Project Description

This is a Phase II proposal to introduce biofilm education rapidly into undergraduate courses in all relevant Science, Technology, Engineering, and Mathematics (STEM) curricula at all academic levels through the creation, dissemination, evaluation, refinement, publishing, and long-term maintenance of ***Biofilms: The Hypertextbook***—a unique, Web-based, active-learning teaching and learning resource on the new subject of microbial biofilms.

1. Introduction

Only occasionally does research generate a revolutionary body of knowledge so extensive that it compels fundamental changes in content across many curricula. Such is the case with the emerging discipline of biofilms. The recognition that microorganisms on surfaces generally live in heterogeneous colonies (i.e., biofilms) with inherent defense mechanisms and other characteristics not found in those same microorganisms in aqueous solution is radically changing our view of microbiology and profoundly affecting practice and research in academia, industry, medicine, and dentistry.

It is imperative that this new knowledge be infused into undergraduate instruction so that students in relevant disciplines become educated in biofilms. Faculty at community colleges, four-year institutions and research-intensive universities in the U.S. and many other countries are clamoring for instructional resources that will help them integrate biofilm education into their courses. Industries are looking for new hires who understand biofilms. Medicine and dentistry need baccalaureate graduates in the health care fields, as well as pre-med and pre-dentistry students, with knowledge of how biofilms will affect their practice. The need for undergraduates prepared to embark on biofilm research for advanced degrees is growing. And it certainly makes good sense to ensure that all students graduating in relevant STEM fields understand the nature and impact of the biofilm phenomenon. (See the letters of support.)

At this point there are very few courses anywhere in the world that incorporate biofilm topics, and no teaching and learning resources (e.g., textbooks) with substantial coverage of biofilms. This proposal outlines a three-year project based on a successful prototype to produce, evaluate, disseminate, and sustain a unique offering that will meet the wide and diverse needs for such a resource: ***Biofilms: The Hypertextbook***, a browser-based, active-learning resource for instructors and students that will be distributed on DVD media.

The project has a student and instructor focus that will result in three important contributions to the STEM knowledge base: (1) innovative methods for rapidly integrating the teaching and learning of biofilms into STEM curricula, (2) an interactive teaching and learning resource in the form of a hypertextbook that meets the pressing need for undergraduate biofilm educational resources, and (3) a unique hypertextbook model that can be applied to any STEM discipline. These will be ready for wide dissemination and commercialization as NSF requires.

The project will be carried out at the Center for Biofilm Engineering (CBE) (www.erc.montana.edu) at Montana State University (MSU). Begun as an NSF Engineering Research Center in 1990 to explore the emerging field of biofilms, the CBE is highly successful and recognized around the globe by researchers and industry alike as one of the world's premiere biofilm research and education centers. This project builds on a pilot project funded by the earlier NSF CCLI Educational Materials Development (EMD) program that resulted in a prototype of ***Biofilms: The Hypertextbook,*** found at www.erc.montana.edu/biofilmbook.

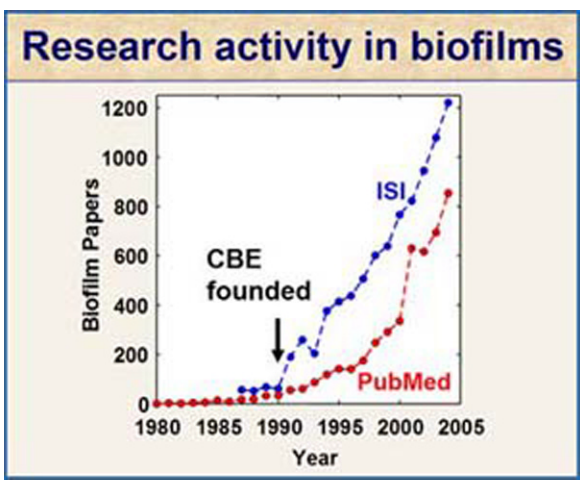
This is an exciting project that involves many collaborators—undergraduate student advisors, instructors in the field, researchers and educators with a wide variety of STEM backgrounds, graphics design and Web experts, computer programmers, an expert education evaluation specialist, and academic and industrial supporters. It is a project with the profound potential for worldwide, positive effects on both biofilm education and the future of interactive teaching and learning resources!

1.1 Biofilms

Biofilms are composed of microbial communities that are attached to an environmental surface. These microorganisms encase themselves in an extracellular polysaccharide or slime matrix[1]. For over one hundred years, students of microbiology and their teachers have been locked in a different learning paradigm in which microorganisms are studied and conceptualized as free-floating cells in aqueous suspension. Research of the past 25 years has revealed that this view of microbial life is misleading, to say the least [24]. In nature, microorganisms on surfaces thrive in communities of a complexity rivaling or perhaps exceeding that of tropical rain forests. These communities consist of many, sometimes hundreds, of species occupying distinct ecological niches and interacting with other microbes in a variety of roles—sometimes synergistic, sometimes antagonistic—but rarely neutral.

All of this might be little more than an interesting footnote to our understanding of microbiology except for this key fact: ***Biofilms exhibit emergent properties not easily predicted from the known properties of the individual species involved. That is, traditional approaches to the study of microbiology do not provide students with an understanding of how microbes actually exist, grow, respond to treatments, and other phenomena in many natural environments***.

Indeed, it is now known that almost everything we have learned about microbiology heretofore needs to be rethought in the light of biofilms. Treatment substances and regimens shown to kill harmful microbes in an aqueous suspension are often ineffective when used on a biofilm. Chronic wound and medical implant infections that seem highly resistant to treatment are now recognized as complex biofilm infections, providing insight into the intractability of these infections. The slime and sludge that plague many industries from petroleum, to chemical, to manufacturing are understood to be biofilms that require special cleaning and treatment processes. The list goes on! Biofilms literally cost the nation billions of dollars every year in energy losses, equipment damage, product contamination, and medical infections.



However, not all biofilms are harmful. Many are neutral and play key roles in the ecology of the earth. Some are also beneficial, and can be engineered to bioremediate hazardous waste sites, biofilter industrial wastewater, and form biobarriers to protect soil and groundwater from contamination.

As seen in the graph at the left, the literature on biofilms is growing rapidly and is too large to cite here. However, reviewers who so desire can gain a better understanding of biofilms by perusing the prototype of ***Biofilms: The Hypertextbook*** at www.erc.montana.edu/biofilmbook. Other websites listed in the references [33, 34, 35, 36, 37] also provide good information. An Internet search on biofilm(s) will uncover yet more sites.

1.2 Need for Biofilm Education and Educational Resources

The upshot is this. A decade ago biofilm science and engineering was the province of only a handful of researchers and students worldwide. Today the importance of biofilms is much more widely recognized. However, because of the highly interdisciplinary nature of the topic, lack of instructor awareness and

[1] Indeed, biofilms are more affectionately referred to as *slime*, and those who study biofilms as *slimeballs*—but only behind closed doors. We originally titled our hypertextbook *The Study of Slime*, but decided in the interest of decorum to change it to the more stately *Biofilms: The Hypertextbook*, even though the first title would undoubtedly have had more appeal to students.

training, and a dearth of courses dedicated to the study of biofilms, few educational resources exist for instructors desiring to teach—and students wishing to learn—biofilm concepts and how to apply them.

A recent search of eight of the most commonly used microbiology texts revealed scant coverage of the topic. These books range in length from 800 to 1000 pages, but their treatment of biofilm microbiology ranges from 0 to 13 pages including illustrations. Among medical texts examined the situation is, if anything, even worse. Among 12 commonly used medical microbiology texts ranging in length from 300 to 800 pages, the longest segment on biofilms is 20 pages; seven of the texts don't mention the term at all, in spite of the fact that biofilms are now implicated in over half of nosocomial infections [26, 27].

The need for biofilm education and educational resources is clearly evidenced in the letters of support. Letters from faculty at a wide diversity of institutions—Princeton, Yale, USC School of Dentistry, University of Minnesota, Texas State University, Little Big Horn College (a Native American tribal college on the Crow Indian Reservation of Montana)—voice unified support for the project and offers to evaluate and/or class test the hypertextbook. Their letters echo a common theme that reverberates with all faculty who have encountered the project: anticipation and encouragement to complete ***Biofilms: The Hypertextbook***. Letters from industry—Albemarle (specialty chemical), American Water, Church & Dwight (consumer products), INL (government national research lab), DuPont (specialty chemicals), Smith & Nephew (medical), and Southwest Regional Wound Care Center—also express strong support for the hypertextbook and underscore two common threads: industry is in need of graduates who have education in biofilms, and industry also needs on-the-job training materials in biofilms.

1.3 A Solution ─ Biofilms: The Hypertextbook

Biofilms: The Hypertextbook will meet these challenges. A *hypertextbook*[2] is a comprehensive teaching and learning resource that can be delivered on DVD media and made accessible through ubiquitous Web browsers, such as Firefox, Internet Explorer, Netscape, and Safari on virtually any computer platform anywhere in the world. Distribution via DVD media implies that there is no need for students to be connected to the Internet to use a hypertextbook; instead, students insert the DVD edition of a hypertextbook into their drive, start their favorite browser, and point the browser to the homepage on the DVD. This brings up the "cover" of the hypertextbook. From that point on students access the hypertextbook using all of the familiar browser operations.

Not to be confused with "electronic books" (e-books) that are generally little more than PDF versions of their hardcopy counterparts, hypertextbooks represent a new paradigm that exploits all of the capabilities of the computer in the presentation of learning material. In addition to the standard text presentations of the subject matter and high-resolution display of images found in traditional textbooks, a hypertextbook can include: ● **audio**; ● **slideshows**; ● **video clips**; ● **dynamic learning aids** (e.g., popup calculators); ● **simultaneously available beginner, intermediate, and advanced tracks** through the material; ● **interactive self-test quizzes** with feedback; ● **interspersed direct links** to primary literature and other related Web-based information, and—most uniquely— ● **active learning models** of important concepts and processes. All of these features are seamlessly interwoven in a hypertextbook to create an integrated resource.

Given the rapid progress in our understanding of the science and engineering of biofilms, a hypertextbook on biofilms is particularly appealing. Unlike traditional hardcopy textbooks, since it is in electronic form and accessible through standard Web browsers, a hypertextbook is: ● **easily updated** as new knowledge emerges; ● **universally accessible** throughout the world; ● **feature rich** in terms of the number of images, illustrations, slide shows, video clips, and active learning models that can be included; ● **extremely flexible** through hyperlinking; ● **affordable** when compared to traditional textbooks (e.g.,

[2] It should be noted that the term "hypertextbook" is used by others to describe various sorts of Web-published material. The hypertextbook concept as described here, however, is unique in that it has been developed and refined by co-PI Rocky Ross over a number of years [3, 4, 9, 11, 23, 40, 41, 42, 43] for his field of computer science, and more recently adapted to the study of biofilms [9, 17, 18].

$10-$15 as opposed to $100-$150); ● **adaptable** to different courses in terms of both academic level and desired content, which can be selected from the hypertextbook with ease; and ● **widely applicable** in that the overall design and structure of a hypertextbook can be applied to any STEM subject matter.

2. Results of Prior NSF Support

Two CCLI pilot projects previously funded by NSF are directly relevant to this proposal.

- Alfred Cunningham, and Rockford Ross. NSF 0089397. Moving biofilm research into teaching: a prototype interactive Web-based approach. February 1, 2001 – January 31, 2003. $74,942. See [9, 19, 39].
- Rockford Ross. NSF 0088728. WebBook: A prototype for the next generation of interactive computer science learning resources. January 1, 2001 – December 31, 2003. $74,717. See [4, 9, 13, 38]

These two grants led to the development of Prototype 1 of ***Biofilms: The Hypertextbook***. It was demonstrated at several venues, including the Biofilms 2003 ASM Conference; the CBE Technical Advisory Conference at MSU in February 2004; the 2004 ASM Conference for Undergraduate Educators; and the Biofilms 2004 IWA Conference. Over 160 educators, practitioners, and industrial observers expressed enthusiastic support for the project and signed up to be kept apprised of progress and/or to serve as evaluators. These activities documented the clear need for biofilm information by academic and industrial practitioners. They did not, however, objectively address the effectiveness of the hypertextbook concept or its impact on student learning outcomes.

In June of 2004, Prototype 1 formed the basis of a “full development” Educational Materials Development (EMD) proposal to the previous NSF CCLI program. The proposal received generally very positive reviews but was not funded. Reviewer feedback indicated that the project team should address the following concerns and then resubmit the proposal: (1) obtain and submit formal letters of support, (2) collect more direct evidence from students and faculty about the ease of use and intellectual impact of the prototype of ***Biofilms: The Hypertextbook***; (3) clarify the dissemination timeline; and (4) include a budget justification (a Fastlane problem). (All of these issues have been addressed in this proposal.)

With these encouragements in mind, the CBE team intensified its commitment to ***Biofilms: The Hypertextbook.*** Prototype 2 was developed. It boasted a new, polished, professional look, new content, and some new features. It was electronically disseminated to the entire list of supporters of the earlier proposal, some of whom have provided new letters of support (attached in the supplementary materials section). Dr. Anderson, the Educational Evaluation Specialist, worked directly with the MSU team to develop and independently field-test student and faculty questionnaires in the Spring 2005 semester. In March 2005, Dr. Judith Kandel, Professor of Biological Sciences at California State University- Fullerton conducted a pilot use of Prototype 2 in her microbiology class. In June 2005, a team member presented Prototype 2 at the ASM Conference for Undergraduate Educators in Atlanta. In July 2005, the entire CBE team, including Dr. Anderson (arriving as a pro bono consultant), interested MSU content specialists, and members of the CBE Advisory Board met for three days to assess the relevance and accuracy of the biofilm content in the prototype, the effectiveness of the hypertextbook technology, and the implications of the pilot data (quantitative and anecdotal). In August 2005, Anderson and a focus group of minority students examined the hypertextbook and discussed using biofilm research in Towson University’s Summer 2006 NIH BRIDGES program GM058264-02. Then, in Fall 2005 the CBE team revised the hypertextbook once again based on formative evaluations of the project. That year of work generated the following products that will enhance and improve this Phase II project:

(a) Prototype 3 of ***Biofilms: The Hypertextbook*** **(local project team)**. This is the most recent prototype of the hypertextbook and is the one detailed in the supplementary materials (placed there on advice from a current NSF CCLI program officer). It contains more content—complete with additional images and applications—and is the version found on the project Web site at www.erc.montana.edu/biofilmbook.

(b) Formal quantitative and qualitative data (project team including Anderson). This data was obtained from the *Student Feedback Form* [48] and the *Instructor Feedback Form* [48]. Tabulations of returned student evaluation instruments (N= 27) across several different instructional levels and types of courses [48] indicated that overall students: (1) had a positive experience with the hypertextbook, (2) felt that the hypertext helped them visualize biofilm concepts better than a textbook, (3) believed that the integrated slide shows, video clips, and interactive model made it easier for them to visualize and understand biofilms and biofilm processes, and (4) had little technical trouble using the hypertextbook. One issue of concern for students stemmed from the intermediate level of the presentation of the content in Prototype 2, which appeared to be too advanced for some of the classes in which the prototype was evaluated. This is addressed in Prototype 3 by including a new "Introduction to Biofilms" module that has both a beginner track and an intermediate track. Instructors (N=5) completing the Instructor Feedback Form [48] concurred with the students on points 1 through 4, but their major concerns were the need for expanded materials at different skill levels. Prototype 3 directly addresses their concerns.

(c) A student learning outcomes pilot study (Anderson). Conducted at Cal State–Fullerton, this study examined the impact of ***Biofilms: The Hypertextbook*** with respect to augmenting microbiology content with biofilm instruction in an intermediate level course. Students (N=60) completed the course unit test; their grades were used to assign them to one of three groups: top 1/3, middle 1/3, and lowest 1/3. Students also completed the *Student Feedback Form* and their responses were test-blueprinted for questions 9, 10, 11, and 15, which were indicative of the "intellectual power" of the hypertextbook to engage the learner. Responses to individual questions were scored from 0 to 3, thus 12 was the highest possible score for these four questions. The mean scores of the groups (N=20 each) were TOP (6.85), MIDDLE (8.00), and LOWEST (6.35). Post-hoc t-test analysis of these data between groups (degrees of freedom -2) and within (DF-57) groups strongly suggested, but did not establish at the .05 level, that the MIDDLE 1/3 scoring students were most responsive to and impacted by the prototype of the hypertextbook. Other formative items that should be noted about student learning in this research study were: 95% of all students, regardless of group, found that the hypertextbook aided them in visualizing biofilm concepts and what STEM practitioners do, 75% of both the HIGH and MIDDLE groups reported using research literature links given in the hypertextbook, a figure that dropped to 45% for the LOWEST group. The frequency and nature of technology-related comments did not differ across the three groups.

Space does not allow for a more thorough analysis of the evaluations here. Suffice it to say that overall these initial observations lead to strong substantiation of the effectiveness of the hypertextbook concept as a way to integrate biofilm concepts into existing STEM courses in various disciplines, help STEM students learn about biofilms, engage STEM students in learning in novel ways that keep them motivated, and in meeting the needs of STEM instructors who desire to incorporate biofilm education into their courses. Thorough evaluation of the Phase II project will shed more light on these aspects of the project.

3. Goals and Objectives of the Current Project

The past year of dedicated effort by the team has been motivated by the results of the evaluations of the prototype and the widespread and enthusiastic encouragement for the project from students, academicians, and practitioners. It is clear from feedback that successful completion of the project will have broad, worldwide impact on the integration of the study of biofilms into the curricula of relevant disciplines (thereby satisfying the "broader impact" goal for NSF sponsored projects).

Project Goal: The challenge, and the threefold goal of this project, is (1) to produce a first complete edition of ***Biofilms: The Hypertextbook***—an accurate teaching and learning resource that satisfies the established national need for STEM undergraduate biofilm educational materials and that meets the needs of students and instructors for such teaching and learning resources, (2) to spur rapid, incremental integration of biofilm instruction into relevant STEM undergraduate curricula, and (3) to provide the STEM community with a successful hypertextbook model and associated student learning assessment protocols that can be adapted to other emerging, critically important STEM topics.

Project Objectives. **Objective 1:** Produce a hypertextbook on biofilms that (a) meets the need for accurate and rapidly disseminated teaching and learning resources on biofilms, (b) can be used at any level (beginner, intermediate, or advanced) and desired depth of treatment in relevant undergraduate STEM curricula, and (c) is easily edited, enhanced, and extended in order to maintain its currency. **Objective 2:** Formulate strategies and instruments to measure how the hypertextbook enables diverse student populations to (a) master specific biofilms content, (b) perform science process skills, and finally

(c) become "empowered and informed learners" prepared to contribute in a complex, multidisciplinary, global scientific and technological workplace [28]. **Objective 3:** Design instructor aids and strategies for introducing biofilm topics into existing courses (or to create entirely new courses on biofilms) in relevant STEM curricula along with evaluation instruments to help them evaluate the results. **Objective 4**: Design, document, and establish a hypertextbook infrastructure and model that can be applied to the authoring and assessing of hypertextbooks on other emerging, critically important STEM content, laboratory, safety, or ethical practice issues. **Objective 5:** Establish a mechanism for sustaining the viability of the hypertextbook after NSF support has ended.

Project Outcomes. This project will result in the following products and data that will significantly impact STEM knowledge of biofilms, construction of instructional materials, methods and models of hypertextbook design and delivery, faculty biofilm resources, and student learning. Corresponding to the objectives above, these are: **(1)** the successful publication of ***Biofilms: The Hypertextbook*** that meets the need for biofilm educational resources for instructors and beginning, intermediate, and advanced undergraduate students; **(2)** the development and publication of field-tested evaluation instruments that measure how the hypertextbook enables diverse student populations to (a) master specific biofilms content, (b) perform science process skills, and finally (c) become empowered and informed learners prepared to contribute in a complex, multidisciplinary, global scientific and technological workplace; **(3)** the delivery of instructor resources and assessment tools for biofilm education; **(4)** the production of strategic guidelines, strategies, and evidences of transferability by which STEM instructors and academic units can author and assess hypertextbooks on other emerging, critically important STEM content, laboratory, safety, or ethical practice issues, and **(5)** the creation and application of model strategies for long-term sustainability of the hypertextbook. The project evaluation plan (section 6) is formulated to measure these outcomes.

4. Detailed Work Plan

In this section the work plan for the project is detailed.

4.1 The CCLI Cyclic Model

This project will focus on two elements of the CCLI cyclic model: (1) *creation of new learning materials* and (2) *assessing learning and evaluating innovations*. With regard to (1), the project will result in new learning materials (on biofilms) impacting STEM curricula—the first widely disseminated, comprehensive hypertextbook teaching and learning resource intended as an alternative to a traditional textbook—that will also serve as a model for authoring similar resources for other STEM subjects. Regarding (2) the hypertextbook represents an educational innovation that will be carefully evaluated throughout the project's life cycle with respect to its effect on student learning and on the effectiveness of its format and content. (A further benefit—rather than a focus—of the project is that *developing faculty expertise* from the cyclic model will also be addressed indirectly in that many faculty needing to develop expertise in the new field of biofilms in order to teach it will utilize the hypertextbook for this purpose.)

4.2. A Scenario

The goals of the project work plan may best be explained by a scenario. Suppose that a teacher in a core freshman course on environmental engineering desires to include a module on biofilms. In addition to a traditional environmental engineering textbook for the course, the students have a DVD version of ***Biofilms: The Hypertextbook***. The instructor indicates which material from the table of contents the students are to study. Upon accessing the table of contents, students are presented with visual links that lead them through the material at different levels: using the international symbols for skiing (green circles point to the easiest way down a slope, blue squares identify intermediate runs, and black diamonds indicate the most challenging terrain) green circles point to the introductory track through the material, with lots of examples, illustrations, and help; blue squares identify an intermediate pathway with fewer examples and less handholding; black diamonds indicate the most abstract and challenging presentation of the material—intended for advanced students—with more technical explanations and fewer examples. As freshmen, most of these students will choose to follow the green circle links in the module as advised by the instructor (although inquisitive or particularly talented students may well choose to explore the advanced treatments of the material as well). Pictures, illustrations, graphics, slide shows, and video clips abound, and students may chose to listen to explanations in addition to reading them.

At appropriate locations in the presentation, models of various concepts appear. In this scenario, for example, students may be studying a module on biofilms in the environment, including a case study on how biofilms grow on an environmental surface. In this instance, an active learning model may appear as an applet directly in the presentation; the model allows students to watch how the biofilm grows in the presence of certain nutrients. Students can change the nutrient parameters at will or in response to the instructor's suggestions in active learning mode to see the effects on growth in answer to "What if?" kinds of questions. The same model can then be used to show how biofilm growth can be managed by the application of an antiseptic. At various junctures the students are presented with an interactive quiz that provides them with feedback on how well they are learning.

4.3 Content

The team settled on core topics with which team members have the most expertise. There are many other topics that might—and indeed will—eventually be included as the hypertextbook is expanded in the future. The team's development strategy is flexible, so that if formative evaluation of the project indicates that certain content should be shelved in favor of other concepts, the team can accommodate the necessary changes.

Below is a table showing the content chosen for inclusion in the first edition. The *Module* column lists the title of each module. The *Content* column gives a brief description of the content of each module. The *Features* column provides a list of hypertextbook features likely to play a role in each module (e.g., slide shows, active learning models, etc.) And the *Contributors* column identifies the person(s) responsible for content generation for each module. A legend at the bottom of the table describes these features by letter. It is important to note that for each module there will be green circle (introductory), blue square (intermediate) and black diamond (advanced) tracks through the material, as described earlier. Space does not allow for in-depth descriptions of this content, but the project team does have a detailed outline of each module and is capable of producing the content for each.

Table 1. Biofilm Hypertextbook Content Overview

Module	Content	Features	Contributors
1. Introduction to Biofilms	What biofilms are, how they form, and why biofilms are important in natural, industrial, and medical environments.	a, b, c, d, e	Cunningham
2. Biofilm Formation and Growth	The biofilm life cycle, including cell attachment, metabolism and growth, detachment, and biofilm ecology.	a, b, c, d, e, f	Lennox Stoodley
3. Genetics and Molecular Biology	Genetic characteristics, gene transfer, proteomics, inter- and intra-species cooperation, and resistance to antimicrobials.	a, b, c, d, e	Lennox
4. Mass Transport and Transfer	Mass transport/transfer concepts important to biofilm systems: diffusion, advection, dispersion, reaction, material balances.	a, b, c, d, f	Cunningham Stewart
5. Biofilms in Natural Environments	Discussion of biofilms in natural environments including oceans, lakes, rivers, soils, and sediments. Role of biofilms in global processes, ecology, and public health.	a, b, c, d, e	Camper Cunningham Lennox Stoodley
6. Biofilms in Industrial Environments	Beneficial applications of biofilms: water and waste water treatment and bioremediation of ground water and soil. Detrimental aspects: biofouling, biocorrosion of industrial systems, and controlling biofilm accumulation.	a, b, c, d, f	Camper Cunningham Stewart
7. Biofilms in Medical	Overview of the importance of biofilms in medical-related applications including antibiotic resistance in	a, b, c, d	James Stoodley

Environments	biofilms, infections in orthopedic implants and catheters, and biofouling in dental water lines. Case studies.		Stewart
8. Methods for Studying Biofilms	An overview of systems, techniques, and equipment for studying biofilms.	a, b, c, d	Lennox Stoodley
9. Laboratory Exercises	These exercises include construction projects, laboratory protocols and exercises which enable teachers to introduce the fundamentals of biofilm science to their students.	a, b, e	Lennox
10. Mathematical Models	A biofilm accumulation model (BAM) which simulates all major biofilm processes and an equilibrium partitioning model (EPM) which simulates partitioning of dissolved organic chemicals.	a, b, f	Cunningham Stoodley

Legend: a) concept or background presentation, b) annotated graphics, c) slide show with audio, d) video clips, e) laboratory exercises, f) active learning models

4.4 Incorporation of Learning Theories and Strategies

The design and implementation of the hypertextbook, its applet tools, and its active learning model applets will continue to be influenced by various ideas from cognitive science and published evaluations of student learning in the presence of systems similar to the hypertextbook. The theory of constructivism [2], the theory of mental models [6, 8, 10, 16], and various concepts found at the "Greater Expectations" website [44] will each influence the way applet tools and active learning models are designed for the hypertextbook. The applet tools already provide different ways (e.g., voice narrations, text explanations, video presentations, and others) for students to access the material, consistent with good educational resource development. The active learning model applets engage the learner; thus they are consistent with active learning principles [5, 21, 22], the best of constructivist theory, National Science Education Standards [29], and the national student engagement and assessment guidelines identified by the American Association of Higher Education (AAHE) [30] and American Association of Colleges and Universities (AACU) [28]. Care has been taken to ensure that active learning models included in the hypertextbook present accurate and functional paradigms to students. Issues important to successful hypertextbook design have also been considered [9, 15, 20].

4.5 Technical Work

Although much of the groundwork for completion of the hypertextbook from a technical perspective was laid in the pilot project, the resulting hypertextbook structure and applets are still in pilot form. That is, they all work, but ongoing formative evaluations continue to lead to enhancements in these tools. New active-learning applets are scheduled for development as well. See Table 2 for details.

4.6 Evaluation

Evaluation will be the key driver of the project. See section 6 and Table 2 for details.

4.7 Time Line

Table 2. Project Timetable

Year	Activity
Year 1	**1. Content Revision and Enhancement**. Content and hypertextbook design team members will polish the implementation of modules 1, 4, and 7, which are partially done in the current prototype, including incorporation of missing tracks at the novice, intermediate, and/or advanced levels (identified content contributors from Table 1 with Cunningham, Ross, Dirckx, and Williams as editors).
	2. **New Content Creation**. Modules 2, 3 and 9 will be created in first draft form and edited (identified content contributors from Table 1 with Cunningham, Ross, Dirckx, and Williams as editors).

3. Supporting Applets. Slide shows and videos on biofilm processes related to the identified modules will be produced for these modules (Ross, Williams, and Dirckx).

4. Technical Updates. Ongoing technical programming work on enhancing the various applets will be done. The Reaction-Diffusion Model active learning applet found at the end of section 3 of Module 4 of the prototype will be modified to include a version that is accessible to the novice track. A new active learning model, known as the Biofilm Accumulation Model (BAM) will be completed (Ross and Goosey).

5. Online Evaluation Instrumentation Creation. The technical work of providing online evaluation instruments will be accomplished (Goosey).

6. Semester Review and Planning Meetings. Before the beginning of each semester a project review and planning meeting will be held.

- Formal and informal evaluations of student learning and other aspects of the project will be reviewed and used as formative evaluation in planning for the new semester (entire team with leadership from Anderson).
- Project status will be compared with projected outcomes, and strategy for the upcoming semester determined based on assessment of project so far, timeline, and project goals (entire team with leadership from Anderson).
- Four faculty, who will receive a modest stipend, will be identified from the list of volunteers to serve as formal evaluators of the project for the upcoming semester (Cunningham and Ross).
- The four selected faculty will each help select one student at their respective institutions to serve as the student advisor (also with a stipend) for the semester (Cunningham and Ross).
- Students, faculty, and institutions will be selected for this purpose in a manner ensuring that over the duration of the entire project a balanced mixture of student and faculty gender and underrepresented classes is achieved, and that a reasonable range of large, prestigious universities, to smaller, less well known schools is represented (one of the Montana Native American Tribal Colleges will be included in this mix during each academic year) (Cunningham and Ross).

7. Rapid Hypertextbook Dissemination. Dissemination of the hypertextbook in its then-current form will be done at the beginning of each semester (an appealing aspect of the hypertextbook is that it is eminently usable in incremental fashion as new modules become available). Dissemination will occur (1) generally to the world by way of the hypertextbook website, (2) by direct electronic announcement to the many faculty and others on the regularly updated list of those who have asked to be kept apprised of the project, and (3) through continuous correspondence with the faculty volunteers selected to be formal evaluators for the semester (point 6).

8. Semester Evaluations. Formative evaluation will be done at the conclusion of the evaluation period for each class in which the hypertextbook is used each semester. This will involve both objective and subjective evaluations to determine the perceptions, technical issues, and desires for various features of both instructors and students (project team with Anderson lead). More specifically, formal evaluation will be done with (1) Web-based evaluation instruments (point 5) constructed to assess biofilms content impact on students, students' working knowledge of scientific processes, and behaviors and skills that reflect an intensified interest in science and technology; (2) focus groups with faculty that address how on-line assessments have been used and what they reveal about the process; and (3) student focus groups that address student perceptions of the on-line content assessments, behavioral checklists, and written projects. See section 6 for more details (Anderson).

9. Dissemination of Results. Results of both the educational and technical aspects of the project to date will be written up, posted to the project website, and submitted to conferences (e.g., ASM, SIGCSE, ITiCSE, at which interested attendees will be added to the contacts list) and related journals (Cunningham, Ross, and Lennox).

10. Faculty Teaching Aids. Faculty teaching hints and aids developed as a normal

	part of hypertextbook development and in response to faculty evaluator input will be gathered, updated, and maintained on a related project website, including options for integrating modules of the hypertextbook into a course, effective ways of engaging students singly or in groups with the hypertextbook, exercises with answers, and effective laboratory experiments (Williams).
Year 2	**1. Content Revision and Enhancement**. Modules 2, 3, and 9 will be updated from their first drafts produced in year 1 based on formative evaluations (identified content contributors from Table 1 with Cunningham, Ross, Dirckx, and Williams as editors).
	2. **New Content Creation**. Modules 5, 6, 8, and 10 will be created in first draft form and edited (identified content contributors from Table 1 with Cunningham, Ross, Dirckx, and Williams as editors).
	3. Supporting Applets. Slide shows and videos on biofilm processes related to the identified modules will be produced for these modules (Ross, Williams, and Dirckx).
	4. Technical Updates. Ongoing technical programming work on enhancing the various applets will be done. A new active learning model, known as the Equilibrium Partitioning Model (EPM) will be completed (Ross and Goosey).
	5. Online Evaluation Instrument Maintenance. The online evaluation system will be enhanced as necessary based on evaluations (Goosey).
	6-10. Same as for year 1.
Year 3	**1. Content Revision and Enhancement**. Modules 5, 6, 8, and 10 will be updated from their year 2 first drafts based on formative evaluations. All other modules will be updated as necessary based on year 2 evaluations as well (identified content contributors from Table 1 with Cunningham, Ross, Dirckx, and Williams as editors).
	2. **New Content Creation**. No new content modules will be generated. Efforts will be directed towards enhancing existing content based on year 2 evaluations (identified content contributors from Table 1 with Cunningham, Ross, Dirckx, and Williams as editors).
	3. Supporting Applets. Slide shows and videos will be produced or updated for all modules as necessary based on year 2 evaluations (Ross, Williams, and Dirckx).
	4. Technical Updates. Ongoing technical programming work on enhancing the various applets will be done. A new active learning model, known as the Biofilm Growth Model will be completed (Ross and Goosey).
	5. Online Evaluation Instrument Maintenance. The online evaluation system will be enhanced as necessary based on evaluations (Goosey).
	6-10. Same as for year 1.
	11. *Biofilms: The Hypertextbook*. The first complete edition of ***Biofilms: The Hypertextbook*** will be widely advertised in the project website, conferences, journals, and relevant professional society mailing lists. The transition to in-house publishing of the DVD version will be finalized.
	12. STEM Knowledge Base. *Biofilms: The Hypertextbook*; the hypertextbook model itself; the hypertextbook infrastructure, including the slide show and video applet tools; evaluation instruments; and collected papers will all be made available and become part of the STEM Knowledge Base.
	13. Phase III. A follow-on Phase III project will be designed and submitted to NSF. The overarching goal will be to ensure that biofilm education is widely and effectively integrated into relevant STEM curricula. The three boxes, "Developing Faculty Expertise" (e.g., through faculty workshops hosted at the CBE that ensure that faculty are empowered to teach biofilms, that they have models for incorporating biofilm topics into their existing courses, and that they become conversant with the hypertextbook), "Implementing Educational Innovations" (e.g., through providing models and directions for all institutions desiring to incorporate the hypertextbook model of teaching biofilms into their curricula), and "Assessing Learning and Evaluating Innovations" (e.g., through a broad and thorough assessment of the efficacy of the hypertextbook model on student learning and for the incremental, rapid infusion of a new topic—e.g.., biofilms—into existing curricula) will be addressed.

This looks like a lot of work. Can it be accomplished within the specified time frame? Most certainly. The local members of the prototype project team have now developed a base of experience and expertise in hypertext construction and thus have a clear appreciation for the amount of time involved. The project team for this Phase II proposal is purposefully large and carefully chosen to ensure success. The content contributors, for example, can develop module content concurrently. The content editors, Cunningham, Dirckx, Ross, and Williams, can in lock-step adapt newly provided content to the three different learning levels. Dirckx, who is the professional graphics designer, and Williams, who is the Web specialist and copyeditor, are each devoted half-time to the project. Programming and other technical aspects will be handled by Goosey and Ross; Goosey, the lead programmer for the prototype, is also devoted half time to the project. Dr. Anderson began planning with the team in July 2005 for formative and summative assessments. This early start, the rapid improvement of the Fall 2005 prototype, and the three-year grant period will facilitate optimum development, field testing, and refinement of program and student learning outcome assessment instruments. Not only will the project thus be completed in the specified time frame through teamwork and judicious division of labor, but incremental versions with new content in ready-to-use form will be rapidly available on a semester-by-semester basis as the project progresses.

5. Experience and Capabilities of the Project Team

PI Dr. Al Cunningham: Dr. Cunningham has been a senior member of the CBE since its inception in 1990 and one of the pioneers of biofilm engineering and science research and education. Dr. Cunningham will provide general oversight of project content and will be both a content contributor and the lead content editor for ***Biofilms: The Hypertextbook***. (See biosketch.)

Co-PI Dr. Rocky Ross: Dr. Ross of the Computer Science Department at MSU is the hypertextbook technical expert on the project. He pioneered the hypertextbook concept as described in this proposal, including the design, implementation, evaluation, and refinement of its numerous applet tools and active learning models. His work, often supported by NSF grants, has been published widely. He brings extensive authoring experience to the project as well. (See biosketch.)

Co-PI Dr. Phil Stewart: Dr. Stewart, Director of the CBE and Professor of Chemical and Biological Engineering at MSU, has been a member of the CBE since 1991. He is likely the author of the world's longest-running course dedicated entirely to biofilms, which he has been teaching and refining since 1992. He has authored review articles for *Science*, *Scientific American*, and *Nature*, and has received awards for his outstanding interactions with undergraduate students. Dr. Stewart will be a content contributor, content reviewer, and classroom evaluator for the project. (See biosketch.)

Co-PI Dr. Anne Camper: Dr. Camper is Associate Professor of Civil Engineering at MSU, Associate Dean for Research of the College of Engineering, and a research member of the CBE. She has taught civil and environmental engineering classes for 14 years, into which she has integrated a number of biofilm topics. Dr. Camper will contribute and evaluate content for the project based on her research and teaching in drinking water and cooling towers and will also act as a classroom evaluator. (See biosketch.)

Senior Collaborator Dr. John Lennox: Dr. Lennox, Professor Emeritus of Microbiology at Penn State Altoona (retired in 2003), has been a champion of undergraduate microbiology education for 37 years. He continues his tireless work to introduce biofilm topics into the introductory microbiology curriculum. He will be a major contributor to the design, content, and evaluation of the hypertextbook, bringing a unique understanding of the needs of entry-level undergraduate microbiology students to bear. (See biosketch.)

Content Provider Dr. Paul Stoodley: Dr. Stoodley is Associate Professor at the Center for Genomic Sciences, Allegheny-Singer Research Institute with a particular interest in biofilm mechanics in the natural environment and in industrial and medical systems (infections and pathogens). He has developed a number of "movies" of biofilm processes in action, some of which have been cited in peer reviewed publications [45] and have led to better modeling of biofilm processes. He will contribute and evaluate movies and content for the project. (See biosketch and letter of support.)

Content Provider Dr. Garth James: Dr. James is the Medical Projects Manager at the CBE with oversight of the Medical Biofilm Laboratory. His specialty in medical biofilms is supported by extensive real-world experience. He will contribute and evalulate content over the course of the project, as described in Table 1. (See biosketch and letter of support.)

Educational Evaluation Specialist Virginia Anderson: Dr. Anderson, Professor of Biological Sciences, Towson University, worked with the MSU team as a pro bono evaluator for three days in July, 2005. Her teaching experiences (majors, non-majors, nurses) and assessment workshops at over 125 colleges and universities are ideal for our project. Dr. Anderson has published widely on primary trait analysis, course-embedded assessment, evaluation of scientific thinking and writing skills, and behavioral checklists. She has worked with design and assessments on five major NSF science education grants and recently completed a three-year "Quality Undergraduate Education" initiative as a consultant for The Education Trust. She will coordinate the formative and summative assessments for the project. (See biosketch.)

Computer Scientist Frances Goosey: Frances Goosey, M.S., is a Research Scientist in the Computer Science Department at MSU. She has collaborated with Dr. Ross for over 10 years on the development of active learning applets and hypertextbooks. She was the lead programmer on the prototype and will continue in this capacity. Her work will contribute enhancements to the applets of the hypertextbook, including the development of two new active learning models, as described in Table 2.

Communications Specialist Peg Dirckx: The CBE is fortunate to have a truly outstanding resource in Peg Dirckx with a background in English education and over 20 years of professional graphic design and illustration experience. Her renderings of biofilms have been featured in many papers, magazines, textbooks, and other publications and have been requested for use by publishers outside the CBE. One of her images was recently featured in *Nature.* She is also the primary designer of the CBE's website and its annual report. Ms. Dirckx's talents will be employed for graphics and illustrations to be included in the ***Biofilms: The Hypertextbook***. She will also serve as chief designer of the hypertextbook format.

Web Specialist Diane Williams: Diane Williams of the CBE has been the managing editor of *Biofilms Online*, a Web-based publication dedicated to education in biofilms; it had 170,116 unique visitors in 2005. Her work is widely followed by those interested in biofilm-related topics and information. Her *Biofilms Online* biweekly newsletter has garnered 1,185 subscribers, since its inception. She is also co-editor of the recently published book, *Advances in Biofilm Science and Engineering*. Ms. Williams will contribute writing, editorial, copy editing, and Web functionality input to the project.

Instructional Evaluators. As noted before, the project team is keeping a regularly-updated list of the many faculty around the world who have expressed a desire to serve as evaluators and/or classroom testers of the hypertextbook. All will receive electronic notification of each new release (at least once a semester) of the hypertextbook, and will be offered the opportunity to provide informal feedback. Four faculty volunteers from this list who intend to teach a course that uses one or more modules from the hypertextbook will be chosen each semester to serve in a formal test and evaluation capacity. These four will correspond regularly with the project team during this period, receiving a small stipend for their efforts.

Undergraduate Student Advisors. Four undergraduate students will also be chosen each semester to provide in-depth objective and subjective assessment and input to the project team on the content and structure of the hypertextbook from a student's point of view. Each student will receive a small stipend and will be in regular touch electronically (e.g., through AIM video chat facilities) with the project team. These students are to be selected in conjunction with the instructors of the previous section. Students, instructors, and institutions will be chosen to obtain a reasonable mix over the course of the project with regard to gender and minority status. In particular, the project team intends to include one student each year from a Montana Tribal College (see the letter from Little Big Horn College President, David Yarlott).

Special Note. PIs of projects funded by the CCLI program that result in new educational materials are generally encouraged to rely on a panel of experts to ensure the scientific integrity of the content of the developed materials. It should be clear from this section that the content contributors and editors of this project are *themselves* among the world's foremost experts on biofilms and hypertextbook technology. In addition, content provided by each of these experts will be reviewed for accuracy by other experts on the project team. Finally, given the broad dissemination and evaluation of the hypertextbook each semester, the content will be further scrutinized and evaluated by yet more experts including instructors in the field. These facts conspire to ensure the accuracy and relevance of the content of the hypertextbook.

Project Team Summary. In summary, the project brings together a highly professional team consisting of experts in (1) biofilm research, knowledge, education, and laboratory practice; (2) hypertextbook, active-learning educational resource development; (3) educational evaluation; (4) Web design; and (5) computer programming for the Web—all backed by the intellectual and physical resources of the CBE and the Computer Science Department at MSU. It is important to note that all team members are very personable, work well together, have a great sense of humor, and enjoy a passion for biofilm education that is sure to infuse the process with excitement and success. The instructors and undergraduate students selected each semester to participate in the evaluation process will experience this team synergy. Contacts with minority institutions, such as Little Big Horn College with a primarily Native American student population and Baltimore City Community College with 99% African American enrollment (where the most recent prototype of the hypertextbook is scheduled for evaluation in the spring of 2006 by Dr. Anderson) ensure a diversity of input to the evaluation process.

This will be a fun project!

6. Evaluation Plan

The programmatic outcomes identified in section 3 will be systematically evaluated by the project team, academic STEM partners, industrial associates, and biofilm practitioners in ways already described. Additionally, this project is explicitly designed to enhance student learning and performance. Dr Anderson will thus develop, administer, analyze, evaluate, and revise assessment tools to measure the following student learning outcomes.

Table 3. Student Learning Outcomes

After using *Biofilms:The Hypertextbook* in a guided class experience, students within each skill level and STEM focus will be able to:	**Assessment strategies used to collect direct and indirect evidence and provide formative and summative data**
1. Develop a working knowledge of biofilms by acquiring selected vocabulary, concepts, principles, applications, laboratory techniques, and safety guidelines at one of the three cognitive levels in one of the three STEM strands.	Written and performance tests (direct evidence) in Hypertextbook and course-embedded tests and reflective learning journals, questionnaires (indirect evidence).
2. Demonstrate an enhanced proficiency in identifying, evaluating, and employing components of the scientific method, forming new research questions, and attending to ethical/safety concerns in planning biofilms research.	Student performance on pre and post problem-based learning tests, hypertextbook responses, and team/industry interviews.
3. Exhibit the ability to utilize, reflective willingness to value, and the propensity to continue finding and using primary literature to inform/ document STEM research.	Hypertextbook monitoring of research hits, sample-group observed technology skills tests, and Research Strategies Behavioral Checklist.
4. Internalize that industrial, biomedical, and environmental problems are complex and persistent and that integrated STEM research actions and intellectual perseverance are needed.	Primary trait analysis of reflective problem-solving research scenario, one year follow-up survey (pilot), and team/industry interviews.

Student data from intact classes in community colleges, four-year colleges, and research (R-1) institutions in introductory, intermediate, and research-oriented courses will be examined. Data will also be collected and analyzed, sampling students engaged in the various STEM areas of biofilm education (allied health, research applications, engineering, etc.).

Dr. Anderson will conduct faculty focus groups on the hypertextbook with instructors (e.g., through invited/selected focus groups or "birds of a feather" sessions at conferences). In addition, all faculty using the hypertextbook will be asked to complete on-line surveys, reflective questionnaires, and a home institution descriptive practice form. She will assist the project team in designing assessment strategies and instruments to measure student performance, including content knowledge tests and primary trait analyses for team scoring for selected student projects [31]. She will also work with the team to develop problem-solving tests and behavioral checklists to assess ways in which students are developing a repertoire of science and technology "deep learning skills" [32] and experiences to become "empowered and informed learners" [28]. She will also help the project team determine the effectiveness of the hypertextbook concept and embedded applets on student learning and motivation to study science. Since this project will engage a significant number (200+) of students, data will be analyzed for the impact of gender, self-reported learner characteristics, class size, and type of institution (two-year, four-year, or major research) on the effectiveness of ***Biofilms: The Hypertextbook***.

7. Faculty Support

There is enthusiastic support for the hypertextbook project among relevant MSU faculty, who are willing and eager to class test the hypertextbook (some have already used the prototype in class). It should be evident, however, that the project team is taking steps to ensure that use and evaluation of the hypertextbook is spread across many different institutions of different sizes, levels, and student-body ethnicity rather than depending mainly on MSU for these purposes.

8. Dissemination

Dissemination of Project Results. As discussed in more detail in Table 2 (Project Timeline), dissemination of project results (e.g., effectiveness of the hypertextbook on student learning of biofilm topics) will be published on the project website, at conferences, and in journals yearly.

Dissemination of the Hypertextbook During Project Funding. Incremental versions of the hypertextbook will be released each semester for the duration of the project (see Table 2). The target audience includes the faculty of all of the curricula in which biofilm education is likely to be of interest (microbiology, particularly environmental and medical microbiology, environmental engineering, environmental science, chemical engineering, biochemistry, chemistry, and others). In addition to website publicity, professional society mailing lists and journals will be used to spread the word about the project and the availability of the hypertextbook. Team members will regularly participate in relevant conferences with informational sessions, workshops and poster presentations about the project. The effectiveness of the dissemination will be measured through surveys developed with the guidance of Dr. Anderson.

9. Sustaining the Project

9.1 Long-term Funding

The project team will begin early on to develop alternative funding sources to sustain the development and refinement of ***Biofilms: The Hypertextbook*** beyond the initial three-year project period supported by NSF. Funding is anticipated from the following sources.

DVD sales: The current plan is to market the hypertextbook on DVD for approximately $10-$15/copy, thereby making it readily affordable to students, teachers and other interested parties. The target for DVD sales is between 500 and 1000 per year thereby generating gross revenue in the range of $5000 to $15,000 annually, which will be used to keep the hypertextbook current with each new release. **Industrial Funding:** The Center for Biofilm Engineering has an Industrial Associates Program with 23 paid memberships. Members are companies with vital commercial interests in biofilms. These, along with other non-member companies, will be approached with specific proposals requesting funding to enhance the content of the hypertextbook with industrial applications. **Non Profit Foundations:** Members of the project team (Drs. Cunningham, Lennox, Camper, and Stewart) are associated with a not-for-profit public benefit corporation called the Biofilm Institute. The function of the Biofilm Institute is to develop financial support for biofilm-related education projects which have a clear public benefit. The resources of the Biofilm Institute will be utilized to solicit donations to support the hypertextbook from private education foundations and other similar sources.

9.2 Long-term Publishing and Dissemination Arrangements for Biofilms: The Hypertextbook

Plan A. Current plans are to update and disseminate the hypertextbook in house at the conclusion of NSF funding. There are good reasons for this. The considerable resources of the CBE can be brought to bear on this effort. This, together with anticipated financial support for the project after NSF funding ends, ensures that personnel and equipment will be available to sustain the continued development and dissemination of the hypertextbook. Furthermore, incremental, "just in time" distribution of the hypertextbook at the source of its development allows for each release to contain the latest knowledge and enhancements. Under this arrangement, the cost of the hypertextbook for students should be kept at a minimum. By this time, the hypertextbook will already be widely known, and we thus anticipate that the usual marketing done by a commercial publisher will be unnecessary for the hypertextbook. However, the project team will work to provide non-exclusive rights to interested publishers and authors of traditional textbooks in related subject areas to package a DVD version of ***Biofilms: The Hypertextbook*** as an addendum to their textbooks.

Post NSF-Funding Dissemination Time Line. After NSF support has ended, the hypertextbook will be updated and disseminated *at least* once a year, just before the fall term of the academic year.

Plan B. The PIs are well aware that expectations can be thwarted. Fallback plans include the following: (1) contracting with one of the many DVD production companies (e.g. DiscMakers) to produce mass quantities of DVDs with quick turnaround, should our own facilities prove inadequate; (2) contracting with such a company to not only produce the DVDs for the project, but to accept and deliver orders from their own shop; and, finally, (3) contracting with a commercial publisher to assume complete publication, marketing, and distribution of ***Biofilms: The Hypertextbook***, perhaps including binding the DVD with some of their already successful, relevant textbooks. Again, the primary reasons for leaving (3) as the last option at this point are that the price for students for the hypertextbook would likely be much higher under that alternative, and there would be much less flexibility with respect to timely revisions. Should the services of a commercial publisher be needed, some of the PIs (e.g., Dr. Ross) have experience in writing textbooks and contracting with publishers that can be called upon.

Web Resources and Descriptive Metadata. Finally, the NSF requirement that all Web pages providing information about ***Biofilms: The Hypertextbook*** be suitably tagged with descriptive metadata, will be addressed. This will be done on the project website and other sites (e.g. *Biofilms Online*) that publicize the hypertextbook.

10. Summary

The project team has reflected on each of the characteristics of successful proposals identified in the Grant Proposal Guide and the Program Announcement. We are satisfied that our project meets all of these criteria very well, not only from our own perspective, but from the results of the formal evaluations of the prototype and overwhelming support from a broad range of people from academia, research, industry, and medicine, as represented in letters of support and our long list of other supporters.

Finally, the overarching NSB criteria of intellectual merit and broader impact—addressed in more detail in the Project Summary—are also well met. There is clear, widespread recognition of the intellectual merit of introducing the subject of biofilms rapidly into relevant undergraduate STEM curricula through a project that has the backing of the intellectual and physical resources of the CBE and its collaborators. It is also clear from documented, broad support that the project will have worldwide impact on relevant STEM undergraduate curricula. In short, this project represents a great opportunity to make a significant intellectual and broad impact on STEM education with profound, positive effects for years to come.