AC 2008-1726: HANDS-ON CHEMICAL ENGINEERING SENIOR DESIGN: EVOLUTION FROM PAPER TO PRACTICE

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Abstract

Historically, the senior design sequence in chemical engineering has differed from that of other engineering disciplines due in large part to problems of scale: a team of mechanical engineers can reasonably design and produce a prototype stapler, for example, but it is beyond most schools' capabilities to have the chemical engineers both design and "produce" a petrochemical plant. Therefore chemical engineering design has focused primarily on the "paper" aspects of design, encompassing unit operations, economics, planning, and process simulation. This approach unfortunately misses out on some potentially important lessons that can be learned from actual process implementation, such as the need for process flexibility and the challenges of controlling a system to the five decimal places that were so easily specified in the paper design.

This paper describes the seven year long evolution at Bucknell University towards a hybrid paper/practical senior design sequence where each team must physically solve a real chemical engineering problem, often from local industry, by the end of the year. Solutions to the problems must be demonstrated experimentally, and have ranged from developing and operating bench- and pilot-scale processes to design and development of novel process equipment to developing novel process conditions for existing equipment to result in superior products. Both survey and direct assessment results demonstrate positive student outcomes from this version of the course sequence. This paper will also reflect upon both the plusses and minuses of this approach from the faculty perspective.

Introduction

Senior design is the capping experience in undergraduate chemical engineering education, wherein students undertake a design process compiling elements from each of their undergraduate courses. Until recently a course of this nature was specified by ABET. While ABET current rules are less proscriptive, there is general agreement among Chemical Engineering programs that senior design continues to be an important and required course. The common goals of this course are for students to realize the design of a chemical facility, incorporating economics, process simulation, control, transport, material and energy balances, thermodynamics, safety, and ethics (among other elements). Due to the scope and scale of these projects, they are generally completed through calculation and simulation only.

Senior design at Bucknell University is a two-semester sequence composed of two four-credit courses. In this paper, we describe how we moved from the traditional senior design sequence, in which both semesters focused on a single simulation-based design of a styrene plant for a simulated company to one in which the second semester is spent in a practical design experience. Overall, the sequence now appears as a course in process design followed by a course in project engineering. For process design, students must go from "soup to nuts": taking a primitive problem, proposing a design to address the problem and then evaluate the economic feasibility of the design. This segment explicitly pulls together most of the curriculum and requires a good deal of teamwork. For the second semester of project engineering, the goal is for students to solve a problem that can be very narrowly focused but which requires a tangible result. Many different skills are needed, some of which include basic technical skills but new skills are added – project management, problem definition, project evaluation, and deadlines that really mean something.

The educational objectives for our senior design sequence are shown in Table 1, and closely correspond with traditional ABET expectations for such courses.

Table 1: Course Objectives for Senior Design

Content Area	Objectives
Professional Development	• Enhance your ability to learn on your own in preparation for your professional careers.
Teamwork	• Continue to build the interpersonal skills required to be successful in a team environment.
Problem Solving	• Apply your knowledge base in chemical engineering (developed throughout the curriculum) to solve problems in a realistic, project setting.
Project Management	• Define a specific problem from a general project area and learn how to plan, execute and assess that project to meet specific base and stretch goals.
Communication	• Continue to develop formal writing skills by conducting pre-writing, drafting, and revision. • Develop good communication skills between team members, clients and a project supervisor.
Laboratory Work	• Design, construct and test physical equipment or software to achieve specific objectives. • Locate appropriate information via web searches and library resources. • Identify safety concerns and apply safety procedures.

The reasons for modifying the senior design sequence are manifold. It was felt that both student and faculty interest in the course could be significantly enhanced by doing something different. We also considered what students were doing with their degrees. Fewer graduates went to traditional production plants and more went to places where they needed to hit the ground running not only technically but organizationally (i.e., they need to understand the requirement for effective planning and assessment of projects as well as the skills needed to implement them). In addition, we were encouraged by ABET to develop multidisciplinary-team experiences and it was thought that having a product-centered design course would be a nice venue to bring in involvement of other people, such as other departments in our university as well as possible customers outside of the university.

History

The alteration of the senior design sequence was evolutionary, and can be broken into three periods. First, the "traditional" sequence (1998-99 and earlier) centered on a paper design of a styrene monomer plant only. In the transitional year (1999-2000) the paper design of the future experimental work was considered by one team. Finally, the current design sequence came into being in 2000-01, and involves a first semester paper design on a variable theme as well as the second semester practical design.

The historical development of this departure from tradition starts in Fall 1998, when Dr. Maneval was approached by a local soap manufacturing facility. While the original project fell through, Maneval realized that the process had numerous features that would make it desirable as a practical experience in process design. The process is relatively simple and safe, utilizing process conditions that are realizable in undergraduate laboratories with existing equipment and safety procedures. In spite of this apparently simplicity, the process is also sufficiently complex in terms of the unit operations required (heating, reacting, multiple separation, washing, drying, and forming steps) to provide a rich variable space for design. He began taking steps to test this possibility, working with numerous undergraduate research students (J. Ward, C. Caputo, M. Bucher, C. Gibson, J. Grimley, D. Daycock, A. Jewel, L. Spagnola, and others) to test this idea.

Another compelling reason to pursue soap as a possible senior design practical process is that any equipment used would be sufficiently flexible to work with other processes should the project change in the future. While this was not known at the time, building this flexibility into the projects from the start enabled the highly flexible design environment currently used.

In the Spring 2000 implementation of Senior Design, one of three course projects was devoted to paper-only design of the soap plant that could be built in the existing unit operations laboratory space. Based upon their work, and continued work by Dr. Maneval and Hanyak, the department faculty were convinced that switching second semester design to the practical process would be a good idea.

From Spring 2001 to 2003, the course model switched entirely to practical implementation of different aspects of the soap making process. Each student team was responsible for a different segment of the process, such that no two teams had exactly the

same design problem. For example, one team might be working on batch reaction chemistry, while another on a design for a continuous reactor, and a third on a continuous separation unit. This meant that the teams were occasionally dependent on each other (the separation design group only having something to separate when the reactor group got their process working), which was initially appealing but subsequently dropped.
In Spring 2004, a personal products manufacturer approached Dr. Maneval and acted as the first outside customer for the course, and a fraction of the student teams worked on a novel formulation to suit customer needs. Through this process it was realized that apparent student motivation was enhanced by having a "real" customer.

Spurred by the excitement provided by an outside customer as well as the inclusion of a new faculty member in the teaching of the course, starting in Spring 2005 the present model was adopted. In this version, projects for both internal and external clients are offered within the course. This represents the latest evolutionary step for the flexible manufacturing environment originally envisioned in 1998. Faculty have opened the class to any chemical engineering project that they believe could be completed with only reasonable changes in existing equipment and resources. Details on how this structure is implemented and graded are included below.

Methods

Second semester design is a radical departure from previous versions of the course. The overall goal of the semester is for students to construct and operate either a process or experiments in solution of a real problem. A key feature of this course is that student assessment is based significantly on the actual operation of their final project; the best idea in the world will not get a good grade unless they actually make it work in the lab, something tangible must be produced. Projects take a wide variety of forms, but all incorporate key elements of project management, experimental design, data analysis, simulation, economics, and laboratory construction and experimentation. Sample projects and customers are shown in Table 2. Figures Y1, Y2, and Y3 show students with their final resulting processes.

Table 2: Sample Project Titles and Customers

Title	Customer
Creation of a process for in-house production of microfluidic devices	Chemical engineering faculty member
Continuous small-scale production of biodiesel	Outside RFP
Pilot scale biodiesel production for home heating	Non-chemical engineering faculty
Continuous flow low-foam "hop infuser" for bar use	External business (national)
Faster cure time formulation for coatings used on athletic mats	External business (local)

Figure 1: Senior team from 2007 with novel design for a low-foam hop infuser

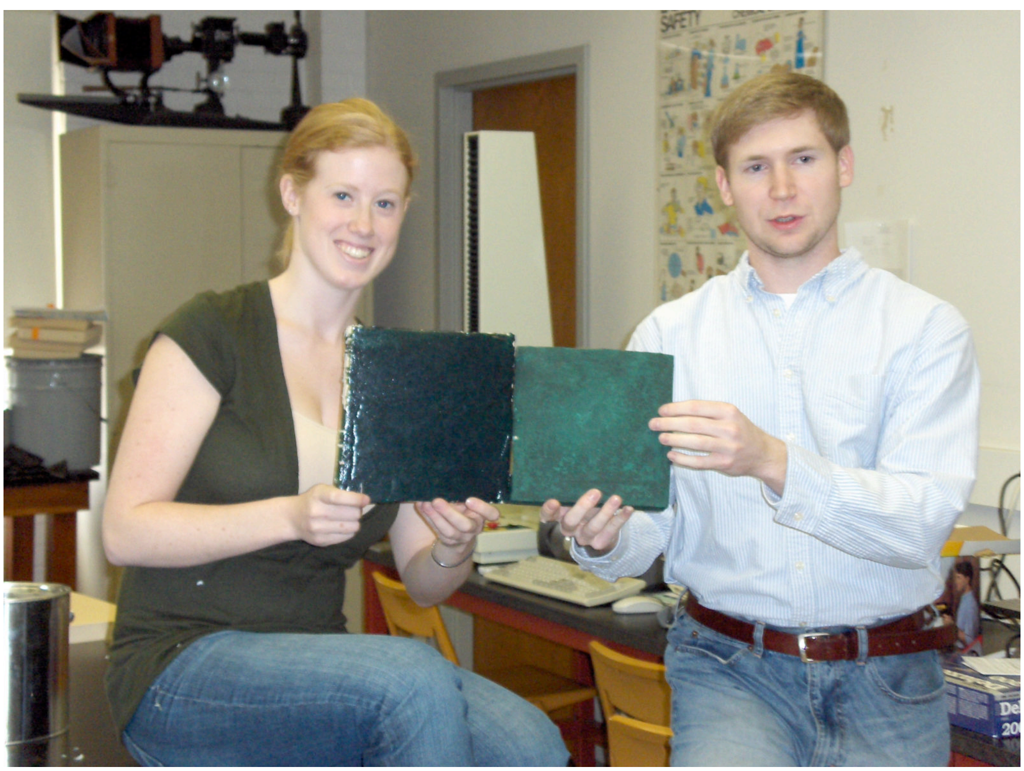

Figure 2: Two members of the class of 2007 displaying alternative fast-cure coatings for athletic mats

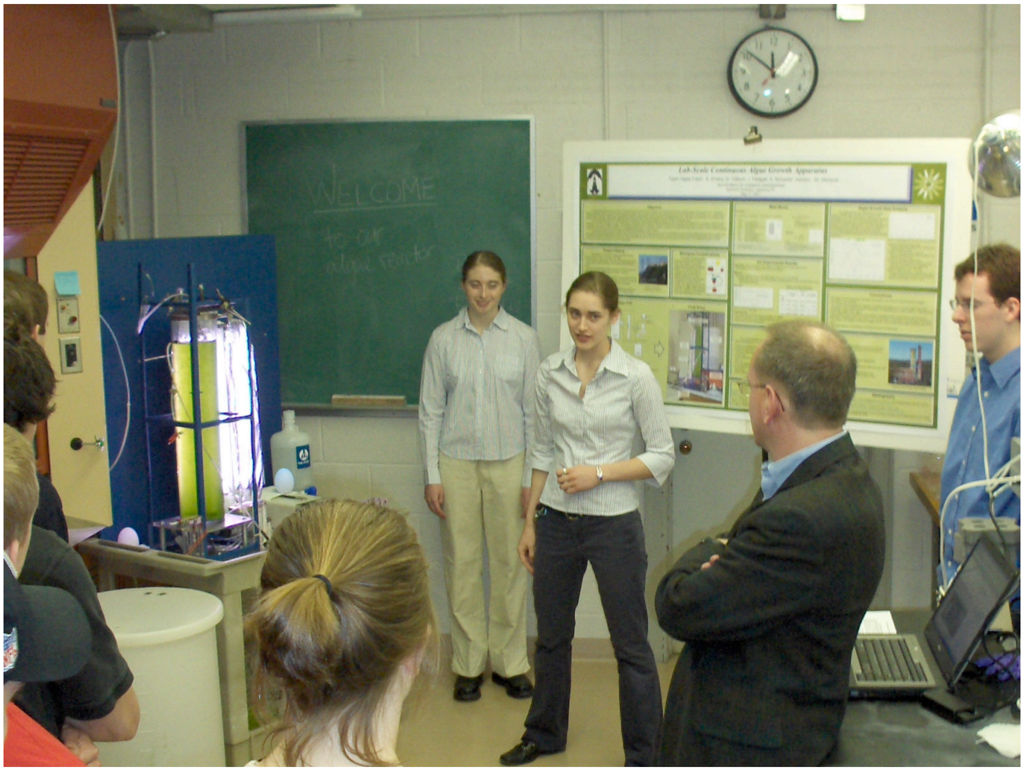

Figure 3: The 2007 algae-growth design team displays their reactor for professors and students during the poster session.

The course structure is such that there are generally two to four faculty teaching the course, each responsible for coaching and grading three to four student teams. Each team will also work with a customer, either external to the university or internal. Occasionally, the customer is one of the course faculty, but more generally it is someone not otherwise involved in the course. Student teams of three or four are formed by faculty with student input; students may request someone they do want to work with, someone they don't want to work with, and a particular project.

Faculty members propose projects with a one-to-two paragraph project statement (see examples in Appendix A). These projects may be solely the idea of the faculty member or they may be one that the faculty member is facilitating in concert with an outside client. Outside clients are solicited in a variety of ways. The university houses a Small Business Development Center, which is happy to direct requests for chemical engineering consulting to the course. Faculty also rely upon personal and alumni contacts to generate projects. Another source of outside projects is research outsourcing companies such as Nine Sigma (http://www.ninesigma.com/) and Innocentive (http://www.innocentive.com). These sites publish requests for proposals that often focus on chemical engineering problems. While the time scale of the RFP may not coincide directly with the course, the RFP may still form the basis of a faculty sponsored problem. An interesting recent development is that some highly motivated student teams have sought out their own projects through offering their services directly to faculty or outside companies working in areas of interest. Finally, interesting projects have also arisen as requests for help or collaboration from faculty outside of engineering. What is common to each of these sources is that the proposed projects are of interest to and useful for the client; they have not merely been made-up by faculty because they would provide students with an interesting experience. This idea of utility is key to the spirit of the course.

The course timeline is broken into three sections, each with milestones and deliverables. The first segment is background and the main deliverable is a proposal, given both orally and verbally, describing how the rest of the project is to proceed. Students propose and commit to the goals for the project which will define its success – thereby creating their own grading criteria. The second segment is experimental development and preliminary experimental work. The deliverable here is an interim report, incorporating problem definition and experimental plan changes as well as preliminary results. Much of the equipment and materials ordering goes on at this stage. Teams must also generate a problem statement for work to be completed on their behalf by juniors in the Unit Operations course. The final segment is project completion; experiments are run, process improvements are demonstrated. The deliverable is the final overall project report, in poster, oral and written form. Poster presentations are made on the last day of class to students at all levels within the department (freshmen-junior) as well as invited administrators. The oral reports are delivered in public, in front of not only the other design students and department faculty, but also any customers who can attend as well. The grading rubric for the overall report is attached in Appendix B. A key aspect of the grading is that not only does a tangible result need to be produced, but the success of this result is judged against what the students themselves said they would do.

Project definition, planning and assessment are all important aspects of "real world" projects where time and money are critical to success. We need to have student say what they are going to do and provide a coherent plan for assessing how they will measure progress. With instructor guidance and good team work, we've shown it is possible for undergraduates to do good work in real problems one a limited budget and in a short time.

Students propose the resources that they will need during the "proposal" section of the course, although faculty try to anticipate the most significant of these needs ahead of time. In general, each team requires at least 10 ft^2 of bench space with utilities and storage, but this varies widely. Other basic necessities include sufficient available glassware, hot plates, stirrers, balances, pumps, valves, and tubing that may be used for each team to construct a bench scale process. Each team should also have access to a computer for data logging and control and simple real-time measurement tools such as those produced by Vernier. While more equipment than just described is used in this course, the beauty of the course structure is that it is the students' responsibility to locate and purchase or otherwise gain access to needed equipment. With an investment in space and some simple flexible pieces of equipment, any university could adopt this same approach.

Results and Discussion

The success of the new senior design sequence is judged in two ways. First, through student course evaluation surveys. This incorporates our most complete data set, and shows clear impact as a result of the course change. Second, instructor observations and reflections are included. While this is understandably a qualitative assessment, it provides a richness of information needed for other schools considering such a change.

Course Evaluations

As can be seen in Table 3, the summary course evaluations numbers (5-point Likert scale, 5 = agree strongly) are statistically identical for both the old and new versions of the course. This may not be striking, but should be read as a success. The new version of the course incorporates different educational elements than the original, each of which makes the project more open ended and less structured than before. Students were moved from the relative safety of a paper design to one where they are responsible for extracting requirements from customers, physically building and operating systems, interpreting data, and communicating their conclusions to their customers. There is significantly less structure and certainty in the second version, yet students continue to feel highly positive about the experience.

Table 3: Mean Course Evaluation Scores (5 = agree strongly; 1 = disagree strongly)

Course Format	n	Course was well organized	Instructor was well prepared	Instructor(s) was fair	I would recommend this course	I would recommend this /these instructor(s)
Paper only (1998)	24	4.5	4.4	4.7	4.2	4.6
Transition (2000)	20	4.5	4.4	4.7	4.4	4.5
New Format (2001-07)	146	4.4	4.4	4.5	4.3	4.6

Student comments from evaluations also illuminate the distinction between the new and old versions of the course. Some key comments are shown in Table 4. While students were apparently satisfied with the paper-only design experience, the depth and scope of their comments broaden significantly after the change. Students specifically mention appreciating and learning from some of the aspects missing from the paper design – such as the apparent freedom to find novel solutions, learning to work with the unexpected, and the process of proposing, carrying out, and presenting finished work.

Table 4: Student end-of-course Evaluation Comments

Time Period	Representative Responses in End-of-Course Evaluations
Traditional "Paper" Design (1998)	• Applying what we learned over 4 years to real world design problems • I like the major projects. Working together for a common goal and putting together a comprehensive report that we can (sometimes) be proud of is a good bit of "fun" (relatively speaking) • Working in teams
Transitional (2000)	• Project Z [soap]. It was different than the other reports and gave us more design freedom. • The variety of chemical engineering applications in this class • Soap production process – learning about new material • Working in teams
"Practical" Design (2001-present)	• Styrene from ethylbenzene seemed sort of mythical [design problem from fall] because we were not going to build it. The IMP [soap project] was a tremendous improvement for the course. • Actually working on a project with our hands and not a straight simulation • I like that the class was very true to what a chemical engineer could do in the real world. I also liked that it encompassed many years of our education and made us realize how much we have learned over the course of our education. • The fact that we were able to create our own project and help further develop the soap process of the department. • The team work and the freedom to find the different solutions. • The fact that we were in charge of everything ourselves. The professors were there merely [!] for consultation and I believe that allowed us to learn a lot. • Preparing a timeline for a project to be carried out over the entire semester and then learning how to cope when things don't go as planned. • This is really the first chance we got to think independently on a project than hasn't ever done by anyone before. This course is the most representative of real life and therefore the most useful and enjoyable.

Faculty Observations

From the faculty perspective, there are both plusses and minuses to the alternate senior design. The traditional design proceeded along a predictable time table, and over the years faculty developed considerable expertise on the design problem and its best solutions. Neither of these is as true when working with actual customers on a set of problems that changes yearly; and while faculty expertise is still useful, we have had to accept that we do not know a priori the "answer" for the problem when class begins. Two other major considerations are resources and faculty time. Many teams require new equipment and chemicals as well as other supplies to complete their work. While they are held to a "small" budget of $500 per team, this sums to a significant expenditure on the part of the department. For some projects, the outside sponsor makes funds available, but this is not the case for all. Laboratory space is another significant consideration. Prior to this version of the course, no lab space was used. Now, space is needed for each team, the requirements for which only become clear once the projects are finalized. The need for square footage and utilities can be considerable, such as for the pilot-scale biodiesel operation. Moving to this format also meant that the faculty had to accept that not every team needs to apply the same skills, and therefore students end the course with differing levels of experience in some areas. For example, one team may need linear programming or optimization to complete their work while another may not. This concern is mitigated by insuring that every project contains the key elements (project management, etc) listed earlier. Finally, faculty invest additional time in arraigning projects and customers relative to the paper-only version, where the project was well known in advance.

An ongoing factor worth noting is that students have consistently commented that "doing their own project" is one of the key features of the course. Any faculty member will recognize that what can be completed during a course is going to typically be only a small part of a larger problem. The course is therefore conducive to projects that build upon previous work and lay the ground for future work. For example in 2007 two student teams worked on algae growth for biodiesel production; one creating a lab-scale chemostat bioreactor, the others working to lyse and isolate oil from the cells. The next logical step would be to combine these and integrate biodiesel production into the system. This structure is beneficial for both students and faculty – it is even more "real life", as projects are often handed off between teams, and faculty can benefit from giving a customer a more complete solution or generating a publication. The downside is that when given the choice, students almost always seek novelty. Even though they can do new and creative work that is their "own" when building upon previous work, there seems to be a pervasive feeling that "that's been done" when a continuation project is offered. Maintaining a careful balance between the desire for novelty and the benefits of continuity is an ongoing challenge for the instructors.

However it is our feeling that these minuses are relatively minor compared to what has been added by the revised course. Student and faculty motivation and interest are increased by the prospect of making a contribution to a "real" problem. Further, student project management skills are enhanced by dealing with customers who often need assistance in defining the true nature of their problem. For the second semester in particular, there is also a difficult to quantify benefit simply from having to physically realize a working design. It is very easy to make a paper design that is excellent under a specified set of conditions, but might not be robust given variable feedstock. Trying to operate something real, on the other hand, forcefully brings home the fact that real processes must be robust to variable conditions in a way that simply telling the students so does not. The course achieves all of these plusses while still accomplishing the course objectives. The change has been well worth the effort.

Appendix A: Sample Instructor Problem Statements

M4: Soap production – client: Prof. NAME and the department

The development of a continuous process for soap production was the first process used in the re-focusing of CHEG410 to a project-engineering direction. A final version of the soap process has been approached but is yet to be fully realized. Last year, a team of seniors re-designed several sections of the process and added the ability to monitor (and potentially control) the operation. These changes greatly improved the operability of the process. However, there are still some weak spots (specifically: product recovery, recycle and effective introduction of the fatty acids) that need attention is the process is to be fully functional and reliable.

For the current year, there are two directions the “soap project” could take. The first is to complete and extend the work started last year by addressing the weak areas in the process that were noted above. The second direction is to re-design the plant to produce a “natural soap” – soap made with fats and oils rather than fatty acids alone. There is ample room for creative thinking here (i.e., design) to develop processes and operations that are effective and appropriate to the production of a specific product from raw materials that are produced in a sustainable manner.

M5: Solvent use/"cure time" reduction at COMPANY – clients: COMPANY and Prof. NAME

COMPANY manufactures mats for athletic use. They coat and paint these mats and, in doing so, use large volumes of solvents. These solvents dissolve into and interact with the mat material. This is considered valuable for promoting paint adhesion to the mat. However, the solvents soften the mat considerably, and these large mats must then be left spread out to dry or "cure" for may days before their final desired properties are achieved. These solvents are ultimately discharged to the atmosphere without treatment. The company is thus interested in exploring ideas along one or more of the following paths: reducing cure time, using more environmentally friendly components; or recovering and re-using the solvent.

The specific path(s) chosen for pursuit will depend in part in conversations with the client. The team for this project should expect to work with the clients in the project-planning and goal-setting phases to ensure a realistic approach to the problem at hand.

Appendix B: Grading Rubric for Final Design Report

Team: ______ **Investigation:** _________________________________ **Date:** _________

Members: ________________, ________________, ________________, ________________

	U P F G E†				Score
Organization	(0 5 6 7 8 9 10)	x	3	=	______
Clarity and Conciseness	(0 5 6 7 8 9 10)	x	4	=	______
Appearance and Neatness	(0 5 6 7 8 9 10)	x	3	=	______
Problem Definition / Objectives	(0 5 6 7 8 9 10)	x	4	=	______
Background	(0 5 6 7 8 9 10)	x	6	=	______
Procedure / Methods	(0 5 6 7 8 9 10)	x	4	=	______
Results	(0 5 6 7 8 9 10)	x	4	=	______
Analysis	(0 5 6 7 8 9 10)	x	6	=	______
Conclusion & Recommendations	(0 5 6 7 8 9 10)	x	4	=	______
Appendices	(0 5 6 7 8 9 10)	x	2	=	______
			Net Points	=	______
Grammar	(6 5 4 3 2 1 0)	x	-4	=	______
Spelling	(6 5 4 3 2 1 0)	x	-4	=	______
Punctuation	(6 5 4 3 2 1 0)	x	-4	=	______

Report Grade = ______ = ________ %

400

____

†Excellent (9.5), Good (8.5), Fair (7.5), Poor (6.5), and Unacceptable (5.5 to 0.0).

Comments: