Navigating Rugged Terrain: Barriers and Benefits to Implementing an Elective Engineering Design Course in a High School Setting

Steve Krause1, Chell Roberts2, Dale Baker3, Senay Yasar4, Sibel Uysal5, Sharon Robinson Kurpius6

Abstract - A team of engineering and education faculty and science education graduate students partnered with a local high school to implement an engineering design course. Course objectives included: learning to apply the engineering design methodology, acquiring and using basic engineering skills and tools, and understanding and valuing engineering as a career and a profession. The objectives were generally not achieved due to a variety of barriers related to the class. These included: varying maturity levels of students due to mixed age groups; lack of diversity; need for enhanced structuring of classes; inappropriate placement of students in engineering classes by guidance counselors; issues of materials management; inadequate application of science and math in design and problem solving; and the level of difficulty of course books. The nature of these barriers is discussed along with implications for teaching engineering design in high school. Recommendations for improvements to fulfill course objectives and achieve learning outcomes are presented.

Index Terms – Diversity, engineering design process, guidance counselors, high school outreach

BACKGROUND

An interdisciplinary team of Arizona State University (ASU) faculty from the College of Education and from the Fulton School of Engineering has been collaborating for over three years on a National Science Foundation grant from the Bridges for Engineering and Education program. The project is entitled “Design, Engineering, and Technology (DET) Expansion for K-12 Teachers”. Two of the goals of the grant were to survey K-12 Teachers about DET and, based on the survey results, create a course for science education graduate students on the engineering design process. The survey was created and administered to 98 K-12 teachers. Two classes for science education graduate students were created and taught. As an extension of the knowledge acquired from the survey and the classes, an opportunity to apply that knowledge directly was presented for collaborating with a local high school to bring an engineering signature program to the curriculum. This paper briefly reports on the results of earlier work and focuses on the design and issues of teaching DET in a high school setting. The results of the earlier survey and the two courses taught will first be discussed since these activities influenced the collaboration of the interdisciplinary team with the high school teacher and administration.

The survey administered to 98 K-12 teachers was entitled “Questionnaire on Technological Education for K-6 Teachers and Middle and High School Teachers of Science”. The results [1]-[2] indicated that the teachers: thought it was important to teach DET; had a desire to teach DET; it was important for students to learn about DET; but the teachers’ preservice education did not generally educate them about DET. Their perception of engineers was positive, but they felt that females and minorities were less likely to succeed on an engineering career path. The high school teachers felt that the counselors did not have the preparation to adequately inform the students about the nature of the engineering profession and careers. The results of the survey influenced the design of the graduate courses and the high school collaboration, especially with respect to minority and gender issues.

The first graduate science education course [3] was based, in part, on the survey of DET needs of K-12 teachers. It was intended to infuse design and engineering concepts into the preparation of graduate students who would become science teacher educators in colleges of education and also to impact their perceptions and skills in DET. The students worked in teams, learned the steps of the design process, and created functioning prototypes of designed artifacts. The students’ progress in learning the nature and practice of the engineering design process was analyzed by a rubric created for analysis of written student documents [3]. In total, each student produced 40 individual pieces of text of varying length (reflections, pre and post tests) that became the data sources for the study. Analysis of the writings were used to determine impact of the on students’ understanding of; 1) engineering as a design process, 2) issues of gender and diversity in relation to DET, and 3) the societal relevance of engineering to students’ everyday lives, 4) students’ technical and tinkering self-efficacy, and 5) their ability to transfer their knowledge of DET to classroom teaching.

1Steve Krause, Professor, Dept of Chemical & Materials Engineering, Arizona State University, Tempe AZ 85287-6006, skrause@asu.edu
2 Chell Roberts, Director of Engineering Development, Arizona State University, Tempe AZ 85287-5906, Chell.Roberts@asu.edu
3 Dale Baker, Professor, Dept of Curriculum & Instruction, Arizona State University, Tempe, AZ 85287-0911, dale.baker@asu.edu
4 Senay Yasar, College of Education, Arizona State University, Tempe AZ 85287-0911, senay.yasar@asu.edu
5 Sibyl Uysal, College of Education, Arizona State University, Tempe AZ 85287-0911, sybil.asal@asu.edu
6 Sharon Robinson Kurpius, Professor, Psychology in Education, Arizona State University, Tempe AZ 85287-0611, Sharon.Kurpius@asu.edu

0-7803-9077-6/05/$20.00 © 2005 IEEE

Session S2F-15
35th ASEE/IEEE Frontiers in Education Conference
October 19 – 22, 2005, Indianapolis, IN
Analysis of data showed the following. Students recognized the differences (as well as similarities) between science and technology; developed an understanding of the design process; developed a vocabulary (e.g. sensors, actuators, microprocessors) based partly on experiences with hands-on activities; and discovered the importance of team work in the design process and problem solving. They found ways to integrate history of technology with social studies in their own classrooms, and they realized the importance of technological literacy in everyday life. They also became aware that they had been using DET in the classroom without knowing it, and they became critical about the implications of technology in schools and the financial limitations of ever-changing technology. It was clear from the data that the graduate students with good science backgrounds learned about DET by doing DET. Even the two engineering-background students increased their knowledge of DET and of the relationship of science and technology from the hands-on activities. This is an instructional approach that we advocate for teacher education and applied to the design of the courses in the high school engineering program. We also used the principle of spending more time doing (and reflecting) on design and less time listening to lectures in order to develop a deeply embedded understanding of DET rather than understanding DET as a procedural activity consisting just of a series of steps.

In the second graduate science education course the goal and focus was to help practicing teachers integrate DET into their curriculum. We used four analytical themes (Reflections on Practice, Changes in Practice, Intentions to Change Practice, and Change in Knowledge) to examine the likelihood that what teachers encountered in the course would transfer to their classrooms [4]. Case studies were done on three graduate students who allowed us to gather data over a semester. The results are presented below.

A third grade teacher intended to change, or changed things, such as teaching the design process explicitly, learning the science behind engineering concepts, developing activities for young children, using everyday contexts, and planning a model building unit. Her third grade students actually used the engineering design process to design and construct a desert tortoise habitat. A local science center outreach coordinator changed her practice by attending to gender, integrating the design process and tinkering into lessons, and adding technology discussions. She helped the museum staff examine the effectiveness of the design of their program activities. Her unit indicated a greater awareness of the time needed for hands-on exploration and discussion. She shifted the focus of a bridge-building activity from a crafts emphasis to an analytical emphasis. A high school chemistry teacher exhibited the most changes. She had students write about science and technology to determine prior knowledge. Based on engineering design principles, her students designed and collected data from a lab instrument that they had built, a calorimeter. She also helped other science teachers incorporate DET into instruction. In creating her unit, she used the design process and an evaluation (including a delayed post test) which indicated that the students had learned everything intended.

As demonstrated from these teachers’ experiences, helping teachers infuse DET into their current practice is not a simple matter, but it can be accomplished under the right conditions. The three cases presented were indicative of the kinds of changes that can occur under varying conditions of context and teacher background knowledge when there is the right kind of support. The teachers were able to change their practice because they were provided the opportunity to read and discuss the research on classroom applications of DET, to discuss possible changes in their own practice, to develop lessons and try them, to then share their successes and failures with one another, and to continually refine their lessons throughout the 15 week period of the course. In short, the class became a community of learners who provided support for one another as they tried to infuse DET into their practice. We believe that we were successful in bringing about change because of the structure of the course. We have and are attempting to use a similar approach in infusing DET into the high school program. The approach to the design, results, conduct, and implications of the high school collaboration will now be presented.

**Theoretical Rationale**

Current models of instruction such as situated cognition, e.g. Blumenfeld et al. [5], social constructivism, e.g. Greeno et al. [6] and project-based learning, e.g. Tobin [7] provide support for using design, engineering, and technology (DET) as a framework for science teaching. All of these models and DET share several important characteristics. They involve groups of students working on real-world problems. They use problems that can be broken down into sub-problems, they are interdisciplinary, and they have multiple solutions. They focus on students creating their own knowledge through social interaction while engaging in inquiry activities. They emphasize doing science rather than reading or listening to lectures and/or procedurally using technologies which are often used to facilitate learning. The link between science and DET is so strong that Plucker [8] recommends situated learning activities, problem based learning, and projects as a way to help students overcome simplistic ideas of inventions and what it means to invent (the design and engineering process).

Sherwood and his colleagues [9] of the Cognition and Technology Group at Vanderbilt, as well as Beneson [10], and Cajas [11] argue cogently for DET as an important, but neglected, context for learning science. However, research to support DET as having a larger role in science education is limited. There is some data to support the positive effects of design on understanding models (i.e. designing an elbow), especially among young children as demonstrated by Penner [12] and technological design as an effective vehicle for learning science content as shown by Roth [13]. Seiler, et al. [14] also showed that design activities appear to have some
potential for stimulating science-like discourse among urban minority students.

The strongest support for the effect of DET on student motivation comes out of the work of The Materials Technology Institute (MTI). This was a project conducted by Stobe, et al. [15] that trained high school teachers to teach the subject of Materials Science and Engineering in a framework of Design, Engineering, and Technology. The goal was to provide teachers with the background and curriculum needed to create a new high school course in Materials Science and Engineering. Surveys of high school students indicated that the MTI-based courses (221 students at 7 high schools) had a positive impact on students’ motivation. The surveys also reported that students who had taken the course: a) made them much more interested in a science career b) increased their enjoyment of laboratory activities; and c) helped them develop their skills for working with equipment in the laboratory setting. One of the most exciting responses was that 96% of the students would recommend, or would probably recommend, the class to their peers.

**CONTEXT OF THE CURRENT STUDY**

In the fall of 2003 Mr. Don Quill (pseudonym), a mathematics teacher at Frontier High School (pseudonym), contacted Dean Peter Crouch in the Ira Fulton School of Engineering at Arizona State University concerning the development of a new engineering signature (magnet) program at his school. Dean Crouch contacted the interdisciplinary team of faculty from the College of Education and School of Engineering who were the principal investigators on the NSF funded Bridges for Engineering and Education grant (NSF #EEC0230726) and who were currently doing research on infusing engineering concepts into the K-12 curriculum. The team consisted of Drs. Dale Baker and Sharon Kurpius (College of Education), and Drs. Steve Krause and Chell Roberts (School of Engineering). In addition there was one doctoral student in science education (Senay Yasar). The team has subsequently added another science education doctoral student (Sibel Uysal).

The team contacted Don Quill and met throughout the spring of 2004 to discuss and develop the objectives for five courses for the signature program (Introduction to Engineering, Survey of Engineering Professions, Technology and Society, Introduction to Computers and Programming, Engineering Technical Communications). The school advertised the Introduction to Engineering course at the high school and at feeder middle schools in late spring of 2004. In Fall 2004 108 students (102 males and 6 females) enrolled in three sections of one class entitled Introduction to Engineering. The design of the class reflected the best practices in the current literature on Design, Engineering, and Technology (DET) as previously discussed. The general structure of the course was based on the Introduction to Engineering Design course taken by all freshman in the School of Engineering at ASU.

The structure of the course reflected its objectives and learning outcomes. For the course objectives, students were expected to: learn to apply the engineering design methodology; acquire and use basic engineering skills and tools; and understand and value engineering as a career and a profession. For learning outcomes, it was expected that, by the end of the course, the students would be able to: 1) prepare and deliver oral presentations; 2) organize and write engineering reports and documents; 3) use electronic means to gather and disseminate information; 4) work effectively in teams; 5) use computing methods and tools to solve engineering problems; 6) use a structured problem-solving approach to complete engineering projects; 7) organize and manage engineering projects; 8) understand the development of the engineering profession and its ethical issues; and 9) be aware of and excited about engineering career options.

**RESEARCH METHODOLOGY**

The interdisciplinary team is evaluating the fulfillment of the course objectives and outcomes as well as sociocultural factors that impact the learning process such as: technical and tinkering self-efficacy; understanding of the social relevance and impact of engineering on society; and career attitudes and intentions. The focus of this paper is on the barriers that were encountered that impeded the fulfillment of objectives and achievement of outcomes. Preliminary analysis of results indicates that there was very limited success with fulfillment of the objectives and outcomes. The research approach will now be discussed. It is followed by presentation, analysis and discussion of the barriers. Finally, implications with respect to teaching and recommendations for future change are presented.

The research design is mixed methods. Data sources include pre and post test data, classroom observations (live and videotaped), student created artifacts (e.g. soda straw airplanes, power point presentations), student focus groups, teacher interviews and informal conversations with the teacher. Pre and post tests, attitudinal measures, and rubrics for evaluating student work have been created and will continue to be created as the research proceeds. Classroom observations were made twice a week with a faculty team (Krause & Baker) and with a graduate student team (Uysal & Yasar) to insure that there was agreement about the classroom descriptions. The entire team also met weekly to discuss observations, to create assessments and rubrics, and to discuss analysis of data. The data was analyzed using NVivo (QSR International 2002) [16]. This is a program designed for qualitative data analysis that allows the researcher to identify patterns, code portions of text and manage large amounts of data from multiple sources.

The conclusions were derived from the classroom observations, from student focus groups and from teacher interviews and informal conversations with a particular focus on the barriers to implementation. It is the hope that others interested in collaborating with schools to introduce an engineering curriculum will learn from observations, issues, analysis, and recommendations derived from our experience.
RESULTS AND DISCUSSION

The primary barriers to successful implementation were; 1) varying maturity levels of students due to mixed age groups; 2) lack of diversity 3) need for enhanced structuring of classes, 4) inappropriate placement of students in engineering classes by guidance counselors, 5) issues of materials management, 6) inadequate application of science and math in design and problem solving, and 7) the level of difficulty of course books. Many of these problems were nested one within the other. There were two overarching issues that inhibited progress in the classes. The first was varying maturity levels of students, since all three sections of the class had students ranging from freshmen to seniors. The other major issue was inappropriate placement by counselors of students who had limited attention spans in the classroom. The counselors perceived the Introduction to Engineering course more as a crafts class and less as thought-provoking, analytical class. In the survey results discussed earlier, teachers had the perception that counselors had little knowledge of, and did not understand, engineering. These perceptions were verified by the counselors’ placement decisions. The consequences of all of the issues presented are discussed below.

The varying maturity levels of students resulted in materials management issues and a need for more structure in class activities than the teacher had anticipated. The nature of the tasks, i.e. teamwork, the design process, and the possibility of multiple solutions required greater amounts of self-directed learning than the less mature students were capable of. This resulted in multiple forms of off-task behavior (abusing materials, talking, and fighting) that frequently disrupted the whole class. There was student disengagement both cognitively and physically, high levels of non-productive noise and unfinished tasks. The problems with maturity also showed up when students critiqued each others’ team designs. Remarks were unkind (“that’s the stupidest design I’ve ever seen”) and did not focus on design criteria with constructive criticism. Older boys were unhappy about the younger boys’ behavior.

Results discussed earlier about the two graduate level design courses showed that developing an understanding of the design process is a slow, iterative process that requires multiple passes at practice and reflection and discussion. The cognitive demands on high school students were high and needed to be more strongly taken into consideration. The first graduate class also demonstrated that team work is difficult for males, even for graduate students. In the graduate class there was a limited ability to negotiate and compromise and males also had difficulty in sharing. This behavior was even more strongly demonstrated by teams in the high school classes, especially by freshmen. As a result of the experience acquired, as described above, the structure of the high school engineering courses for the upcoming school year have been modified. Courses have been stratified to put students with different levels of background knowledge and maturity in an appropriate level of class.

Major problems arose because the guidance counselors viewed the class as an elective and a good class for students who had difficulties with more traditional instruction since they would be engaged in hands-on building activities. For these students, the design activities became craft activities devoid of math and science content. Frustrations for these students ran high when the teacher emphasized the science and math, especially when modeling in Excel. These frustrations led to disruptive behavior that was manifested in management issues and abuse of materials. Some students deliberately destroyed towers built by others. Because of the chaotic conditions that frequently plagued the classroom, it was usually not possible to conduct discussions or hold a forum on the nature of engineering design or strengths and weaknesses of design project artifacts. Thus, there was little self-reflection and discussions and critiques were more limited and shallow which made them less insightful and stimulating. This resulted in some of the older students feeling that they would have learned more if projects and problems had greater depth and more difficulty. The issue of inappropriate placement was addressed for the spring semester’s engineering classes through discussions with counselors about the nature of the engineering classes and by screening of enrollees to eliminate the previous semester’s disruptive students. This has resulted in a calmer classroom environment with students on task a much greater percentage of the time.

Don had a difficult time engaging students in discussions, even about such things as disaster videos. He had hoped that the students would discuss the science and math principles seen in the videos and in the building activities in order to link the activities to the application of science and math in design and problem solving. However, the students were reluctant to answer his questions and he was unable to launch any discussions. Opportunities to make the science and math links were lost because he was unable to generate discussions. To remedy this problem, Don modified his approach by writing a series of questions on the board that students had to answer in groups and then present their answers to the class (What is the design impact?, What is the science behind the disaster? What engineering is involved?, What is the societal impact?). This additional structure resulted in more involvement and attention than during the previous semester’s classes.

The engineering textbook and textbook activities were not engaging for the younger students (freshmen) and too difficult for their more limited math and science backgrounds. In contrast to the older students, the younger students did not do the in-class assignments or work to answer the text-based questions in their group. Some of the students lacked basic knowledge about mathematics (e.g. scatter plots, sine and cosine) needed to follow the Excel textbook and do the Excel exercises. Older students sailed through the chapters while younger students never finished chapter exercises. Furthermore, Mr. Quill realized that the Excel activities were decontextualized and that students were unable to make the link between the calculation exercises and engineering. Many students spent their time playing games rather than attempting the calculations. To address this problem, Mr. Quill created a
series of contextualized problems for the spring semester’s class (e.g., calorie calculations).

The problems encountered were further exacerbated by the student composition, which was almost all male (102 males and 6 females). Research done by Baker [17] in single sex science and math classrooms indicate that both teachers and boys want girls in the classroom because the girls dilute the effect of the destructive and/or antisocial behavior tendencies of the boys. This helps keep groups on task and projects moving forward while also helping the boys with difficult content. Recruiting for the elective engineering courses had been done the prior spring at the high school and at feeder middle schools. The content of the course descriptions was oriented more toward male-oriented interests in traditional engineering disciplines such as civil, mechanical, and aerospace engineering.

In order to improve gender diversity in the upcoming classes for the 2005 – 2006 school year changes were made in the recruiting process. One significant change made was creating improved recruiting materials that described a broader range of engineering disciplines with gender friendly examples of disciplinary applications and careers. Another important change was including two females from the engineering classes into the recruiting activities so that they could act as role models to other girls who might have an interest in engineering but were intimidated by perceptions of the male oriented examples of activities and careers. Another change has been to work with counselors and provide material about the courses. Counselors have been made aware of the maturity and background knowledge for each course. A particular emphasis has been placed on the breadth of engineering careers and opportunities for females and minorities, especially in fields where engineering can have an impact on society, such as bioengineering. The result of these changes has been a tripling of tentative female enrollment in the engineering courses for the upcoming school year.

**Implications for Teaching Engineering in a High School Setting**

Before setting up an engineering curriculum in a high school several factors must be addressed. The first of these is to determine the student population the program is being designed for and to communicate this information to parents and counselors. Next, the necessary pre-requisite knowledge and skills for student success have to be identified. Courses that explore engineering careers may not require as much mathematical ability on the part of students as a design course. Appropriate activities and texts must also be selected that reflect the students’ maturity, reading level and background knowledge and that have a strong engineering context. Explicit strategies to link the science and math to the engineering design activities must be identified and used to insure that the links are obvious to students. Consideration must also be given to the amount of structure students will need based on their maturity, skills and knowledge. Activities need to be structured to promote reflection and to promote writing, which typically high school boys find difficult and do not enjoy. Correspondingly, team work skills need to be promoted so individuals on teams work together in discussions, reflections, and reporting. Teachers must also be ready, as Mr. Quill was, to modify classroom content and activities as they go along. Finally, the engineering classes could be strongly facilitated by having more than a single teacher participate so a community of learners could develop. This would promote the support and reflection on instruction critical for developing high quality classes and a satisfying teaching experience. As demonstrated at Mr. Quill’s high school, limited resources may make this difficult.

Engineers and faculty participating in K-12 outreach must remember that, although there is little difference between a college freshman and a university senior there is a huge difference between a high school freshman and a high school senior. Furthermore, they must realize that programs targeted to the able older student does little to address the pipeline problems currently facing engineering because the older able student interested in engineering in high school has already decided on a career path. Early high school recruiting into the engineering pipeline means designing programs for the less mature student who needs more structure and may lack certain critical math and science skills. With some thought, and by working cooperatively with teachers, these students could become the engineers of the future.

**References**


