utilization	<p>M 3 – Microbial kinetics (module under development at NU) <i>Assessment:</i> <i>Survey on Module</i> <i>Presentations</i></p>
Assessment: Post Test 2 (as part of Midterm Exam 2) Concept mapping activity	
<u>Week 11 (out of class activity)</u> Product Recovery: Impact of Recombinant DNA Technology on Protein Recovery Product Recovery: Separation of Insolubles; Initial Isolation and Concentration; Primary Purification; Final Purification	
Assessment: Presentations	

Table 3: Challenge Statements of the Educational Modules

Module 1 (M1):

The production of therapeutic proteins from mammalian cells requires consideration of multiple, connected issues. The optimal conditions for cell growth depend of the cell type, the desired rate of product synthesis, bioreactor design and operating conditions. Commercial production of therapeutic proteins presents a particular set of challenges resulting from the large scale required.

We will consider two cell types that could be used to support the production of rFVIII - '293 cells' and CHO (Chinese hamster ovary) cells.

We need to decide which one of these cells will be the best host for producing the product in terms of both efficient and correct synthesis. Our first challenge is to identify the conditions that will best sustain robust growth for each of these cell types.

Therefore, what is the best bioreactor design for growing the desired amount of each cell type?

Module 2 (M2):

CHO cells grown on 200 mm diameter microcarriers have been selected for the large scale production of Recombinate. Economic analysis suggests that the optimum production strategy requires recovery of 2,200 liters of raw cell culture product per day. The resulting bioreactor volume is 2,500 liters and three such bioreactors are required. For this production volume, and the specified use of microcarriers, the design must be a stirred bioreactor. The goal of our challenge is to design the bioreactor to optimize Recombinate production. Therefore, you need to consider at least two important questions:

1. What physical and operating characteristics must be considered?
2. What additional data is required before the optimum conditions can be predicted?

Module 3 (M3):

The Board of Directors of Microbaway Antibiotics, Inc. has just voted on allocating funds towards construction of a new production facility to be used for the production of penicillin, a highly profitable antibiotic. As members of the Microbaway Antibiotics, Inc. Product Development team, it is your task to develop a mathematical model describing the microbial kinetics of penicillin production. This model will be used to maximize penicillin production at the new plant prior to production.

You will need to review production data in order to generate your model. Anne T. Biotic, a fermentation expert from SporeTech Pharmaceuticals, will help you run some experiments at one of SporeTech's penicillin production facilities, PenSim. Anne will provide you with the initial operating conditions from the last several production runs as a starting point in your analysis (we are also planning to run our plant at these operating conditions). Microbaway's management has requested that a preliminary report defining and assessing the kinetics of penicillin production be presented at the manager's meeting next week. This report should include the proposed model of the relationship between biomass, nutrients, penicillin and/or others as they are related, any assumptions, simplifications etc. It is very important that you substantiate your proposed model via simulation results and support your findings.

After the development of this initial report, your team will need to test your proposed model based on a set of experimental data that will be provided to you by the fermentation expert. This will allow you to validate/invalidate your model. Your team will need to generate another report for presentation at the quarterly Director's meeting to take place in Maui, Hawaii, in November.

Table 4. Pre/Post Test

General Instructions: This activity is designed to help you explore the multiple dimensions of cell growth and product manufacturing. The challenge below is a complex problem that includes new vocabulary, biological and engineering concepts. Over the next few weeks we will be learning more about all of the ideas presented in the challenge below. You need to take this opportunity to participate in this activity to the best of your ability. You should identify anything you are uncertain of and identify what you would do to research more to remove this uncertainty. Your effort on this activity represents -10% of your score on the first midterm exam.

Part A. Recent sports reports have focused on the use of proteins as supplements to enhance an athlete's performance. As such, there is great interest in the pharmaceutical industry to produce protein-based products that can be used in over-the-counter performance enhancing supplements. You have just been promoted to project manager at ProteinPlus Corporation. ProteinPlus Corporation's primary role is to design protein production facilities and to oversee the implementation and production process. Your first task in your new role as project manager is to design a protein production facility that will supply the necessary protein products for use in these supplements. As part of this assignment please address the following tasks.

- Discuss the factors that are involved in the design of a protein production facility. This should include biological issues, modeling issues, and any other technical or practical issues you feel are important.
- Describe a plan for how you would carry out the necessary steps in your design.
- Identify who you would recruit and what resources you would use to help you with this project and why.

Some background information:

In order to get FDA approval milligram quantities are necessary to carry out clinical trials. The laboratory-scale bioreactors used in the pre-production are inadequate to meet the expected product demand (annual protein product market need to be 100 g per year). Since the ProteinPlus used to obtain FDA approval was produced by SHP-77 cells, which are a human lung tumor cell line and grow in small clusters in suspension, these same cells will be used for the large scale production. Observations of cell behavior in the laboratory-scale bioreactors suggest that the cells are both sensitive to mechanical damage and have a high metabolic rate. The doubling time of SHP-77 cells under ideal conditions is 96 hr. The maximum cell density observed was $8.0 \times 10^{+5}$ cells/cm³ and typically occurred 384 hr after the initial inoculation of cells at $1.0 \times 10^{+5}$ cells/cm³. The process was terminated at the time of maximum cell density and the final ProteinPlus product was recovered at the rate of 0.8 mg per laboratory-scale bioreactor of which specifications are given below. The largest laboratory-scale ProteinPlus bioreactor previously used had the following characteristics:

bioreactor volume ≈ 1000 cm³, bioreactor diameter = 7.5 cm, bioreactor fluid height = 22.5 cm
impeller type = single paddle, impeller diameter = 2.5 cm, impeller rotational speed = 80 rev/min
cell type = SHP-77, ProteinPlus final product = 0.8 mg

Instruction for Part A: The goal of this activity is to help you explore what you know about the factors involved, how these factors relate to each other, and how you would propose and execute a plan to develop and implement your design. Therefore, you need to identify a method to represent this relationship of factors so that you can explore and communicate multiple solutions to this problem.

Part B.

Design the scaled bioreactor(s) to meet the estimated annual need for ProteinPlus. Report the following in a clear way: number of bioreactors, [number], volume per bioreactor, [cm³], bioreactor diameter, [cm], reactor fluid height, [cm], impeller type, [type], impeller diameter, [cm], impeller rotational speed, [rev/min]. *This is a long problem without additional intermediate solutions to guide your work. There is also no single correct solution. Maximize your score on this open-ended question by providing clear answers to the following questions at the appropriate point(s) in your solution:*

- describe the options available at each point in the design
- identify the basis for your choice among options
- comment on and provide support for the likely validity of your assumptions
- note the additional information you would seek before finalizing the design

Part C.

In this part, propose a kinetic model of for the protein production to be used as a basis for data prediction. For the given bioreactor configuration, write down the rate of change of biomass, protein, substrate concentrations and other substance(s)' concentrations that you think should be included.

Keeping in mind that there is no single correct solution, maximize your score on this open-ended question by providing clear answers to the following questions at the appropriate point(s) in your solution:

- describe how you would make use of information provided in the background,
- consider different limitations/constraints that cells may encounter during growth and/or protein production,
- write the rate expression(s) explicitly,
- comment on and provide support for the likely validity of your assumptions,
- propose a strategy to find the model parameters
- note the additional information you would seek before finalizing your proposed model.

Table 5. Reflection Activity

Earlier in the previous challenge (M1 or M2) you responded to several thought questions. Take a moment to review your responses (distributed by your instructor) and expand on them by answering the questions listed below. Articulating what you currently know will help you identify potential ideas for how to refine your exploration of the challenge question in PreTest.

- a. What more could I teach someone about producing the ProteinPlus product?
- b. What did I record earlier that is not right and why?
- c. What more do I need to know to solve this challenge?
- d. Where could I find this additional information?

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Biographical Information

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Gülnur Birol received BSc, MSc and Ph.D. degrees in chemical engineering from Bogazici University in 1990, 1992 and 1997 respectively. After a postdoctoral year at Louisiana State University, and two and a half years as a senior research associate at Illinois Institute of Technology where she has taught a number of courses in Chemical and Environmental Engineering, she joined Biomedical Engineering Department of Northwestern University as a Research Assistant Professor. She is one of the project leaders in biotechnology domain in the VaNTH Engineering Research Center (ERC) sponsored by the National Science Foundation.

ANN MCKENNA

Ann McKenna is currently a Post-Doctoral Fellow at Northwestern University. She received her B.S. and M.S. degrees in Mechanical Engineering from Drexel University in Philadelphia, Pennsylvania and a Ph.D in Engineering Education from the University of California at Berkeley. Before returning to graduate school to obtain an interdisciplinary degree in engineering education, she spent two years in Japan as a research engineer. In addition to research, Ann has taught an Introduction to Engineering class to high school students through an outreach program at the University of California, and frequently holds workshops to encourage women to pursue science and engineering.

TODD D. GIORGIO

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SEAN BROPHY

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