Integration of Engineering Education by High School Teachers to Meet Standards in the Physics Classroom

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Dedication

This dissertation is dedicated to the memory of my grandfather, Dr. Miles S. Kersten. Grandpa was my inspiration for doing this work. In his quiet way, he encouraged his family to pursue education. As a civil engineering professor at the University of Minnesota, he also encouraged countless others to attain their academic potential. It is with great pride that I become the third generation of the Kersten family to obtain a Ph.D. from the University of Minnesota. I know this would not have been possible without the example, encouragement, and support that my grandfather provided.

Abstract

In recent years there has been increasing interest in engineering education at the K-12 level, which has resulted in states adopting engineering standards as a part of their academic science standards. From a national perspective, the basis for research into engineering education at the K-12 level is the belief that it is of benefit to student learning, including to "improve student learning and achievement in science and mathematics; increase awareness of engineering and the work of engineers; boost youth interest in pursuing engineering as a career; and increase the technological literacy of all students" (National Research Council, 2009a, p. 1).

The above has led to a need to understand how teachers are currently implementing engineering education in their classrooms. High school physics teachers have a history of implementing engineering design projects in their classrooms, thus providing an appropriate setting to look for evidence of quality engineering education at the high school level. Understanding the characteristics of quality engineering integration can inform curricular and professional development efforts for teachers asked to implement engineering in their classrooms. Thus, the question that guided this study is: How, and to what extent, do physics teachers represent quality engineering in a physics unit focused on engineering?

A case study research design was implemented for this project. Three high school physics teachers were participants in this study focused on the integration of engineering education into the physics classroom. The data collected included observations, interviews, and classroom documents that were analyzed using the *Framework for Quality K-12 Engineering Education* (Moore, Glancy et al., 2013). The results provided information about the areas of the K-12 engineering framework addressed during these engineering design projects, and detailed the quality of these lesson components. The results indicate that all of the design projects contained components of the indicators central to engineering education, although with varied degrees of success. In addition, each design project contained aspects important to the development of students' understanding of engineering and that promote important professional skills used by engineers. The implications of this work are discussed at the teacher, school, professional development, and policy levels.

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Chapter 1: Introduction

There is the belief that the United States is facing a shortfall in the number of people trained in the science, technology, engineering, and mathematics (STEM) fields (Maltese & Tai, 2011). It is projected that STEM employment opportunities will grow 17 percent over the next decade (Carnevale, Smith & Strohl, 2010). The Bureau of Labor Statistics projects that by 2018 the combination of newly created STEM jobs and the replacement of STEM retirees will create more than 3 million job openings (Lacey & Wright, 2009). Employment estimates for science and engineering jobs indicate that the science and engineering workforce continues to grow more rapidly than the total workforce (National Science Board, 2010). Given this current context, it is of value to explore methods to encourage students to become more involved in education within STEM disciplines.

Rationale

With the United States facing a shortage of trained engineers (Gomez, 2000), there is concern "about the quantity, quality, and diversity of future engineering talent" (Brophy, Klein, Portsmore, & Rogers, 2008, p. 369). While college engineering programs do not have higher drop out rates compared to other majors, "…after matriculation, engineering attracts far fewer students than any other major" (Ohland, Sheppard, Lichtenstein, Eris, Chachra, & Layton, 2008, p. 275). Additionally, there is an under-representation of minorities and women in engineering programs and in the engineering profession (Brophy et al., 2008).

At the high school level, within the last 30 years the United States has had a steady growth in the number of students taking physics classes (White & Langer Tesfaye, 2010). However, according to the United States Department of Education, in 2005 the percentage of high school graduates who had taken a physics class, 32.7%, was still far below that of other sciences: 66.2% for chemistry and 92.3% for biology (Snyder & Dillow, 2011). The American Institute of Physics Statistical Center estimates that of high school students graduating in 2008-2009, 37% had completed a physics class (White & Langer Tesfaye, 2010). In relation to the small percentages of high school physics students, research conducted on the consequences of enrolling in physics reveals that high school students have “a fear of failure” and believe “physics is hard or boring” (Crawley & Black, 1992).

As a result of a need to broaden the engineering pathway, as well as a desire to increase enrollment and engagement in high school physics, determining how to effectively integrate engineering education into the physics classroom is of importance. The benefits of engineering in K-12 classrooms may include the following: “improve student learning and achievement in science and mathematics; increase awareness of engineering and the work of engineers; boost youth interest in pursuing engineering as a career; and increase the technological literacy of all students” (National Research Council [NRC], 2009a, p. 1). The benefits of integrating engineering into the physics classrooms may promote interest by high school students to take physics classes and to investigate the careers of engineers. The study presented investigated the strategies that high school physics teachers are currently using to integrate engineering education and the quality of the engineering represented.

Less than 10% of K-12 students have taken part in formal engineering curricula in the last two decades (NRC, 2010). Stand-alone elective engineering classes can promote engineering, but the number of students enrolled in these classes is limited when compared to required classes. School leaders currently feel the pressures of state required "standards-based" testing and accountability to the "No Child Left Behind" federal legislation (Burr-Alexander, Carpinelli, Kimmel, & Rockland, 2006). Classroom instruction is often directed toward these state standards and achievement tests (Brophy et al., 2008). However, national interest in integrating engineering education at the K-12 level is increasing, as can be seen by the publication of a number of national documents (NRC, 2007; NRC, 2009b; NRC, 2010; NRC, 2011).

In 2007, the NRC released the document, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*. This document contained a response to federal policy-makers enquiring how to enhance science and technology enterprise in the United States. The document set in motion a heightened national interest in STEM education at the K-12 level. What has followed is a focus on national K-12 engineering education, as can be seen in the documents *Engineering in K-12 education: Understanding the status and improving the prospects* (NRC, 2009b) and *Standards in K-12 engineering education?* (NRC, 2010). In 2011, the most recent national document was published, *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (NRC, 2011). Although national engineering standards do not yet exist, the recommendation from the NRC is for the integration of engineering education into science curricula. While attention has been gaining at the national level, states have begun to include engineering in their academic standards. Currently only 13 states have explicit engineering standards within their science standards (Moore, Tank, Glancy, Kersten, Ntow, 2013). Minnesota is one of these states and has engineering standards at all levels K-12. These national documents and state standards indicate that engineering education at the K-12 level is a new concept that is gaining momentum. As a result, the need to study engineering integration is critical.

With growing support for national standards in engineering, it is essential to turn attention to those who facilitate engineering integration in the classroom, the teachers. Most science teachers have little experience with, or background knowledge of, engineering. Engineering coursework is not required for most science degrees and teaching certifications. "Often, just mention of the word engineering brings about feelings of intimidation, at least for those outside the engineering field" (Dukes & Lamar-Dukes, 2009, p. 18). “Teachers are typically uncomfortable teaching content they do not understand well and thus they will often shy away from such content for fear of being unable to answer students' questions” (Brophy et al., 2008, p. 381). However, as the focus on engineering education in K-12 strengthens, it is these teachers who will be expected to provide engineering integration.

In-service teachers need professional development in how to integrate engineering education in the classroom. "Compared with professional development for teaching science, technology, and mathematics, professional development programs for teaching engineering are few and far between" (Katehi, Pearson, & Feder, 2009, p. 8). "Some projects and initiatives have been undertaken to assist teachers in teaching engineering-related curricula, but relatively little research has been conducted to determine what works" (Custer & Daugherty, 2009, p. 9). Without a clear picture of best practices and how they can be implemented, there is need for research on current engineering integration that is occurring in the classroom.

Statement of the Problem

Many teachers of physics content are integrating components of engineering education into their physics curriculum without being explicit about the engineering concepts being implemented (Wang, 2012). Engineering and physics are a natural fit with many physics curricula containing design projects, such as catapults, egg drop containers, and balloon rockets. This use of design in the physics classroom is an important step towards intentional engineering integration. Some teachers have been intentionally integrating engineering education in a fashion that is transparent to the students in their secondary physics classrooms. Learning about the practice of these teachers is of value. The knowledge of educators experienced with integrating engineering into a physics curriculum can be shared with those who are in the learning stages or have yet to begin their journey with engineering education. Within the context of national and state engineering education standards, the integration of engineering education into the high school physics classroom is the focus of this study. The following research question guided this study: How, and to what extent, do physics teachers represent quality engineering in a physics unit focused on engineering?

Overview of Following Chapters

The chapters that follow provide an overview of this study. In Chapter 2, an in-depth review of the literature is given in this relatively new field of K-12 engineering education. Following the literature review, Chapter 3 contains the details of the research method used for this work, including the method of participant selection, the data collection methods employed, and the data analysis process. In Chapter 4, a detailed account is given of the three engineering projects, which constitute the case studies. In Chapter 5, a cross-case analysis of these cases is provided. Finally, in Chapter 6 a discussion of the results is offered, as well as the implications of the results and suggestions for further areas of research.

Chapter 2: Literature Review

In Chapter 1, an introduction and overview of this study was given. In Chapter 2, a literature review is presented. The literature review begins with looking at K-12 engineering at the national level. The focus is then narrowed to look at K-12 engineering at the state level. In the third section, the *Framework for Quality K-12 Engineering Education* is introduced. Then each indicator of the K-12 framework is provided and relevant literature is used to support each indicator's inclusion. Finally, an overview is given of the current research in K-12 engineering education, with particular attention provided to implementing engineering education in secondary science.

K-12 Engineering at the National Level

Historically, engineering has been a domain left almost exclusively to higher education. "It is not, therefore, an intuitive choice of studies for those who are not somehow exposed to engineering – for example have a relative who is an engineer" (DeCohen & Deterding, 2009, p. 223). Selingo (2007) asserts there are "countless studies over the years that show if students encounter engineering early on in school, they are more likely to choose it as a career" (p. 26). By promoting engineering at the K-12 level, one aspiration is to attract a wider range of students to engineering careers, thus responding to the anticipated shortages (Apedoe, Reynolds, Ellefson, & Schunn, 2008). In addition to responding to these shortages, another purpose of K-12 engineering education is the advance of scientific and technological literacy (Custer & Daugherty, 2009) as the next generation of workers will need more sophisticated science, mathematics, engineering, and technological skills (Nugent, Kunz, Rilett, & Jones, 2010).

This increased interest in engineering education at the K-12 level has taken on national significance in the last decade.

Engineering as a part of the recent STEM movement can be followed on a national level starting with the publication of *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future* (NRC, 2007). This document was written in response to federal policy-makers enquiring about actions that could be taken to enhance the science and technology enterprise in the United States. The findings from the committee indicated that they were "deeply concerned that the scientific and technological building blocks critical to [the United States'] economic leadership are eroding at a time when many other nations are gathering strength" (NRC, 2007, p. 3). To address this problem, the committee set forth four recommendations, one of which was focused on K-12 science and mathematics education. The three actions suggested to meet this education recommendation were: recruiting more qualified science and mathematics teachers, providing professional development for current science and mathematics teachers, and increasing the pipeline of students graduating from college with degrees in science, mathematics, and engineering (NRC, 2007). "The report received widespread media coverage when it was released and generated extensive discussions among policymakers and business leaders" (NRC, 2009a, p. 4). Momentum was created by the report as both the public and private sectors began responding.

In 2009, the NRC produced another document, *Engineering in K-12 Education: Understanding the Status and Improving the Prospects*. The focus of this document was on the engineering portion of the STEM movement. Although engineering was just slowly moving into the K-12 setting, it was noted, "The presence of engineering in K–12 classrooms is an important phenomenon … because of the implications of engineering education for the future of science, technology, engineering, and mathematics (STEM) education more broadly" (NRC, 2009a, p. 1). It was anticipated that the implementation of engineering could have multiple benefits; "K–12 engineering education may improve student learning and achievement in science and mathematics; increase awareness of engineering and the work of engineers; boost youth interest in pursuing engineering as a career; and increase the technological literacy of all students" (NRC, 2009a, p. 2). The goal of the document was to provide guidance for the implementation of engineering curricula. The document was seen as lending "credence to the value and import of K-12 engineering education programs and learning opportunities for all students" (Rogers, Wendell, & Foster, 2010, p. 181).

With STEM education being a priority and value being given to K-12 engineering education, a third report was released in 2010, *Standards in K-12 Engineering Education?* With no existing national standards in K-12 engineering, this report traced the history of academic standards in the United States that included engineering. The committee was assessing, on a national level, "the potential value and feasibility of developing and implementing content standards for engineering education at the K-12 level" (NRC, 2010, p. 1). The committee concluded that regarding the development of stand-alone standards for K-12 engineering education, "it would be extremely difficult to ensure their usefulness and effective implementation" (NRC, 2010, p.1). Instead, the committee recommended the infusion of engineering learning goals into, or the mapping of engineering "big ideas" onto, current standards in other disciplines such as science or mathematics (NRC, 2010). Thus the stage was set for the creation of national standards that included engineering.

In July of 2011, the NRC released a fourth report, *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas.* This report represented "the first step in a process to create new [national] standards in K-12 science education" (NRC, 2011, p. vii). This report was released as many states were adopting national common core standards in mathematics and English/language arts (citation). The report contained a framework "that articulates a broad set of expectations for students in science" (NRC, 2011, p. ES-1). The framework detailed several significant changes to K-12 science education, particularly the inclusion of engineering and technology in order to "reflect the importance of understanding the human-built world and to recognize the value of better integrating the teaching and learning of science, engineering, and technology" (NRC, 2011, p. 1-1). The NRC report did not suggest stand-alone engineering standards; rather it promoted the integration of engineering across the science content areas of physical science, life science, and earth and space sciences. The NRC framework is the guiding document being used to develop the common core standards in science, the *Next Generation Science Standards,* which will include engineering standards.

K-12 Engineering at the State Level

As no national engineering standards exist, many states have taken it upon themselves to develop their own engineering related standards (Strobel, Carr, Martinez-Lopez, & Bravo, 2011). Strobel et al. (2011) completed a national survey of P-12 engineering standards and found that 34 states had standards related to engineering and technology design; 15 of these states had explicit engineering standards and 10 states had engineering standards within the context of technology design. In a follow-up article (Carr, Bennett, & Strobel, 2012), it was reported that 41 states "have engineering content in their educational standards" (p. 549). Of the 41 states, only 36 were found to have a strong presence of engineering. Within the 36 states, "11 have their own explicit engineering standards and six have standards present in engineering in the context of technology design" (Carr et al., 2012, p. 549). The findings indicated that 12 states had engineering content within their science standards, the area in which "engineering is most often found" (Carr et al., 2012, p. 560). These articles indicate that the topic of engineering currently exists in state standards for the majority of the country. However, there is wide variation among the states as to the extent and placement of engineering standards.

The first state to implement K-12 engineering standards into their required science standards was Massachusetts in 2001. For their standards, technology/engineering is listed as one of the four strands in the Science and Technology/Engineering curriculum framework. In Massachusetts, technology/engineering is considered a "science discipline equivalent to physical science, life science, and earth and space science" (Foster, 2009, p. 25). Within the framework, there are specific technology/engineering standards for each grade band from K-12 (Massachusetts Department of Education, 2006).

More closely related to the current study, Minnesota recently implemented revised academic standards in science that included engineering (Minnesota Department of Education, 2009). One of the four content strands in the standards for K-12 students is "The Nature of Science and Engineering." Of the three substrands within this strand, two are: “The Practice of Engineering” and “Interactions Among Science, Technology, Engineering, Mathematics, and Society.” The benchmarks in these substrands begin at the kindergarten level and continue through high school.

Engineering education at the K-12 level has made significant steps over the last several years at both the national and state levels. State engineering standards for multiple states are integrated into their academic science standards. At the national level, work is ongoing to include engineering standards within the new *Next Generation Science Standards*. With the focus centering on including engineering education at the K-12 level, it is of value to determine what quality K-12 engineering education includes.

Framework for Implementing Quality K-12 Engineering Education

Without national standards related to engineering at the K-12 level, the consistency of engineering standards from state to state is very low. Work has been done to create a framework “for describing and evaluating engineering at the K-12 level in order to help further our understanding and development of robust engineering and STEM education standards and initiatives” (Moore, Glancy, Tank, Kersten, Stohlmann, & Ntow, 2013, p. 1). The *Framework for Quality K-12 Engineering Education* contains “indicators” that define quality K-12 engineering education. The framework was designed to be used “as a tool for evaluating the degree to which academic standards, curricula, and teaching practices address the important components of a quality K-12 engineering education” (Moore, Glancy et al., 2013, p. 1). The intention is that the framework will help guide K-12 engineering education to be more complete and comprehensive by addressing the many facets of quality K-12 engineering education. In the following section, the development of this framework is briefly described, followed by a description of the twelve indicators contained within the K-12 engineering framework.

Development of the K-12 engineering framework.

Standards in engineering education have their longest history at the undergraduate level. For undergraduate programs in applied science, computing, engineering, and technology, the primary accrediting body is ABET (formerly known as the Accreditation Board for Engineering and Technology). The ABET standards are the most widely used set of criteria for accrediting undergraduate engineering programs in the United States. Included in the ABET standards is Criterion 3, a list of 11 engineering program outcomes for students, labeled a-k (ABET, 2009; see Table 2.1).

Table 2.1

ABET Program Outcomes, Criterion 3 a-k

Baccalaureate degree programs must demonstrate that graduates have: a) an ability to apply knowledge of mathematics, science, and applied sciences b) an ability to design and conduct experiments, as well as to analyze and interpret data c) an ability to formulate or design a system, process, or program to meet desired needs d) an ability to function on multidisciplinary teams e) an ability to identify and solve applied science problems f) an understanding of professional and ethical responsibility g) an ability to communicate effectively h) the broad education necessary to understand the impact of solutions in a global and societal context i) a recognition of the need for and an ability to engage in life-long learning j) a knowledge of contemporary issues k) an ability to use the techniques, skills, and modern scientific and technical tools necessary for professional practice.

Note. Table from ABET, 2009, p. 3

These ABET program outcomes were a logical starting point to develop the *Framework for a Quality K-12 Engineering Education* (Moore, Tank, Glancy, Kersten, Stohlmann, 2012). With support from the engineering and STEM education literature, the categories were modified to be more specific to K-12 education.

The modified ABET outcomes were used to code state standards from the 15 states with explicit engineering standards (Strobel et al, 2011). Some of the ABET categories were well supported in the standards documents; others were almost nonexistent, leading to the development of a set of indicators better aligned with engineering at the K-12 level. These indicators are described in detail in the following section.

Indicators of quality K-12 engineering education.

The final *Framework for a Quality K-12 Engineering Education* contained 12 key indicators that together summarize quality K-12 engineering education. "The order of the key indicators within the framework was carefully chosen based on the degree to which the benchmark is unique or central to engineering as compared to other disciplines" (Moore, Glancy et al., 2013 p. 4). The key indicators, along with brief descriptions, are listed in order in Table 2.2. In the following paragraphs, each indicator is described in detail, including a review of the literature related to each indicator.

Table 2.2

K-12 Engineering Education Framework Indicators

Indicator Name	Abbreviation	Brief Descriptor
Process of Design	POD	Design processes are at the center of engineering practice. Solving engineering problems is an iterative process involving preparing, planning and evaluating the solution. Students should understand design by participating in:
Problem and Background	POD-PB	Identification or formulation of engineering problems and research and learning activities necessary to gain background knowledge
Plan and Implement	POD-PI	Brainstorming, developing multiple solutions, judging the relative importance of constraints and the creation of a prototype, model or other product
Test and Evaluate	POD-TE	Generating testable hypotheses and designing experiments to gather data that should be used to evaluate the prototype or solution, and to use this feedback in redesign
Apply Science, Engineering, and Mathematics Knowledge	SEM	The practice of engineering requires the application of science, mathematics, and engineering knowledge and engineering education at the K-12 level should emphasize this interdisciplinary nature.
Engineering Thinking	EThink	Students should be independent and reflective thinkers capable of seeking out new knowledge and learning from failure when problems within engineering contexts arise.
Conceptions of Engineers and Engineering	CEE	K-12 students not only need to participate in an engineering process, but understand what an engineer does.
Engineering Tools,	ETool	Students studying engineering need to become familiar and proficient in the processes, techniques, skills, and tools

Techniques, and Processes		engineers use in their work.
Issues, Solutions, and Impacts	ISI	To solve complex and multidisciplinary problems, students need to be able to understand the impact of their solutions on current issues and vice versa.
Ethics	Ethics	Students should consider ethical situations inherent in the practice of engineering.
Teamwork	Team	In K-12 engineering education, it is important to develop students' abilities to participate as a contributing team member.
Communication Related to Engineering	Comm-Engr	Communication is the ability of a student to effectively take in information and to relay understandings to others in an engineering context.

The Processes of Design (POD).

The *Framework for a Quality K-12 Engineering Education* describes POD as follows:

> Design processes are at the center of engineering practice. Solving engineering problems is an iterative process involving preparing, planning, and evaluating the solution at each stage including the redesign and improvement of current designs. At the K-12 level, students should learn the core elements of engineering design processes and have the opportunity to apply those processes completely in realistic situations. Although design processes may be described in many forms, certain characteristics are fundamental. This indicator represents all of the three POD sub-indicators (POD-PB, POD-PI, POD-TE) below (Moore, Glancy et al., 2013, p. 6).

Engineering design is at the heart of engineering education. Crismond and Adams (2013) provided evidence that engineering design is well documented in the literature. They stated that there are "more than 170 peer-reviewed design journals, of which over 30 identify engineering design as a primary subject of interest to their audiences" (p. 744). Crismond and Adams (2013) provided a synthesis of over 85 articles from the design cognition literature by identifying key performance dimensions that are central to doing "informed design." It is through the design process that students bring together many aspects of engineering. While there is no one specific engineering design process (Dym, 2004), the general process contains the main engineering practices of identifying a problem and gaining background knowledge, determining a plan and then implementing this plan, and finally, testing and evaluating the resulting product or system (NRC, 2009a; Richards, Hallock, & Schnittka, 2007; Rogers & Portsmore, 2004).

The POD indicator was separated into three sub-indicators in order to better organize the large volume of information about design found in the literature and state standards. These sub-indicators will be discussed in logical order; however, it is important to note that the design cycle rarely proceeds in a linear fashion (NRC, 2009a).

The POD-PB sub-indicator is related to the formulation of an engineering problem and the application of background knowledge; it is described in the framework as follows:

> General problem solving skills are prerequisites to solving engineering problems. An engineering design process begins with the formulation or identification of an engineering problem. When confronted with open-ended problems, students should be able to formulate a plan of approach and should be able to identify the need for

> engineering solutions. This stage also includes researching the problem, participating in learning activities to gain necessary background knowledge, and identifying constraints (Moore, Glancy et al., 2013, p. 6).

Albert Einstein was quoted as saying, "Scientists investigate that which already is; engineers create that which has never been" (ThinkExist, n.d.). The NRC (2009a) differentiates the two domains by stating, "Whereas scientists ask questions about the world around us—what is out there, how do things work, and what rules can be deduced to explain the patterns we see—engineers modify the world to satisfy people's needs and wants" (p. 27). Engineers must begin their work with some sort of need or want, a problem. Engineers then use their knowledge of science, mathematics, and technology, along with the design process, to solve these practical problems. Thus for K-12 engineering education, students must begin with an engineering problem (Chae, Purzer, & Cardella, 2010). At the K-12 level, engineering problems can either be identified by the student or presented to the student. These problems should be accompanied by constraints.

Once an engineering problem has been identified, background knowledge must be gathered or applied in order to begin finding a solution to the problem. This includes what has already been done to solve similar problems, as well as pulling in knowledge from multiple disciplines to try to understand the problem and begin planning for a solution.

The Plan and Implement sub-indicator (POD-PI) is described as follows:

> At this stage, students develop a plan for a design solution. This includes brainstorming, developing multiple solution possibilities, and evaluating the pros

> and cons of competing solutions. In doing so, they must judge the relative importance of different constraints and trade-offs. This stage likely concludes with the creation of a prototype, model, or other product (Moore, Glancy et al., 2013, p. 6).

The POD-PI sub-indicator is related to the planning of multiple solutions to an engineering problem and the subsequent implementation of one of these solutions. Once the engineering problem has been defined and background knowledge has been obtained, it is time to start brainstorming ideas for possible solutions. Engineering problems rarely have one correct answer and multiple solutions are possible. English (2008) maintains that engineering is an interdisciplinary process "(c) employing creative, innovative, careful, and critical thinking in solving problems" (p.189). Solving the engineering problem also requires the considerations of constraints, such as: budget, environmental impact, size, efficiency, manufacturability, and aesthetics (Welty, Katehi, Pearson, & Feder, 2008).

Once solutions to the problems have been synthesized, a single solution must be chosen for implementation. The implementation of the design solution often comes about through the creation of a prototype of the product or system. Carlson and Sullivan (2004) contend, "There is no substitute for fabricating working (or not!) prototypes of conceptual designs" (p. 379). It is here in the design process that its iterative nature can be particularly noticed. As the creation of a prototype unfolds, problems are often encountered, testing must take place, and modifications may be made. Effective implementation of engineering education requires students to articulate and justify their design plan rather than embarking on an exercise in trial and error (Chandler, Fontenot, &

Tate, 2011).

The POD-TE sub-indicator is associated with the testing and evaluating of a prototype or system that was created during the implementation process and is described as follows:

> Once a prototype or model is created it must be tested. This likely involves generating testable hypotheses or questions and designing experiments to evaluate them. Students may conduct experiments and collect data (and/or be provided with data) to analyze graphically, numerically, or tabularly. The data should be used to evaluate the prototype or solution, to identify strengths and weaknesses of the solution, and to use this feedback in redesign. Because of the iterative nature of design, students should be encouraged to consider all aspects of a design process multiple times in order to improve the solution or product until it meets the design criteria. (Moore, Glancy et al., 2013, p. 6)

This sub-indicator, in the process of design, often connects back to the previous sub-indicators (POD-PB and POD-PI), thus making the process iterative (NRC, 2009; NRC, 2010; Shepard, 2003). For example, testing may necessitate the development of new solutions and prototypes or the refinement of the original problem itself.

The engineering design process should encourage students to evaluate different solutions to the same problem (NRC, 2009a) and may happen at various points during the design cycle. Students may be asked to articulate and justify their design choices (Chandler et al., 2011), including the positives and negatives of solutions other than their primary choice (NRC, 2009a). The evaluation processes used in engineering design may be different to those commonly encountered with analytical problems with a single right answer (Kelley, 2009). Within engineering, the "correct" answer is merely one that presents a solution to the problem that falls within the constraints.

Apply Science, Engineering, Mathematics Knowledge (SEM).

SEM is described in the framework as follows:

> The practice of engineering requires the application of science, mathematics, and engineering knowledge, and engineering education at the K-12 level should emphasize this interdisciplinary nature including the integration of these areas. Students should have the opportunity to apply developmentally appropriate mathematics or science in the context of solving engineering problems. This could occur within a mathematics or science classroom where students study mathematics or science concepts through engineering design problems. Or this could happen within an engineering course where students are asked to apply what they have already learned in mathematics, science, or engineering courses. (Moore, Glancy et al., 2013, p. 6).

As one of its three principles for K-12 engineering education, the NRC (2009b) states that engineering education should "incorporate important and developmentally appropriate mathematics, science, and technology knowledge and skills" (p. 5). The work of engineers requires the application of a combination of science, engineering, and mathematics knowledge (NRC, 2010; Shepard, 2003). Unlike the artificial separation of subjects that is so common in secondary and college level education, the content and processes within STEM are inherently integrated. Chae et al. (2010) contend that engineering literacy requires the solving of basic problems in everyday life by employing the concepts of both science and mathematics. English (2008) believes that problem solving related to engineering design requires interdisciplinary contexts and approaches. This includes interdisciplinary knowledge of "core engineering ideas and principles and how these draw upon mathematics and science" (English, 2008, p. 189). It also includes the interdisciplinary process involving "applying mathematics and science learning in engineering" (English, 2008, p. 189). It follows that "engineering design activities are a powerful strategy for the integration of science, mathematics, and technology" (Cantrell, Pekcan, Itani, & Velasquez-Bryant, 2006, p. 302). Thus, engineering education provides students with a learning opportunity that integrates the STEM knowledge they have obtained.

Another anticipated benefit of K-12 engineering education is the strengthening of the background knowledge that is required to solve design problems. The NRC (2009b) maintains that in most cases, the primary reason for including engineering is to enhance the study of science and mathematics. Brophy et al. (2008) explored "how engineering education can support acquisition of a wide range of knowledge and skills associated with comprehending and using STEM knowledge to accomplish real world problem solving through design, troubleshooting, and analysis activities" (p. 369). The authors determined that engineering requires the application of content knowledge as well as cognitive processes to work through complex systems (Brophy et al., 2008). It follows that cognitive processes are of little use if there is no content knowledge to draw upon (Zuga, 2004).

Schnittka and Bell (2011) conducted research on how students could learn significant science concepts, at a deep conceptual level, through an engineering design project. They based their work on research that indicated students involved in design projects do not implicitly learn science (Silk, Schunn, & Cary, 2007). The results of the work done by Schnittka and Bell (2011) showed that students involved in an engineering design project, that also contained targeted demonstrations to facilitate student learning, increased their knowledge about the applicable science concepts to a greater degree than students who did not have the learning demonstrations imbedded in their design project. Application of science content to an engineering design project can increase the gain in content knowledge when compared to a stand-alone design project (Schnittka & Bell, 2011). As a result, the application of science content to an engineering design project can create the difference between science learning and a simple building project.

Engineering Thinking (EThink).

EThink is described in the framework as follows:

> Engineers must be independent thinkers who are able to seek out new knowledge when problems arise. In the K-12 setting, engineering can help students learn to use informed judgment to make decisions, which can lead to informed citizenry. Students must be empowered to believe they can seek out and troubleshoot solutions to problems and develop new knowledge on their own. Engineering requires students to be independent, reflective, and metacognitive thinkers who understand that prior experience and learning from failure can ultimately lead to better solutions. Students must also learn to manage uncertainty, risk, safety factors, and product reliability. There are additional ways of thinking that are important to engineers that include systems thinking, creativity, optimism, perseverance, and innovation. (Moore, Glancy et al., 2013, p. 7)

"Young children are inherently active with strong impulses to investigate, to share with others what they have found out, to construct things, and to create. In other words, a child is a natural engineer" (Genalo, Bruning, & Adams, 2000). These traits of the "natural engineer" are related to portions of the EThink indicator such as seeking out solutions and being creative. In 2004, the NRC released the document *The Engineer of 2020: Visions of Engineering in the New Century*. The document proposed that engineering graduates by 2020 will need the following traits: "strong analytical skills, creativity, ingenuity, professionalism, and leadership" (p. 5). The NRC (2008) also suggested that engineering unleashes the spirit of innovation. If these are general traits of engineers, it is of value to encourage this same type of thinking in K-12.

The engineering education literature provides support for the concept of K-12 students thinking like engineers. English (2008) included in her interdisciplinary processes of engineering "employing creative, innovative, careful, and critical thinking in solving problems; … trouble shooting and learning from failure" (p. 189). Welty et al. (2008) believe that K-12 engineering can develop problem-solving skills. For elementary students, Rogers and Portsmore (2004) deemed it most important to teach curiosity, enthusiasm for learning, self-confidence, how to find answers, and how to test validity of answers. Engineering education is noted to unleash creativity and motivate deeper learning, as well as encouraging learning how to sift through details to find essential information and push beyond determining just a single answer (Carlson & Sullivan, 2004; Kelley, 2009). It is these types of skills that will allow students to develop thinking parallel to that of professional engineers.

Conceptions of Engineers and Engineering (CCE).

CEE is described in the framework as follows:

> K-12 students not only need to participate in engineering design processes but they should also come to an understanding of the discipline of engineering and the job of engineers. This includes some of the big "ideas/conceptions" of engineering, such as how their work is driven by the needs of a client, the idea of "design under constraints," and that no design is perfect. Students should learn about engineering as a profession, including an understanding of various engineering disciplines and the pathways to become one of those types of engineers. Students should also gain knowledge about the engineering profession as a whole, for example: diversity, job prospects, and expectations. (Moore, Glancy et al., 2013, p. 7)

Educational research shows that K-12 students generally have a poor understanding of what engineers do (Cunningham, Lachappelle, & Lindgren-Streicher, 2005; Cunningham & Knight, 2004). The NRC (2009a) encouraged an increased awareness of engineers and their work, stating:

> Improving students' awareness of engineering and the work of engineers can be of great benefit to a society because engineering is central to technology development, and technology influences the well-being of everyone. Conversely, a lack of awareness of engineering and misconceptions or ignorance about what engineers do can be detrimental to a society (p. 55).

English (2008) includes in her interdisciplinary processes of engineering "what engineering is, what engineers do, and the different fields in which engineers work" (p. 189). According to Chubin, May, and Babco (2005) an effective pre-college program must "promote awareness of the engineering profession" (p. 79). If students are to understand engineering as a field, they must not only be able to navigate the design process but must also understand what an engineer does.

In addition to what engineers do, K-12 students should have a general understanding of the current status of the engineering profession. The awareness of engineering that students learn in the K-12 setting may be different than the understanding their parents have of engineering. It is of significance to know that the field of engineering has an underrepresentation of both women and non-whites (Chubin et al. 2005; De Cohen & Deterding, 2009; NRC, 2009). Understanding the current job market for different types of engineers may be of use to secondary students who are contemplating going on to college in these areas.

Engineering Tools, Techniques, and Processes (ETool).

ETool is described in the framework as follows:

> Engineers use a variety of techniques, skills, processes, and tools in their work. Students studying engineering at the K-12 level need to become familiar and proficient with some of these techniques, skills, processes, and tools. Techniques are defined as a step-by-step procedure for a specific task (example: DNA isolation). Skills are the ability of a person to perform a task (examples: using Excel, creating flowcharts, drawing schematics). Tools are objects used to make work easier (examples: hammers, rulers, calipers, calculators, CAD software, Excel software). Processes are defined as a series of actions or steps taken to achieve a particular end (examples: manufacturing, production, universal systems model and **excluding** engineering design process because it is a specific and foundational process covered in POD). K-12 students should be learning and

> implementing different techniques, skills, processes, and tools during their engineering education. (Moore, Glancy et al., 2013, p. 7)

In 2009, Fralick, Kearn, Thompson, and Lyons published an article about 1,600 middle school students who were asked to draw a picture of either a scientist or an engineer at work. While scientists were frequently drawn working indoors in a lab setting, engineers were frequently drawn outdoors doing manual labor. The authors noted that over 30% of the engineers drawn were making something, while just 10% were shown designing (Fralick et al., 2009). A common image found in these drawings of engineers was some type of tool (Fralick et al., 2009).

As the middle school students made visible, engineering is often associated with the use of some sort of engineering tools. In ABET category *(k)* the importance of the use of engineering techniques, skills, and tools was highlighted for college engineering students. The same ability to use techniques, skills, and tools is necessary for K-12 students participating in engineering activities. Students in K-12 can begin to use techniques such as drawing three-dimensionally, skills such as sorting, and tools such as a wire cutter.

The literature shows support for the use of engineering tools at the K-12 level. In her interdisciplinary processes for engineering, English (2008) included “understanding the central role of materials and their properties in engineering solutions” (p. 189). Understanding the property of materials is important when deciding which type of tool to use in an engineering project. Brophy et al. (2008) identified how design contexts increase students’ competencies in evaluating and explaining the “structure, behavior, and function of complex systems” (p. 376). Using a complex system may be a skill required to solve a design problem. Zemelman, Daniels, and Hyde (2005) included as one of their ten best practices for teaching math and science, the integration of technology. Engineering skills often require the ability to use technology. Using a computer simulation, Svarovsky and Shaffer (2006) showed results that indicated middle school students developed an understanding of the center of mass through virtual engineering design challenges. These students used the virtual computer challenges as tools for understanding. These are examples of articles where students used tools while involved in engineering design.

Issues, Solutions, and Impacts (ISI).

ISI is described in the framework as follows:

> The problems that we face in today's society are increasingly complex and multidisciplinary in nature. In order to solve these problems, students need to be able to understand the impact on and of their solutions in a global, economic, environmental, and societal context. Additionally, it is important to prepare students to be able to incorporate a knowledge of current events and contemporary issues locally and globally (such as urban/rural shift, transportation, and water supply issues), which will help to bring about an awareness of realistic problems that exist in today's ever changing global economy. (Moore, Glancy et al., 2013, p. 7)

Engineering education uses STEM knowledge to find solutions to real world problems that have impacts on current issues and may effect current situations. English (2008) includes knowledge of "how society influences and is influenced by engineering" in her requirements for an interdisciplinary approach (p. 189). Chae et al. (2010) list in their core concepts of engineering literacy the ability to "discuss, critique, and make decisions about national, local, and personal issues that involve engineering solutions" and also to "understand and explain how basic societal needs (e.g., water, food, and energy) are processed, produced, and transported" (p. 9). The 2004 NRC document mentions impacts numerous times including: the development of technologies that will help humankind, the potential role of future engineers to reduce the impact of natural disasters, and a connection between the work of engineers with globalization and global conflict.

As a result of the potential influence of engineering, the curriculum should present engineering as relevant to both individuals and to society (NRC, 2009). For example, a middle school engineering challenge researched by Olds, Harrell and Valente (2006) contained the context of a war-torn nation with a high percentage of amputees. The engineering challenge of building simplistic prosthetic limbs was related not only to individual amputees but also to the actions of society through the acts of war. Kelley (2009) used engineering case studies, for example the design of the pop tab, to teach the engineering design cycle; this allowed the students to "understand engineering in the broad context in which engineering is actually practiced" (p. 7).

In 2008, the National Academy of Engineering [NAE] published a document titled *Grand Challenges for Engineering*. The purpose of this document was to outline engineering challenges that face civilization's continuing advancement. Within this document are the outlines of 14 different engineering challenges central to the sustaining and improvement of human life. Example challenges include: the development of carbon sequestration methods, engineer better medicines, restore and improve urban infrastructure, and secure cyberspace (NAE, 2008). The challenge to which the most attention is brought is our need for new energy sources. The NAE also created the Grand Challenge K12 Partnership Program to address the grand challenges with K-12 students. The K-12 program contains a "5-Part Make it Happen Plan" in which the five components of the Grand Challenge Scholar Program are translated into appropriate K-12 terminology (NAE, 2012). As a result, an understanding of the complexity of many of the problems we as a nation face, as well as the possibility of designing engineering solutions, can be of value for engineering education at the K-12 level.

Ethics.

The Ethics indicator is described as follows:

> A well-designed K-12 engineering education should expose students to the ethical considerations inherent in the practice of engineering. They have the responsibility to use natural resources and their client's resources effectively and efficiently. Engineers must also consider the safety of those using or affected by a product, and they should consider the potential effects of the product on individual and public health. Governmental regulations and professional standards are often put into place to address these issues, and engineers have the responsibility to know and follow these standards when designing products. Engineers should conduct themselves with integrity when dealing with their client and as part of the engineering community. The products and solutions they design should work consistently and as described to the client. In creating these products, engineers must respect intellectual property rights. Engineering curriculum and activities at the K-12 level should be designed to expose students to these issues, and as a result students should be aware of the importance of these issues in the field of

engineering. (Moore, Glancy et al., 2013, p. 8)

The literature related to ethical responsibility as a part of K-12 engineering education is limited. The state standards related to ethics comprised only 5% of engineering state standards topics (Moore, Tank et al., 2013). In 2004, the NRC outlined its attributes for the engineers of 2020. They called for the development of "technically proficient engineers who are broadly educated, see themselves as global citizens, can be leaders in business and public service, and who are ethically grounded" (NRC, 2004, p. 51). In the NRC's (2009a) list of engineering habits of mind that should be promoted in K-12 engineering, issues such as ethical and social responsibilities are included.

Teamwork (Team).

Team is described in the framework as follows:

> An important aspect of K-12 engineering education is developing the ability of students to participate as a contributing team member. This may include developing effective teamwork skills, participating in collaborative groups and activities that allow students to assume a variety of roles as a productive member of a team. This team can include partners or small groups where students are engaged in working together towards a common goal or project. This may also include aspects of cooperative learning that focus on collaborative work as students build effective teamwork and interpersonal skills necessary for teamwork. Some of these skills include, developing good listening skills, the ability to accept diverse viewpoints, or learning to compromise and include all members of the team in the process. (Moore, Glancy et al., 2013, p. 8)

It is the uncharacteristic engineer who works alone. Engineers frequently work on teams and collaborate with people from a multitude of disciplines. The NRC (2009a) included the ability to collaborate within the engineering habits of mind. Multiple authors suggest that engineering education can develop teamwork skills in students (Carlson & Sullivan, 2004; Dym, 2004; Selingo, 2007; Shepard, 2003; Welty et al., 2008). Data collected from classrooms engaged in the engineering process describe the students in these studies to be working in some sort of group (Apedoe et al., 2008; Klein & Sherwood, 2005; Olds et al., 2006). Overall, the literature shows a strong connection between engineering education and teamwork.

Communication Related to Engineering (Comm-Engr).

Comm-Engr relates to communication that is specifically connected to the communication engineers engage in to be successful with their work. Comm-Engr is described in the framework as follows:

> K-12 engineering education should allow students to communicate in manners similar to those of practicing engineers. Engineers do technical writing to explain the design and process they have gone through in their work. The audience for this technical writing is someone with background knowledge in the area being addressed. In addition, engineers need to be able to communicate their technical ideas in common language for those without an engineering background. With these two types of communication, engineers write client reports, create presentations, and perform explicit demonstrations. Engineers need to embody information through multiple representations. In addition to verbal communication, communication will take place by using symbolic representations, pictorial representations, and manipulatives all within a real-

world context. For example, reports may not only contain written language but also drawings, plans, and schematics. (Moore, Glancy et al., 2013, p. 8)

When the NRC (2009a) listed the promotion of engineering habits of mind within its three general principles of K-12 engineering education, it included the habit of communication. Authors have noted that the communication used in engineering makes it a social process (Shepard, 2003; Dym, 2004). Selingo (2007) states that students involved in engineering education learn the valuable skill of communication. Students need to learn to communicate effectively both with their team members and with the client of their design projects. Rogers and Portsmore (2004) pointed out that during the engineering process both secondary and elementary students learn to identify and formulate a problem, design a solution, create and test a solution, optimize and redesign, and communicate and disseminate the solution. With engineers commonly working together as teams to complete projects, it follows that engineering education would contain a significant portion related to communication.

Quality of engineering education.

In the sections above, literature has been used to support the inclusion of each of the twelve key indicators in the *Framework for a Quality K-12 Engineering Education*. As a part of the development and original application of the framework, state science standards related to engineering were assessed using the indicators to code the presence of components of engineering education (Moore, Tank et al., 2013). To have quality engineering education, all twelve key indicators should be met at some point during K-12. However, if the focus is turned from state standards, or from an entire K-12 engineering curriculum, to the unit implementation level, it is not reasonable, nor necessarily desirable, to include all twelve key indicators during the implementation of one engineering unit or project. Including each of the twelve indicators in every engineering unit K-12 requires each unit to be extensive and time intensive. It also does not allow a given unit to focus on certain aspects of the framework.

To consider engineering education of quality, the authors of the *Framework for a Quality K-12 Engineering Education* grouped the twelve indicators from the K-12 engineering framework into three broader groups (Moore, Glancy, Tank, & Kersten, in review). Grouping allows for the suggestion of those indicators that should be included in every K-12 engineering unit and those indicators that may be included less often.

The first group includes the three indicators that are most central to engineering and engineering education: POD (POD-PB, POD-PI, POD-TE), SEM, and EThink. The Process of Design is included because reports "consistently identify design as central to engineering education" (Crismond & Adams, 2012, p. 739). The application of science knowledge, as in SEM, is included because it can increase the gain in content knowledge (Schnittka & Bell, 2011) and it requires students to justify their design plan instead of using trial and error (Chandler et al., 2011). Thinking like an engineer, as in EThink, allows the students to develop problem-solving skills (Welty et al., 2008).

In the document, *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*, the NRC considered "eight practices to be essential elements of the K-12 science and engineering curriculum" (2011, p. 49). The indicators from the K-12 engineering framework that are most central to engineering and engineering education map onto these practices. POD is well represented in these essential elements of K-12 engineering curriculum. Example practices include:

"Defining problems (for engineering)," "Developing and using models," "Planning and carrying out investigations," "Analyzing and interpreting data," and "Engaging in argument from evidence" (NRC, 2011, p. 49). SEM is represented in the practice, "Using mathematics, information and computer technology, and computational thinking" (NRC, 2011, p. 49). EThink is represented in the practice, "Engaging in argument from evidence" (NRC, 2011, p. 49). The mapping of the key indicators onto the practices from the NRC document provides support for the three indicators, POD (POD-PB, POD-PI, POD-TE), SEM, and EThink, being considered most central to engineering and engineering education. As a result, these three indicators are central to quality engineering education and should be included in each engineering unit K-12.

The second group of indicators includes those important to the development of students' understanding of engineering: CEE and ETool. CEE allows students to understand what engineering is and what engineers do. According to Chubin et al. (2005) an effective pre-college engineering program must "promote awareness of the engineering profession" (p. 79). ETool allows students to work with some of the same tools used by practicing engineers. Students commonly associate engineers with some type of tool (Fralick et al., 2009) and technology integration has been included as one of the best practices for learning science content (Zemelman et al., 2005). For this second group of indicators, while not needed for every engineering unit, inclusion of these in strategic places can increase the authenticity of the engineering project and provide an opportunity for students to learn about other topics related to engineering.

The third group includes the four indicators that promote important professional skills used by engineers: ISI, Ethics, Team, and Comm-Engr. The professional skills used by engineers include taking into consideration the impact of their projects, and the consideration of the ethics of their work. Chae et al. (2010) believe that it is important for students to have the ability to "discuss, critique, and make decisions about national, local, and personal issues that involve engineering solutions" (p. 9). The NRC's (2009a) list of engineering habits of mind includes ethical and social responsibilities. As with the CEE and ETool indicators, for quality K-12 engineering education the ISI and Ethics indicators do not need to be present in every engineering unit or project, however, Team and Comm-Engr are required. This will be explained in the following paragraph.

Engineers are required to work on design teams and produce documents and representations that can be understood by others. As teamwork and communication are important aspects of the engineering profession, they should be required in every K-12 engineering unit or project. Related to the Team indicator, multiple authors suggest that engineering education can develop teamwork skills in students (Carlson & Sullivan, 2004; Dym, 2004; Selingo, 2005; Olds et al., 2006). There is a long history of research on the benefits of students working together in cooperative groups (Johnson, Johnson, and Holubec, 2008). Related to the Comm-Engr indicator, Selingo (2007) states that students involved in engineering education learn the valuable skill of communication. The Comm-Engr indicator also maps onto the final essential practice outlined in the NRC document, "Obtaining, evaluating, and communicating information" (2011, p. 50).

Related to the Team and Comm-Engr indicators, one point to mention is that teamwork and communication are not just components of the *Framework for Quality K-12 Engineering Education*. These concepts are grounded in constructivist learning and best practices in integrated STEM education (Moore, Stohlmann, Wang, Tank, &

Roehrig, in press). Teamwork and communication are also related to best practices in pedagogy. However, within the engineering education context, communication is given a specific meaning as outlined by the indicator. The Comm-Engr indicator is not related to the general inclusion of communication needed for quality education. This type of communication is certainly important relative to the assessment of engineering education. However, the Comm-Engr indicator is specific to communication related to engineering, including client reports, presentations, and explicit demonstrations. For quality K-12 engineering education the Team and Comm-Engr indicators must be present in every K-12 engineering unit or project (Moore et al., in review).

The *Framework for Quality K-12 Engineering Education* provides twelve key indicators that are required for quality K-12 engineering education. Including all of the twelve indicators into every engineering design project would make each project a large undertaking, and could provide so many various angles to the problem that the students may find themselves overwhelmed. As a result, the focus of the project could become lost. Instead, the goal is that all of the indicators in the K-12 engineering framework will be addressed during each separate grade band (K-2, 3-5, 6-8, 9-12) providing a quality engineering education for all students. Some of the indicators must be present in every engineering unit or project in order to be considered quality K-12 engineering education. This includes the indicators that are central to engineering education, POD (POD-PB, POD-PI, POD-TE), SEM, and EThink. Without meeting each of these indicators, a project can become merely a craft or a tinkering project, rather than an engineering design project. Unlike this first group of central indicators, others are not required for every engineering design project implemented but can increase authenticity when included. This group includes the indicators important to the development of students' understanding of engineering: CEE and ETool. In addition, included are two of the indicators that promote important professional skills used by engineers: ISI and Ethics. Instead of being a part of each engineering project, these indicators should be addressed at least once during each grade band. To assure quality K-12 engineering education the remaining two indicators, Team and Comm-Engr, should be included in each engineering project.

K-12 Engineering Education Research

Research on the effectiveness of engineering education in the K-12 classroom is limited. In 2008, Brophy et al. published a seminal article in which they explored "the opportunities for achieving important STEM learning outcomes through engineering activities situated in P-12 formal learning environments" (p. 370). The authors agreed, "very little research has been done to describe how particular engineering education experiences differ from regular mathematics and science instruction" (Brophy et al., 2008, p. 380). They resolved that "P-12 engineering education programs need to conduct research on the extent to which they are reaching all students with respect to acquiring content and skills for problem solving, and in developing a sense of self as a learner and as a potential STEM professional" (Brophy et al., 2008, p. 380).

Studies have been published about engineering education in the K-12 classroom. However, there is a limited amount of data on the effectiveness and impact of implementing engineering curriculum programs (Brophy et al., 2008). The literature search revealed only a few articles specifically about engineering education related to secondary science, and just two of these articles contained a portion related to high school physics. Two articles related to engineering education in secondary science were published in practitioner-based journals. Nugent et al. (2010) presented the results of their project designed to address the lack of student awareness of engineering by exposing teachers to the work of engineers. Olds et al. (2006) revealed the results of a middle school engineering challenge to construct prosthetic arms for amputees in a war-torn country.

Other engineering education articles related to secondary science were published in research-based journals. Klein and Sherwood (2005) conducted a three-year study on the attainment of central concepts, where secondary physics and advanced biology students were taught using a biomedical engineering context. Apedoe et al. (2008) investigated possible evidence of the value of a design-based unit on the creation of a heating/cooling system, for teaching difficult chemistry concepts and increasing student interest in engineering. Ellefson, Brinker, Vernacchio, and Schunn (2008) researched a middle grade science and mathematics outreach initiative that immersed students in the engineering design experience. Svarovsky and Shaffer (2007) investigated the design-build-test cycle using a simulation environment with middle-school students to develop their conceptual understanding of center of mass. Chiu and Linn (2011) conducted research on how engineering could be infused into existing secondary science classrooms to increase STEM literacy.

The literature provides some evidence that engineering education, which has been integrated into a secondary science classroom, can be effective in the following: (1) increasing the conceptual understanding of science, (2) motivating students, and (3) increasing awareness of the role of engineers in society (Apedoe et al., 2008; Chiu &

Linn, 2011; Ellefson et al., 2008; Klein & Sherwood, 2005; Mooney & Laubach, 2002; Olds et al., 2006; Schnittka & Bell, 2011; Schnittka, Bell & Richards, 2010; and Svarovsky & Shaffer, 2007). Evidence of increasing conceptual understandings of science supports the idea of integrating engineering education into the science classroom. Motivating students is an ongoing need throughout education. Awareness of the role of engineers has the potential to encourage a greater cross section of the population to become involved in an engineering career. All three of these points are addressed in the following paragraphs.

Results from five articles provided empirical evidence for the first point: engineering education can increase conceptual understanding in science. Klein and Sherwood (2005) presented statistically significant differences in pre-test/post-test scores from unit assessments in high school physics, biology, and anatomy and physiology classes that implemented biomedical engineering modules. The authors concluded that compared to the control students, the students participating in the engineering modules performed better on a "measure of basic conceptual understanding," and had "greater growth in content specific knowledge" (Klein and Sherwood, 2005, p. 393). In the work of Apedoe et al. (2008), pre-test and post-test data on a *Heating/Cooling Systems* unit in high school chemistry showed statistically significant results for accuracy gain in the topics of atomic interactions, reactions, and energy change questions. These results provided "a demonstration proof that design-based learning can be effective for teaching and learning difficult core concepts in chemistry" (p. 463). Ellefson et al. (2008) published results from a design-based learning unit for high school biology students focused on genetic engineering. The authors concluded, "The increased performance between pre-unit and post-unit on this difficult assessment indicated that the students had gained a good understanding of genetics and gene expression during this unit" (Ellefson et al., 2008, p. 298). The work of Svarovsky and Shaffer (2007), provided evidence about middle-school students involved in a weekend engineering design workshop. Their data suggest, "the middle school students … developed understanding of center of mass through virtual engineering design challenges using computer simulation" (Svarovsky & Shaffer, 2007, p. 148). Finally, Chiu and Linn (2011) published results from implementing a Web-based Inquiry Environment to infuse engineering into secondary science classes. They worked with two projects, one related to airbags and another related to chemical reactions. The results of pre-test and post-test data for the project related to airbags suggested, "Students participating in *Airbags* made significant learning gains" (Chiu and Linn, 2011, p. 8).

In addition to the above articles about engineering increasing conceptual understanding, Schnittka and her fellow researchers have published a number of articles related to the use of engineering education in middle school to effectively learn the science concepts of thermal energy and heat transfer (Schnittka, 2012; Schnittka, Brandt, Jones, & Evans, 2012; Schnittka & Bell, 2011; Schnittka et al., 2010; Sheerer & Schnittka, 2012). The first article published was a practitioner-focused explanation of the *Save the Penguins* curriculum (Schnittka et al., 2010). The second article gave empirical evidence of the conceptual understandings and attitudes towards engineering, assessed when using the same curriculum (Schnittka & Bell, 2011). Three additional articles, also using the *Save the Penguins* curriculum, have been published: one focused on an after-school environment (Schnittka et al., 2012), the second was a case study of one teacher implementing the curriculum to both her standard and advanced classes (Schnittka, 2012), and the third article gave the perspective of a student teacher using the curriculum in an interdisciplinary science unit (Sheerer & Schnittka, 2012). The articles provided empirical evidence that engineering education can promote conceptual change. Based on the data, students who were involved in the *Save the Penguins* engineering treatment that included targeted demonstrations showed statistically significant "gains in understanding heat transfer and thermal energy," compared to "students in other classes" (Schnittka & Bell, 2011, p. 1877). Schnittka's work looks at the implementation of engineering education from numerous angles. The articles listed in the previous paragraph, as well as those here, written by Schnittka and her colleagues, point to the possibility that engineering education can be an effective method to increase the conceptual understandings in science (Park, Nam, Moore, & Roehrig, 2011).

Many of the previously noted articles also contain evidence for the second point: engineering education can motivate students. Brophy et al. (2008) state that "engineering activities and goals are not trivial and can be intrinsically motivating because they engage a natural desire to make something and they tap into the curiosity that comes from wanting to know how things work" (p. 371). When integrating engineering education, researchers concluded "many students demonstrate high levels of engagement" (Apedoe et al., 2008, p. 460); "participation in the project increased their … enjoyment in science" (Olds et al., 2006, p. 25); "teachers expressed an increased interest and enthusiasm for learning among their students" (Mooney & Laubach, 2002, p. 316); "the lessons were effective in encouraging student interest in math, science, and engineering" (Nugent et al., 2010, p. 17); and the results "provide evidence that the youth were very interested"

(Schnittka et al., 2012, p.23). Student motivation may not be the primary goal of engineering education, but it is commonly known that when learning situations are engaging, students are more involved with the material, and it follows that involvement can lead to greater understanding.

The third point, that engineering education can be effective in increasing awareness of the role of engineers in society, is mentioned in many of these articles. Most students are not conscious of how products that they use every day came into being. An engineer has designed items that are not naturally made. Engineering education has the potential to increase "awareness of and interest in the role engineers play in supporting and advancing humanity" (Brophy et al., 2008, p. 370). Referring to the engineering challenge, *Get a Grip!,* Olds et al. (2006) concluded, "The results indicate that participation in the project increased [the students'] understanding and interest in engineering" (p. 25). Apedoe et al. (2008) similarly reported results "that students who completed the *Heating/Cooling Systems* unit in their chemistry classroom were more likely than their non-participating peers to agree with the statement 'I want to be an engineer' … In addition, students who experienced the unit in their classrooms tended to show more agreement with the statements: 'I know what engineering is,' 'I would like to have classes that let me design products that solve problems' and 'I would like to participate in after-school or summer engineering technology experiences'" (p. 462). Lastly, with regards to the *Saving the Penguins* curriculum, Schnittka et al. (2012) asserted that the "results from the questionnaire indicate[d] that youth better understood the *usefulness* of engineering, science, and computer science as a result of participating in

Studio STEM" (p. 22). This limited evidence gives support to the idea that engineering education can increase engineering awareness in students.

As a result of work published, it is apparent that the research implies that K-12 engineering education can be beneficial. In addition, engineering can be integrated into a wide range of secondary science classes: middle school science (Olds et al., 2006; Schnittka & Bell, 2011), chemistry (Apedoe et al., 2008), biology (Ellefson et al., 2008; Klein & Sherwood, 2005), and anatomy and physiology (Klein & Sherwood, 2005). The only two example articles found that specifically talked about integration of engineering into the high school physics curriculum were by Klein and Sherwood (2005) and Chiu and Linn (2011). This may seem surprising because physics classes offer an opportunity to integrate engineering with commonly implemented projects such as building a bridge, creating a tower, or designing an airplane. However, many of these projects are framed as project-based science and not as engineering design projects. The search focused specifically for engineering in high school physics classes. In the Klein and Sherwood (2005) article, physics was one of three subject areas in which engineering integration took place. In the Chiu and Linn (2011) article, physics was the content of one of the two engineering units implemented. It was with knowledge of the limited research published about the K-12 engineering education in high school physics classes that the need for the current study developed.

Summary of Chapter 2

This chapter has provided a review of the literature that is relevant to this study. The literature review began by looking at the national level and then moved to the state level. The *Framework for Quality K-12 Engineering Education* was introduced. Each of the indicators for the K-12 framework was presented and relevant literature was provided. Finally, an overview of the current research in K-12 engineering education was included, with attention being given to the implementing on engineering education in high school physics.

Chapter 3: Research Design and Methods

In Chapter 2, a literature review of K-12 engineering education was provided. In addition, the *Framework for Quality K-12 Engineering Education* was introduced. The aim of Chapter 3 is to provide detailed information about the research design, methods, methodology, and data analysis that was used to answer the research question: How, and to what extent, do physics teachers represent quality engineering in a physics unit focused on engineering?

Context of the Study

In 2009, the State of Minnesota enacted into law a new set of academic standards in science (Minnesota Department of Education, 2009). For the first time, the science standards contained a significant portion related to engineering, found in Strand 1: Nature of Science and Engineering. These standards span the entire K-12 range. Minnesota is now one of 13 states that has explicit engineering standards within its academic science standards (Moore, Tank et al., 2013).

Although the academic standards pertaining to engineering are now law in Minnesota, districts and teachers have been struggling with where and how to implement curriculum that meets these standards. Few K-12 teachers have an academic or employment background in engineering. In addition, professional development for the integration of engineering education in science has not reached the majority of science teachers within the state. However, there are teachers who are currently integrating engineering into their science classes. Physics curricula lend themselves closely to the design aspect of engineering. Many physics teachers have students involved in projects where they are building some type of device to meet a goal within a given set of constraints. It was within this climate of new engineering standards that the current study was designed.

The Minnesota Academic Standards in Science focused on engineering are related to the indicators listed in the *Framework for Quality K-12 Engineering Education*. Within the strand “The Nature of Science and Engineering” there is a substrand titled “The Practice of Engineering.” For high school, this engineering substrand contains two standards, each of which has underlying benchmarks. In Table 3.1, a list of those standards and benchmarks is given along with the indicators from the *Framework for Quality K-12 Engineering Education* to which the standards and benchmarks relate.

Table 3.1

Relationship between Minnesota Science Standards Related to Engineering and Indicators from the K-12 Engineering Framework

Standard identification	Standard wording	Related indicator(s)
Practice of Engineering Standard 1	Engineering is a way of addressing human needs by applying science concepts and mathematical techniques to develop new products, tools, processes and systems.	CEE, SEM
Benchmark 9.1.2.1.1	Understand that engineering designs and products are often continually checked and critiqued for alternatives, risks, costs and benefits, so that subsequent designs are refined and improved.	POD
Benchmark 9.1.2.1.2	Recognize that risk analysis is used to determine the potential positive and negative consequences of using a new technology or design, including the evaluation of causes and effects of failures.	EThink, Ethics
Benchmark 9.1.2.1.3	Explain and give examples of how, in the design of a device, engineers consider how it is to be manufactured, operated, maintained, replaced and disposed of.	EThink
Practice of Engineering Standard 2	Engineering design is an analytical and creative process of devising a	EThink

	solution to meet a need or solve a specific problem.	
Benchmark 9.1.2.2.1	Identify a problem and the associated constraints on possible design solutions.	POD
Benchmark 9.1.2.2.2	Develop possible solutions to an engineering problem and evaluate them using conceptual, physical and mathematical models to determine the extent to which the solutions meet the design specifications.	POD

Note. Information from Minnesota Department of Education, 2009 and Moore, Tank et al., 2013

These connections between the Minnesota standards and the K-12 engineering framework makes the use of the framework a reasonable option for assessing quality engineering education within the context of Minnesota high school classrooms.

There is value in exploring the engineering education that is currently happening in high school physics classes. As a result, the work of three high school teachers who were integrating engineering education into their physics classes was explored. By investigating how these teachers represented engineering education, it was expected that an understanding of their practice could evolve. It is anticipated that this understanding will be helpful to others in the future integration of engineering education into the science curriculum.

Methodology

In the following paragraphs the methodology used for this study is outlined. This includes introducing the case study and the method for participant selection.

Case study.

This study was approached from a qualitative perspective. A multi-case study (Yin, 2009) was used to explore teachers' use of engineering education in high school physics classrooms. Creswell (2007) asserts, "*case study* research involves the study of an issue explored through one or more cases within a bounded system" (p. 73). The case study methodology was employed because it allowed for detailed understanding of the integration of engineering education within the context of three physics classrooms. This study aimed to provide a holistic picture of individual teachers integrating engineering education into their physics curriculum.

Participant selection.

A combination of convenience sampling and *purposeful sampling* was used to select participants for this study (Creswell, 2007, p.75). To begin with, teacher participants to whom the researcher had access were chosen. The teacher participants were then chosen based upon their current use of engineering in the physics classroom. The goal was to have a geographically diverse group of participants, including at least one female. The three participants chosen for the case studies met the following requirements: willingness to participate in the study, currently teaching high school physics, and experience with integrating engineering into the physics classroom. Originally, five participants were selected for this study, however, due to district rules against collecting research data, two of the participants could not be included. The final sample included three teacher participants with a range of teaching experience. The sample had two male teachers and one female teacher.

Protection of human subjects.

IRB approval was obtained for this study. Informed consent was obtained in writing from all participants and from the school administration where the teacher was employed. All participants were informed of the risks and benefits of this study and had the option of choosing, at any time, to leave the study. Data were kept in a secure location: a locked file cabinet or on a computer that was password protected. The only people with access to the data were the researcher and her advisors.

Methods of Data Collection – Spring 2012

The data collected for this study were intended to provide for a rich description of three different cases where engineering was being integrated into the high school physics classroom. Three types of data were collected for this study: interviews, classroom observations, and curricula document collection. There were two major purposes for the data sources selected. First was to understand the nature of the engineering integration that occurred within the courses. Second was to study the connection to standards made by the teachers. For a visual representation of the data collection process, see Figure 3.1.

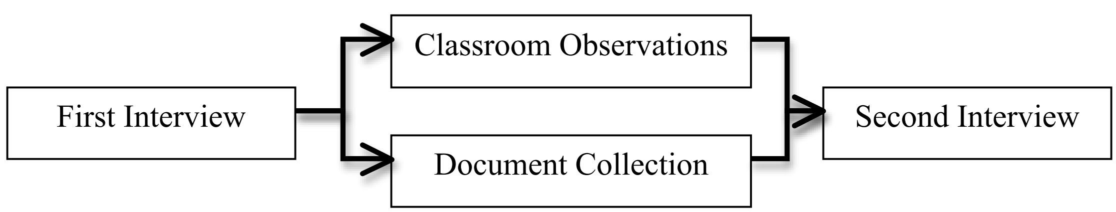

Figure 3.1. Data Collection Process

Interviews.

Two interviews were conducted for each participant: one previous to the observation and the other following the observation. The interviews were structured largely by the *general interview guide approach*, where a list of questions and issues were explored during the course of the interviews (Patton, 2002, p. 342). The use of an interview guide ensured the same topics were explored in interviews with each of the participants but also left room for probes and spontaneous questions. The choice to use the general interview guide approach was made because it allowed for flexibility during the interview while the main topics were certain to be addressed. In addition to the pre- and post-observation interviews, *informal conversational* interviews also took place during the course of the observations (Patton, 2002, p. 342). These took place before or after a class period when the observation occurred. The conversations included clarifying questions or general impressions.

The interview protocol for the pre-observation interview was designed to collect information about the participant and the setting. The participant was asked to define engineering and give input on the current Minnesota science standards related to engineering. The participant was also asked to outline the engineering design project that was planned. The interview protocol for the post-observation interview was centered on gathering information about the implementation. The participant was asked to reflect on the implementation of the design project. The *Framework for Quality K-12 Engineering Education* was introduced. The participant was also asked for an opinion about the advantages and barriers to engineering education. The interview protocol for both the pre-observation and post-observation interviews are included in Appendix A.

Observations.

The second type of data collected for this study was direct classroom observations (Yin, 2009). Naturalistic observations take place in the field, which for this study was the physics classroom of the teacher participant. Classroom observation for each participant included a number of days observing the curriculum implementation for one physics section. This observation was anywhere from just two class periods to multiple weeks of a physics class. The observation duration depended directly on the length of the engineering integration activity. The first purpose of the observations was to describe the setting, activities, and people in which the observation was set (Patton, 2002). The focus of the observations was the strategies the teacher used to integrate engineering into the physics classroom and the response and action the students made in relation to these strategies. The researcher was the sole observer in all cases: present in the physics classrooms but not participating in the class. Observations were open-ended as related to the focus. The observation protocol contains places to write down information that identifies the observation, such as participant name and date of observation. The observation protocol then provides space for observations to be written and a time stamp to be included. During observations the *Framework for Quality K-12 Engineering Education* was available for reference. The observation protocol used for all of the observations is available in Appendix B.

Documents.

Curricula documents were the third type of data to be collected for this study. These documents were obtained from the participant teachers and contained items such as design descriptions, laboratory instructions, worksheets, schematics, and background information. These documents were reviewed during the course of the observations in an attempt to not only learn from them but also to stimulate paths of inquiry that could be addressed through observations and interviews (Patton, 2002). With these documents being the third type of data collection to be used in fieldwork during this study, it is believed that the data provided a comprehensive perspective on the engineering education that happened in each physics classroom.

Data Analysis

The analysis strategy used for this study was the development of case descriptions (Yin, 2009) with a theoretical lens to analyze each case. The cases were organized by providing: an overview of the engineering design project implemented, day-by-day description of what was observed, and the aligned responses given in the interviews. Case profiles for each participating teacher were written. Data analysis was done using a deductive approach. Finally, cross-case analysis was conducted (Miles & Huberman, 1994).

Once all of the data were collected, they were prepared for the analysis process. All of the audio-recorded interviews were transcribed. All of the observations were collected and organized. The curricula documents were scanned and stored electronically. When these processes were complete, data analysis commenced.

The deductive analysis required the use of an explicit theoretical framework (Patton, 2002). The framework allowed for grouping of specific observations. For this study, the theoretical framework used was the *Framework for Quality K-12 Engineering Education* K-12, which contains twelve different indicators. As mentioned in Chapter 2, this K-12 engineering framework outlines the major themes expected to be present for meeting standards associated with quality engineering education at the K-12 level. The framework was used as a classification scheme to classify the curricular strategies observed or mentioned by the teacher. All coding was done with the use of the computer program, *NVivo 10*.

Once all of the data were coded and divergence had been completed, case profiles for each of the three participants were written. Interview transcripts, observation notes, and documents were used to write individual profiles. Each case contains a summary of the teacher's background and experience with engineering, the school context, the daily observations, and reflections on the engineering project. Four peers, two who were familiar with the K-12 engineering framework and two who were not, conducted reviews of the cases. The reviews gave consistent results between the two groups. A diagram of the individual case analysis process is available in Figure 3.2.

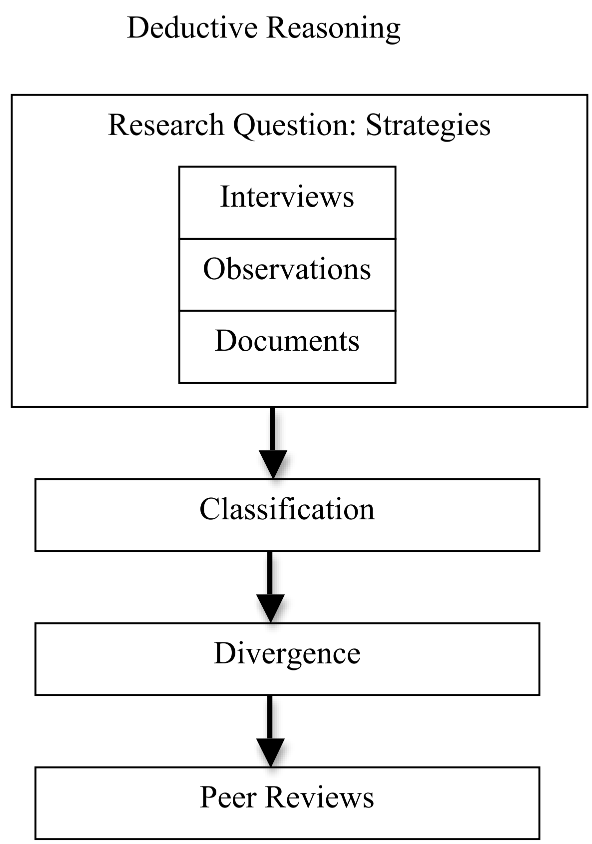

Figure 3.2. Data Analysis Procedure for Each Case

Finally, data analysis included cross-case synthesis (Yin, 2009). Cross-case synthesis is relevant in this study because it contains a total of three cases. The use of cross-case synthesis make the findings of this study more robust. Yin (2009) suggests the creation of "word tables" to display the data from the individual cases in an organized fashion. Cross-case synthesis was the final type of data analysis that was performed in this study.

Validity and Reliability

The validity of qualitative research can be understood as the evaluation of the accuracy of the findings from a study (Creswell, 2007). Yin (2009) presented four tests to judge the quality of a study: construct validity, internal validity, external validity, and reliability. Construct validity was described as "identifying correct operational measures for the concepts being studied" (Yin, 2009, p. 40). Three tactics were suggested to meet this test: using multiple sources of evidence, establishing a chain of evidence, and having the draft case study report reviewed by key informants (Yin, 2009). First, in this study three sources of evidence were collected: curricula documents, classroom observations, and interviews. Second, a reader of the final case studies should be able to "follow the derivation of any evidence from initial research questions to ultimate case study conclusions" (Yin, 2009, p. 122). In order to provide this, sufficient citations to the database were made, the database revealed actual evidence, and the data collection followed the outlined protocol. Third, peers of the researcher reviewed each draft case.

Yin (2009) described internal validity as applicable to explanatory or casual studies only, not descriptive or exploratory studies. Since the current study was exploratory and descriptive, internal validity tests were unnecessary. External validity was described as "defining the domain to which a study's findings can be generalized" (Yin, 2009, p. 40). The term "generalizable" has caused debate in the objective versus subjective research clash. Objective researchers contend that research generalizability is essential. In naturalistic research, it is the contextual variables that must be disconnected; variables have to be controlled and samples randomized. In subjective research, contradictorily, it is the detailed and in-depth description that allows others to determine if the findings are transferable to other settings (Cohen, Manion, & Morrison, 2000). Yin (2009) described quantitative research as relying on statistical generalization, where "an inference is made about a population (or universe) on the basis of empirical data collected about a sample from that universe" (p. 38). He differentiated this from case studies, which rely on analytic generalization where a "previously developed theory is used as a template with which to compare the empirical results of the case study" (Yin, 2009, p. 38).

The final test Yin (2009) proposed, to judge the quality of a study, is reliability. The objective of reliability is "to be sure that, if a later investigator followed the same procedures as described by an earlier investigator and conducted the same case study all over again, the later investigator should arrive at the same findings and conclusions" (Yin, 2009, p. 45). Reliability was addressed in the current study by documenting the procedures followed and using a case study protocol. Peer review, from colleagues, was used once the data analysis was complete. It was with the implementation of the above tests that validity and reliability was met in this study.

Researcher Background

My interest in physics developed during my senior year in high school. I had a very dynamic physics teacher who piqued my interest in the subject. I went on to college to pursue knowledge in this field and earned my undergraduate degree in physics and mathematics. However, during my undergraduate studies my excitement with physics dwindled, partly due to very brilliant professors who severely lacked pedagogical knowledge. For me, physics became difficult and boring. As graduation neared, I decided to take the physics knowledge I had gained and apply it to solving problems. As a result, I earned a Master's of Science degree in environmental engineering. Engineering put the science to work; it gave it purpose.

While I enjoyed the learning I had done in engineering, I decided to finally give credence to the interest I had in teaching. While obtaining my physical science teaching license and earning a Master's of Education degree, I became interested in educational research. I was fascinated with the information I could obtain about the effectiveness of my teaching by using action research. This initial research experience allowed me to understand the complexity of the art of teaching. My eyes were opened to what misconceptions my students had, how they were internalizing what was happening in the classroom, and the attitudes my students had towards science. I was amazed at how many of my students had strong negative feelings about science.

As a classroom teacher, I was dissatisfied with my own knowledge and abilities to get through to students about the science content I was teaching. I wanted to know more about how to bring understanding to my students in a way that was motivating to them. As a result, I began my Ph.D. work. While involved with coursework, I became aware that there was a growing interest in bringing engineering education into the K-12 arena. I became interested in this movement and started integrating some of the ideas into my own classroom. Now, after thirteen years of teaching high school science (physical science, Earth science, chemistry, physics, and astronomy), I see how much of a benefit context can be for students to understand science content. I have integrated engineering education into my own physics classes. I see this as a powerful tool. However, I am aware that the majority of my colleagues do not know how to integrate engineering into their science classes, regardless of the new required Minnesota State Science Standards focused on engineering.

It is with this background that prompted interest in investigating engineering education in the physics classroom. I truly believe that engineering can be an effective method to use in teaching conceptual understandings in science. I also believe that regardless of standards that are enacted, teachers will not be able to integrate engineering education into their classrooms without sufficient training. I am hopeful that the results of this study will add to the growing literature on engineering education in K-12, which will ultimately guide the integration of this process into the science classroom.

Limitations of the Study

As with all interpretive research, the current study had limitations. First, the sample size used, three teachers, is very small. In addition, instead of random sampling, *purposeful sampling* (Creswell, 2007) was used to select particular participants for this study. Second, it was preferable to do post-observation interviews directly after the observation. However, due to the teachers' schedules, the interviews took place at a later date. Third, this study was focused on teacher input only; students were not investigated. The addition of student output could have created a more holistic picture of what was happening in the classroom. Fourth, the same person did all of the data collection and analysis. Another person could have coded the data in an attempt for intercoder agreement, but the notes written have inherent bias from the primary researcher who wrote them (Creswell, 2007).

The final possible limitation highlighted is related to the bias of the investigator. I did not begin this study as a blank slate. My own experiences of being educated as an engineer, having thirteen years of teaching experience, as well as being an active high school physics teacher during the completion of this study, certainly had some influence on how I viewed and heard the information presented. Although I was aware of my bias and tried to minimize it, my interpretations of the data have the potential of misrepresenting the teachers' stories.

Summary of Chapter 3

In this chapter an overview of the research design and methods has been given. This overview included the context of the study, methodology, research methods, data analysis, validity and reliability, researcher background, and limitations of the study. In Chapter 4, each of the three cases for this study will be outlined in detail.

Chapter 4: Individual Cases

In Chapter 3, an overview of the research method was provided and each school setting was described. In the current chapter three individual case studies are provided. The cases are described in detail using all of the various types of data collected: interviews, observations, and documents. For each case, an overview of the setting and the teacher participant is given. The first section of each case focuses on the overview of the engineering design project. The second section of each case outlines the observations made in the classroom setting. The final section of each case provides details about the interviews conducted with each participating teacher. In Chapter 5, a cross-case analysis of the three cases will be presented.

Marvin

Marvin had taught for three years at a suburban charter school. During this time, Marvin taught high school physics, physical science, and engineering classes. The school described itself as "a tuition-free public college preparatory school" with the aim of keeping class sizes to 22 students. In 1999, the school opened as a middle-school and five years ago opened a separate high school campus. The school was located in an outer-ring suburb. The high school followed an alternating day schedule with 80-minute class periods. The student body consisted of a total of 173 students: no identified limited English proficiency students, 9% students of color, and 35% students on free or reduced lunch (Minnesota Department of Education, 2012). Physics was a required class for graduation from this school. The section of senior level physics observed consisted of 20 students: 90% white, 10% students of color, 30% male, and 70% female.

Engineering project overview.

During the school year Marvin had planned four different engineering design projects. The first project, which was completed at the beginning of the school year, focused on building chemical rockets from film canisters, baking soda, and vinegar. The goal of this project was to teach the students about isolating variables. The second project focused on the equations of motion. The students were asked to design a parachute or other device that would allow a small Lego figure to descend slowly and make a safe landing on the ground. The third project was related to the concepts of work and power. Students were asked to design their own blades to optimize the efficiency of a wind turbine.

The fourth engineering design project occurred near the end of the school year. This "egg drop" project was related to the concepts of momentum and impulse. For this design project students needed to make a connection between the amount of time for an impact and the force produced. The students were asked to design a container that would deliver an egg safely to the ground after being dropped from a specified height. Marvin designed this project to have two different iterations. The first iteration had taken place about a week previous to the time that observations were made of the second iteration. During the first iteration, only one out of a total of twenty teams, in two physics sections, had adequately protected their egg during the fall. For the second iteration the students were given some different materials to work with compared to the first iteration.

As a part of the design process, the students were asked to draw their design solution before beginning to build their prototype. In addition to drawing designs for the egg drop container, Marvin said he typically gave the students a sheet of questions "to describe the process that you went through" for the designing and testing. Marvin gave some example questions. "So, what did you start with? How did you use the material? What did you and your partner have troubles with? How did you turn around that?" He also said, "and then there is usually, because it is physics and it's tied to content, there will be some calculation that they have to do." Marvin said while the students would answer these types of questions for the engineering project, they would not do a typical lab write up "with the objectives and procedure and, you know, data and analysis, and conclusion."

Observations.

Marvin's high school physics class was observed for a total of two class periods. Each class period was 1 hour and 20 minutes in length.

Day 1. (Wednesday, May 2)

The classroom where Marvin taught was centered towards Marvin's desk and a whiteboard mounted to the front wall. Marvin did the majority of his class-wide instruction standing at the front of the classroom. Students sat at tables that faced the front of the room; each table had room for two students. Off to the side at the front of the room was a table where Marvin made supplies available to the students. Towards the back of the room, off one side, were two medium sized work rooms where approximately three to four students could work on a project.

Marvin started class on the first day by telling the students they would be doing the experiment "Egg Drop 2.0." He told the students that they should not feel bad about the failures they had during the first egg drop iteration. Marvin said he had looked online for examples of other students doing this same type of project and learned that these students also had difficulties. Marvin then asked the students what science concepts were connected to the egg drop project. A student responded to this question and on the board Marvin paraphrased "impulse – a trade off between force and time." Marvin asked the students why their previous designs had failed. One student responded that some of the contraptions initially landed safely but then tipped over and the egg broke.

Marvin showed the class a video from the Insurance Institute for Highway Safety depicting a car crash where the occupant wore a seatbelt and had an airbag deploy and compared that to the same crash without these safety devices being in place. During the video Marvin pointed out the time difference for the two crashes. Students were engaged with the video content. After the video, Marvin talked about crumple zones in cars and stated that some of the original egg drop containers were rigid structures. Marvin played another video for the students showing the crashing of race cars. Marvin commented that the race cars had crumple zones meant to break away and leave the occupant compartment intact. Marvin related this to the egg drop containers and told the students that they should "make parts that can fall apart or break away so they can absorb the energy of the crash."

Marvin told the students he felt "OK" showing them frames from the next video, even though it showed designs for egg drop containers. He said the materials used for the containers in the video were toothpicks and superglue whereas in his class the students primarily used craft (Popsicle-like) sticks. After he showed the video frames of the containers, Marvin asked his students why they thought these students used toothpicks. One student responded that the toothpicks would crumple better. A student in the class asked Marvin to show them the entire video of the toothpick containers being tested.

Marvin agreed and played the entire video. The video showed the toothpick egg drop containers being dropped from the top of a two-story building onto pavement. Some of the containers in the video broke as a result of their fall.

The next topic addressed in class was the materials the students had available for building their second iteration egg drop container. Marvin wrote a list of new allowable materials on the board that included a limited number of balloons, straws, toothpicks, craft sticks, cotton balls, an egg carton section, paper, string, tape, white glue, hot glue, and rubber bands. Marvin commented that he was limiting the number of rubber bands they could use, as during the first iteration some teams had wrapped their egg in rubber bands and he felt this did not necessarily protect the egg. Marvin also said he was running out of rubber bands.

Marvin told the students they could choose a partner to work with for the second building of a protective container for an egg. Marvin said they may only work in groups of two, no more, or they could choose to work alone. Marvin reminded the students of one of the constraints for the project: he must be able to see part of the egg when it is in the container; the egg must be able to "breathe." The students moved around the room, decided on a partner, and found a place to work. Marvin handed out to each group the paper titled "Egg Drop Project 2.0" (see Appendix C).

Once Marvin set the students to work, some students started collecting all of the materials they were allowed to use for their project. Students at the supply table were heard discussing what materials were present. Marvin checked in with each team as they were working. Some students told him they were thinking about what they were going to do. One team discussed the design they used for their first egg drop container. Marvin mentioned to these students that their previous design had not turned out so well. The students said they did not know what else to do. Marvin reminded them that they had different materials this time, so they may be able to do something a bit different. While most groups were discussing their previous design, only one group was observed sketching a design on a piece of paper.

Marvin continued to circulate and interact with the students. A student asked Marvin to come to her group because she had an idea for a design. Marvin listened to her idea and made a few comments. Marvin asked students in another group, after seeing their design, "So, when it hits the ground, what will these pieces do?" A third group talked through their idea with Marvin. He asked them what the intent of the craft sticks was in their design, and the students responded that they were for the bottom of the container. He reminded the students that in the first egg drop trial many of the containers toppled over during their drop and because the top of the egg was not protected, the egg broke. A student was heard telling his partner, "I really don't want to scrap the old idea." This student wanted to work with the old idea but make it better. Many of the groups appeared to be starting their work from the design they used in their first iteration.

Marvin checked in with a group that had success with their first egg drop container. The students ask Marvin if "they just got really lucky last time." He answered, "probably yes and no." He asked the students if they were going to use the same design in their second container. The students responded that they would but that they were going to make some changes. They explained that they were going to use triangles this time. Marvin asked them why they were going to use triangles and one student responded that it was a structurally sound shape. Marvin reminded the students that the last time they had used paperclips in their design and for the second trial they did not have paperclips as one of the available materials.

After 15 minutes of work time two of the groups in the class were off task, talking together about the field trip planned for Friday of that week. When this conversation was over one of the teams began talking about how they were going to use the hot glue in their design. One student was observed sitting at the supply table building something with rubber bands. He mentioned to his partner that what he had built so far used four rubber bands and that the constraint they had been given was to use a maximum of five rubber bands. In another group one member asked the other what they were doing. The other member responded that she didn't know but she knew they needed to get started building. The original group member said, "We can't just start building, we need to plan." The other member disagreed and said they could just start building. Some of the students in the class began singing as they were building. Marvin gave the students a hard time and then turned on some music for the whole class to listen to as they worked. Marvin noted to the class that while washers were on the supply list for the first iteration, they were not available for the second iteration.

A team in the classroom appeared to be struggling with their design. Marvin asked them what they were thinking. A group member replied that they had no ideas. Marvin asked the team if they would like for him to pair them with other students so they could hear some of their ideas. The students did not want to be paired with others and so they started verbalizing some ideas for a design. Marvin listened to these ideas and then tied in the concepts of a crumple zone and the "give" of an object. Marvin told the students, “Surrounding the egg with just a bunch of ‘stuff’ does not particularly protect it due to the destruction that happens to the ‘stuff’ and the egg itself.”

While the class was working, one student told Marvin that she liked doing these types of engineering projects. She said the projects made her think. The majority of the students in class appeared to remain on task by building their containers. However, some students were building other small objects out of the materials just for fun. Marvin announced to the class that they had 20 minutes remaining before they needed to begin cleaning up. Marvin spent time managing the use of the hot-glue guns, as there was a greater demand for them than there was availability. Marvin made sure that the groups were passing the glue guns along when they had finished with them.

One student caught Marvin’s attention and told him her group was having a bit of difficulty. She said they were trying to make a cage out of straws. Marvin asked if they were going to suspend the egg in the middle. The student replied “yes” but they were not sure how to do that. Marvin continued to circulate through the class, checking in in with each group and assessing their progress. He encouraged one group to “step up” their design. He talked with a group that appeared to be somewhat lost or off task. He asked them what they were doing with the balloon. The group had a balloon that was blown up to its capacity. Marvin asked if there was much give in the balloon and then explained that there may be more give if they let out some of the air. Marvin reminded the group that the balloon would not slow the descent of the egg drop container because it was not filled with helium. Marvin left the group for a few minutes and then returned to give them a bit more guidance in an effort to keep them moving ahead. Marvin asked them about the pieces of their container that would crush upon impact. The group asked him for reinforcement on every step they made. Marvin told the students not to get frustrated, but to just keeping going.

A girl from Marvin's other section of physics stopped by the classroom. She asked Marvin if there were any better designs in this class compared to her class. Marvin responded that there were certainly different ideas in this class, compared to the other class, but he did not make any judgments about which designs were better.

Marvin announced to the class that they had seven minutes remaining before they needed to clean up for the day. Students began asking if they would have time to work on their containers during the next class period. Marvin told them they would have about 40 minutes of work time during the next period and that the remainder of the class time would be devoted to testing the egg drop containers. Marvin told the students that they were welcome to come in after school or during lunchtime to continue their work.

Day 2. **(Tuesday, May 8)**

Marvin began class by making a change to the list of materials allowed for the engineering project. To the original list he added five additional straws and seven additional rubber bands. Marvin told the students that the reason for this change was because he was able to purchase some additional supplies. Marvin gave very little other verbal direction to the class. The students went to work quickly. Some students in the class examined the successful projects from the previous class, which were then on display in the classroom. The students were interested in who had built each of the successful devices. Other students voiced concern about the eggs that had been left at room temperature for the last week. Marvin responded that the U.S.A. was one of the only countries in the world that refrigerated eggs; most countries kept eggs at room temperature.

The students were told they had about 60 minutes to complete their building. Marvin began circulating around the classroom, checking on the progress of each group. Marvin talked to two girls who felt their container was complete. The container was box shaped with the egg on the inside and had a blown up balloon attached to each side. Marvin asked the girls the purpose of the balloons in their design. Neither student was able to answer. Marvin held the container in the air and then gently lowered it to the table. He again asked the girls what the balloons did. The response was that the balloons just floated on the sides. Marvin asked them how the balloons would increase the time of impact for the container. The girls responded that the balloons would not increase the time. Marvin remarked that if the balloons were not going to slow the impact then all that was left was a rigid box container. Marvin told the girls that the class had learned from the previous attempts that boxes did not work well to protect the egg. Marvin said the girls had 60 minutes to improve their design. The girls did not appear enthusiastic about the idea of going back to work on their project but they did collect supplies and brought their container to a table to work on it.

Another group was using blown up balloons in their design. One member asked Marvin how much he thought they should have blown up the balloons. Marvin gave some feedback and then the student asked if they could trade in their current balloons for new ones. Marvin responded that this was acceptable. The student asked if they were allowed to cut their balloons. Marvin said they could do anything to their supplies that they wished. Marvin moved on to work with other groups. One group was making their container by creating triangles with the craft sticks and then putting multiple triangles together. Another group was making triangles with bendable straws. Some students asked Marvin to assess their containers. Marvin asked the students what supplies they had already used and suggested additional resources they might find useful. For example, one group used straws to build their containers but Marvin reminded them that for this day the limit on straws was increased. The group decided to add more straws to their design.

I spoke with some of the students about their designs. One group had toothpicks, pointing out, around their structure. I asked the students what was the purpose of these toothpicks. One student told me that the toothpicks were there to prevent the egg from hitting the ground. I asked how the toothpicks could prevent the egg from hitting the group when they were located on the sides of the container. The student responded that during the first iteration their container fell because after it hit the ground it tipped over and then the egg hit the ground and cracked. He told me the toothpicks on the new design were meant to keep the container from overturning, thus preventing the egg from falling out.

Many teams in the class have traded their plastic egg for a real egg. Marvin reminded the class that the eggs must be able to “breathe.” The constraint is that the egg cannot be completely covered. Marvin said he must be able to see some part of the egg so he could determine if it was broken after it was dropped. Some of the students had made up names for their eggs. Marvin informed the class that they had 20 minutes remaining before testing was to begin.

As teams completed their containers they asked Marvin if they could test them. Marvin told the students that they had to wait until everyone moved out into the entryway at the same time. Other teams were putting finishing touches on their containers. One student told his partner that he did not want to add toothpicks to the design because he was afraid the toothpicks would fall off and puncture the egg. The group building the craft-stick triangles had put them together into a double-sided bridge. Individual craft sticks connected the two sides of the bridge.

With 30 minutes remaining in the class period, most groups had completed their building. The students moved out of the classroom and into the entryway of the school. In this area there was a second floor balcony that was accessible by stairs. Marvin has placed a large sheet of plastic on the floor below the balcony. The students were to drop their containers from the balcony onto the floor.

Testing occurred for one group at a time. The team members took their container with the egg inside up the stairs and onto the balcony. Marvin stayed below on the main level for the testing. When the students dropped their egg containers Marvin filmed each test using his cell phone. Of the eight tests, half resulted in a cracked egg.

As the tests came to an end the students began asking Marvin about their grades on the project. Students were heard lobbying why their group should earn an A. Students were also heard talking to one another about why their containers failed. For example, one group had used a similar design for their first iteration and they believed the rubber bands they used this time were not as stretchy as the first time.

With 20 minutes remaining in the class period, Marvin asked the students to return to the classroom and clean up their work areas. He asked them not to just pile unused supplies on the table but to put them away in the correct bin. Marvin remained in the entryway and began cleaning up the destroyed egg containers and broken eggs.

After five minutes, two remaining groups emerged from the classroom to test their egg containers. They had not been ready with their design when the other members of the class had tested. Container 9 was tested and the egg survived the fall. Marvin mentioned to the group that the balloons bounced off the ground, reducing some of the momentum. Marvin looked again at the egg and noticed that a piece of the shell had come off. He determined that the container was still a success because the egg membrane had remained intact. Container 10 was then tested. This was the container built by the two girls who Marvin had pointed out as not being very involved in the class or in the engineering design project. The egg in this container survived the fall. After the test the girls told Marvin he could keep their container to show to the other physics class. Marvin investigated the container a bit. His non-verbal communication indicated he was a bit surprised by the success of the design.

During the testing of all of the containers Marvin did not write down any information. He had not indicated to the students how they were going to be assessed on this project. The only data collected during the testing were the filming of each crash.

When everyone had returned to the classroom and finished their clean up, Marvin addressed the class. He told the students that they had been more successful during this second iteration than they had been during the first. The students said they knew more the second time. Marvin spoke to the students about increasing the time of their collision, which would reduce the force on the egg. He talked to the students about how the crumple zone had to be on the outside of the container in order to protect the egg.

Marvin then demonstrated the last container (#10) and how it had some area that acted like a crumple zone but it also had rubber bands that increased the impact time. He said that these two things combined had allowed for the force on the egg to be low enough that the egg landed safely.

Interviews.

Marvin participated in two interviews for this project. He was interviewed previous to the engineering integration into his classroom and then after the conclusion of the engineering project. The first interview was 40 minutes in length and the second interview was 42 minutes in length.

What is engineering?

Marvin defined engineering as "a process to solve a problem." He expanded his idea by saying:

> But in my mind engineering is where you are developing something that might not have ever been developed before. You are meeting a list of wants that, say, the client, or whatever, wants an end product. And then you are figuring out ways to deliver that. Again, it's you come up with something unique in the end.

Later in the interview Marvin also made a comparison between inquiry-based learning and engineering. He said:

> There's that fuzzy line between inquiry and, inquiry-based science learning, and where it kind of becomes engineering. So, I guess engineering is where the outcome is totally unknown, whereas inquiry, its hands on but you still know where you are going to get to, say force equals mass times acceleration or something.

Preparation for teaching engineering.

Marvin entered the field of teaching as a second career. He earned a bachelor's degree in physics in the early 1990s. During his undergraduate work he had done PC programing and when he graduated he found a company that was looking for a PC programmer, and although this had not been his anticipated career path, he took the job. Through this original work Marvin ended up being in charge of technology implementation for a brokerage firm. He worked in this field, in which he originally had little interest, for 15 years. Marvin said he appreciated the people with whom he worked, he enjoyed the problem solving, and liked the project management aspect of his job. The company for which he worked sold off pieces and Marvin was asked to move to New Jersey. Marvin did not want to move and so he looked for another career.

During his time working for the brokerage firm as a software engineer, Marvin had volunteered on a regular basis in public school science classrooms. Marvin decided he had enjoyed this work and as a result enrolled in a Master of Education program to obtain a high school physics-teaching license. Marvin obtained that license and began his second career working at his current school. He had six credits remaining in order to complete a master's degree in education.

When Marvin was asked if he had taken any engineering courses or done any professional development related to engineering education he referred back to his software engineering job. He explained that as a software engineer he had written computer programs that he felt had an engineering component to it based on the problem solving involved. Marvin also mentioned that during his master's program some of his methods courses had touched on the integration of engineering into science classes. He explained that they had worked with both hands-on and engineering learning. Marvin said his advisor for the M.Ed. program had been involved with the writing of the engineering standards and in class "she was showing us some of her ideas so I was, kind of, at the forefront of that [implementation of engineering into the K-12 level]. In addition to his education classes, Marvin said he had taken one course in bioengineering that focused on green technologies.

Addressing state standards.

Marvin's school had not yet officially placed the Minnesota Nature of Science and Engineering standards into their high school science scope and sequence. Marvin explained that he had independently placed "The Practice of Engineering" sub-strands into his engineering class. The engineering class Marvin taught was a semester-long elective course that was very popular with the students. In that class, the engineering design cycle was taught and put into practice with a variety of design projects. In addition to his engineering class, Marvin stated that he met "The Practice of Engineering" sub-strands in his physics class. Marvin admitted that his school had aligned its curriculum with the previous state standards, but "hadn't started up the project again to realign" with the new standards. Marvin said he was "feeling pretty good" about the standards he was meeting but he did not have a document that listed the placement of the standards.

Marvin was provided with a copy of "The Practice of Engineering" sub-strands and benchmarks and asked to indicate which benchmarks he covered in his physics class. In relation to the five benchmarks listed within "The Practice of Engineering" strand, Marvin indicated that “by and large” he met all of the benchmarks in his physics class except for Benchmark 9.1.2.1.2, which related to risk analysis (see Table 4.1).

Table 4.1

Marvin’s Implementation of “The Practice of Engineering” Benchmarks

Benchmark	Benchmark wording	Marvin’s implementation
9.1.2.1.1	Understand that engineering designs and products are often continually checked and critiqued for alternatives, risks, costs and benefits, so that subsequent designs are refined and improved.	Covered through implementation of four engineering design projects throughout the course
9.1.2.1.2	Recognize that risk analysis is used to determine the potential positive and negative consequences of using a new technology or design, including the evaluation of causes and effects of failures.	Not covered- “I don’t really talk about risk analysis, with those words specifically.”
9.1.2.1.3	Explain and give examples of how, in the design of a device, engineers consider how it is to be manufactured, operated, maintained, replaced and disposed of.	Covered through implementation of four engineering design projects throughout the course
9.1.2.2.1	Identify a problem and the associated constraints on possible design solutions.	Covered because each of the four engineering design projects began with a problem and had its own constraints
9.1.2.2.2	Develop possible solutions to an engineering problem and evaluate them using conceptual, physical and mathematical models to determine the extent to which the solutions meet the design specifications.	Covered because each of the four design projects included a testing phase that produced results

Note. Benchmarks from Minnesota Department of Education, 2009

Influence of standards.

During the interview, Marvin was asked if the new Minnesota science standards had prompted any changes in his physics curriculum. Marvin responded, "If I am honest, no." He explained that he took the curriculum he had and then lined it up with the new standards. He said, "I mean I just kind of know them [the standards] by in large and know what I am teaching covers them." He felt that what he was teaching covered "90 something percent or more of them" and he was "comfortable doing that."

Marvin said that some of his comfort with his coverage of the standards might have come as a result of his school not yet placing the new standards in specific classes. He said two years ago, teachers in his school had done an exercise to place all of the standards. Marvin's response to this was, "and then nobody checks on it, you know. No one is going to come through and actually [say], like, 'Did you really [meet those standards]?' in my school." Marvin explained that his charter school district was just "too little." Since the standards placement exercise, the state science standards had changed and no additional alignment had been done. Marvin felt the offering of an engineering course "that almost everybody takes, [and] right there, there's all the engineering standards dealt with."

Student Assessment.

Related to the assessment process for the egg drop project, Marvin replied to a few questions during his first interview. Before the project was implemented, when asked if the students had to turn in the "Egg Drop 2.0" handout, Marvin replied, "They do, yeah. They do turn it in. But I'm really lax on, you know. I don't want to nail them on it. So, I offer it up but I don't grade if, like, they didn't give me the drawing." Marvin explained his grading would be based on "whether the egg cracks or not. That's pretty much it. And I have a rating thing, like, totally cracked you lose two points, a little bit of a drip or whatever, lose one point or whatever. There is a scale."

During the implementation of the egg drop engineering project, Marvin was observed recording the drop of each of the containers with his cell phone. Marvin was not observed taking any notes or writing down any values.

In the interview following the implementation of the project, Marvin was asked how he ended up grading the students on this project. He responded: "Mostly on effort. I kind of told them I would be grading them on whether their egg cracked or not. You know, certainly those that didn't, they got maybe a little higher score. But most kids got As and Bs and a couple of students who I felt didn't really do anything I gave a C or a D." Marvin spoke about one group he felt did not put forth a valid effort but ended up having their egg survive. He said, "So, I actually graded them pretty well. I probably gave them a B or something. Just because they ended up with one that survived and was actually quite elegant."

Reflection on the project.

Marvin provided a tour of the school, during which he spoke about the class period observed. He noted that it must have been obvious which students were and which were not engaged in the engineering project. He referred to three female students in particular. Marvin said that while these students were not engaged in the engineering project, they had also not been engaged in other physics work during the semester. Marvin added that at this time during the school year, just before summer break, it was difficult to push students to be engaged in the class. He said that at this point it seemed as if any effort he put into that encouragement had “little chance for a positive outcome.” Marvin explained that originally he had set up a bowl with strips of paper, each of which contained the name of a class member in the class. His plan had been to pull names out of the bowl in order to determine partners for the engineering project. Marvin told me he had changed this plan just as class began. He said his dilemma was about these three female students who had not been engaged in the class. Originally he planned to draw for partners so that the girls would not end up in a group together. He hoped that not grouping them together would help facilitate their involvement in the project. However, when it came time to make the groups he decided that it was not fair to the other students to draw for partners since some of them “would end up being stuck with one of these girls as a partner.” He believed the other students would end up doing all of the work while the girls would not become involved. In the end, Marvin decided to let all of the students choose their own partner. As anticipated, two of the female students formed one group and the third female student found a male partner. Both of these groups had located themselves in one of the back study rooms during class. Marvin pointed out that eventually he had moved both pairs back out into the main classroom.

Marvin said that the majority of his students “really got engaged in these types of engineering projects.” He said he tended to “think of them as ‘fun’ days for the students.” However, he said that some students just did not get interested and often were also not interested in other aspects of the physics class as well.

Before building the egg drop container, Marvin explained that he had asked the students to first draw their design. He said it was difficult to stick to this because although the students knew what materials are available and what they were being asked to build, in working “with the materials, ideas come.” He explained that with the students just seeing the materials on the table “they may not think of something but if they get the straw in their hand and they start bending the straw, ‘oh, hey, wait, if we put a bunch of straws together that might hold the egg better,’ or whatever.” Marvin admitted that there was always a desire to begin with the drawing “but it doesn’t take long and they are up getting materials … and the drawing part goes away.” When asked if Marvin collected the design drawings and question answers he responded that the students, “do turn it in, but I’m really lax on, I don’t want to nail them on it. So, I offer it up but I don’t grade if, like, they didn’t give me a drawing.”

Marvin explained that this was the first year that he had the students do a second iteration of the egg drop project. He said that the students were allowed and encouraged to make adjustments to their project. For example, Marvin said, “and then even the day of, I had people that dropped [their container] and it broke and it was because, oh, it turned over in their air and so I didn’t protect that other side as well. I wanted it to fall on this side. And I’m like, well there is still 30 minutes left of class. Do you want to go try and get that egg out” and make some changes? Marvin explained that he encouraged the students to make changes to their designs if they felt something was not working.

After the completion of the engineering unit, Marvin was asked about any changes he had made to this project over his last three years of teaching. Marvin explained that this year was the first time he had done two iterations of the egg drop project; in previous years he had always done just one trial. He said that adding the second iteration was the “biggest thing” he had changed. He explained that before, with the one iteration, “either they got it or they didn’t and then we moved on.” Marvin had liked the change to doing two iterations of the egg drop and wanted to continue with this during upcoming years. Marvin also noted that he had always taught the students the scientific concepts involved, calculated answers with the equations, and then done the design project. Marvin said he “might flip that [order] around for next year.”

Marvin talked about one other strategy he had used in prior years. He explained that each group was given a budget and then they had to purchase their supplies. Marvin recalled that this strategy had not worked well: “probably just too much work for me.” He said that by the second day of the project he had put all of the supplies “on sale.” He explained that this had led him to stop keeping track of the money as he told students to “just go get it. I trust you.” Marvin felt the budget idea was good but that he had been unable to manage it.

In terms of the materials Marvin offered the students for their project, he said they were different this year compared to past years. Marvin said, “I have no idea what materials I gave them the last two years.” Marvin explained that the choice of materials used was based on “availability [of materials] in my room and then, sort of, whatever I feel like buying at Wal-Mart the day before.” Marvin added that he felt that some of the materials he had offered were “red herrings.” He said for example, “What would you use the paper clips for?” He said some students were committed to finding a use and so they might think, “We have three paperclips, we’ll use them somehow.” Marvin explained that in regards to the paper clips many students, “They find a way [to use them].”

In reflecting on the egg drop engineering design project from this year, Marvin talked about the addition of a second iteration in the project. He said, “I thought it was good the second time around." Marvin explained his thoughts on what the students had experienced with this second iteration:

> I think they definitely learned more about slowing it down. I think their original thought was 'How can I slow the egg's descent?' not so much 'When it crashes how can I slow the egg down?' And so I think I got that through to them when we talked about it. And also they were thinking the first time that a rigid body was the way to go. 'So if you surround it in something really hard then that will protect the egg.' And again not thinking about slowing down the egg's actual impact.

Marvin believed the conversation he had with the students, including asking the question "What did we learn last time?" had helped the students switch their focus from the egg's descent to the egg's impact. Marvin also felt that giving them some different materials for the second iteration was helpful.

Marvin commented on the group of two girls who had to be removed from the study room on the first day but had made a successful egg drop container. Marvin said, "They ended up with one that survived and was actually quite elegant." He explained, "They were driving me crazy the first day." "It took them two days to finally get it together." He was surprised at the performance of their product considering the lack of motivation they had exhibited in class.

As he reflected, Marvin saw a place to make a change in the future. Marvin explained that groups turned in "ten [total for both sections of physics], at most, sheets where they actually wrote it up, you know, drew what they were supposed to and label what they were supposed to label." He was referring to the "Egg Drop 2.0" sheet he had handed out to the students before they began this second iteration (see Appendix C). Marvin admitted that while he had not received many of the sheets, he “didn’t also, you know, pry either.” Marvin explained that he could have been stricter about making the sheet a requirement. However, he said, “But likely what seems to happen with these engineering projects is once they get, once they get in and sort of get their hands dirty, then sort of the worksheet and the whole follow through kind of go by the wayside a little bit.”

Another change Marvin suggested related to the timing of the two iterations. This year he explained, “There was a gap between the first time and the second time of a couple of weeks.” He also mentioned that by the time they had done the second iteration they had already had a test on forces, momentum, and impulse. Marvin said that next year he “would put them closer.” He wanted to give them fewer materials for the first iteration and then expand the materials for the second iteration. He also wanted to “talk about what worked and didn’t work because I think that really, really hit home and it gave those kids who didn’t do well the first time, sort of, feeling like they could have a second shot at it.”

Teaching strategies/philosophy.

Marvin felt that the teaching methods he employed during the engineering unit were different from those he used in physics class on other days. Marvin believed the two methods were different “because with engineering there’s not a whole lot I can do to guide their discovery.” He said that when he was teaching other content, particularly that which used equations, “That’s me up there. ‘This is how we do it. Let’s practice the algebra.’” He felt this type of teaching method was “teacher-centric.” Marvin explained that some of his students were comfortable with this type of teaching because they "want to check me every step of the way." Marvin explained that with the engineering design he did not have all of the answers. Those students who liked to check in still asked him questions such as, "Is this a good idea, to put the rubber bands [here]?" However, Marvin said he often responded, "I don't know, what do you think?" He said when he responded in this way, "I'm being honest when I say that I don't know whether that is going to work or not… I have no idea how it's going to turn out."

Marvin characterized his teaching strategy while implementing engineering as "stand back and let them create." He said he saw this reflected in the students because on the second day of the project "they just came in, started grabbing materials and, like, sat down and started working." He said the students did not question what they were doing or why but just went to work. Marvin felt this stand back strategy was "definitely a different strategy that they are experiencing."

Benefits and drawbacks of integrating engineering

When asked what he felt about engineering education being placed at the high school level, Marvin responded saying, I "absolutely think it should be in high school." He continued:

> I think the country as a whole is in dire need of engineers and I think its catching children even in middle school or even in elementary school on some engineering topics or some approaches is, I think, a really good thing. I think we need it. And having it a part of the science curriculum is the way to make it happen.

Marvin expressed his belief that leaving engineering education as a choice at the K-12 level would not draw the involvement of a large percentage of schools. He said making engineering a part of the science standards provided the extra emphasis that might get more schools involved than if it was not in the standards. Marvin said he felt lucky having his engineering and engineering education background which gave him confidence in the classroom but "I don't know how that is for other teachers, if you have been teaching for 15 years, or whatever, teaching your physics classes and now all of the sudden you've got to teach some engineering standards."

During the interview Marvin talked about some of the benefits and some of the drawbacks he had seen related to implementing engineering into his physics classes. He said that implementing engineering into his physics class was "fun" for the students as well as "engaging" and thought that having a challenge or a competition for the students motivated them. About the engineering projects Marvin said, "It's engaging kids, I think, I normally wouldn't get engaged." When compared to working with relationships and formulas Marvin believed "engineering is more, it's free. It's freeing. It's more creative. It taps into kids that aren't maybe so analytical but it's like 'oh, I can make a parachute.'" Creativity was another benefit Marvin included. He explained that from each engineering project he implemented, new ideas and designs were generated that he had not seen before in his classes. With regard to the second iteration of the egg drop he said, "I mean some of them had some just cool ideas with things sticking out all over."

Marvin mentioned that another benefit of his engineering projects was the teamwork in which the students were involved. He stated, "Talk about team building too. I mean to hear, like, the discussions or arguments that have to go on. 'That's not going to work,' you know." He said he seemed to get more of this discussion during engineering projects than he did even in his inquiry-based physics labs. Marvin said, "There's more teamwork [in engineering]… Even when you are doing a lab… it seems like one of them [students] will do the work and the other one will record it, whereas with the engineering it seems like there is a lot more 'Do you think this? Now what do you think of that?'"

Marvin also felt that engineering design "is more meaningful" for the students. Marvin understood that he needed to teach the physics state standards to his students regarding topics such as equations of motion, Newton's Laws, and the relationship for work. However, in terms of impulse he felt that the students, "are going to forget delta t [the equation], but they are probably not going to forget that if I give my egg a crumple zone it is going to land softer, now that they've done it." Marvin felt that engineering taught the students something different than his traditional teaching. He said, "It teaches teamwork and it teaches how to problem solve and it teaches how to meet requirements and how to use materials smartly and be creative." He felt that all of these skills "were needed in the job world."

Marvin believed that his engineering projects allowed the students to learn content in another way. With regard to his other teaching methods related to content he said, "I don't know which way they are learning it better but I can tell you that the engineering, it's more fun for them and it's more practical." Marvin gave an example of how the students interpreted science content in their own voice in relation to his wind-turbine engineering project. About the students he said, "You know, I don't see them talk about, like, well the force on the blades could be increased if the ratio of the whatever to the whatever would… No, [they say] 'I want to capture more wind … but I want to cut through the wind so I am going to trim this. And birds have feathers, I bet if I cut some and start thinking more about biomimcry…'" Marvin felt that the engineering projects allowed the students to use science in their own context.

In additional to engineering being beneficial to the students, Marvin believed it was also beneficial for him. In regards to teaching engineering in his physics class he stated, "And I find it more exciting too." He explained, "I mean to, like, plop down six different materials on [a table at] the front of the room and say your task today is to build the best paddleboat, the fastest paddle boat with these materials. Have at it." Marvin indicated that he enjoyed watching this process. He said that each time he did an engineering project he saw new designs.

Along with the benefits of engineering integration, Marvin pointed out some drawbacks as well. While the creativity allowed was freeing for some of the students, Marvin said, "Well, those that don't think they are creative are going to put up a huge roadblock." Marvin explained "those that don't think they can work with their hands and those that don't like open-ended results" also had difficulty. While the majority of Marvin's students liked doing hands-on work, he said, "There are certainly students who like to listen to lecture and take notes and then spit back that information on a test and move on to the next thing." Marvin said that these students dealt with this barrier to engineering "by wanting to check all the way." Marvin said, "I try to encourage them, that they can do it." As those students asked him questions about each step they took, Marvin said that he responded with questions of his own. "So, where are you stuck?" "Why is that?" "Remember what we talked about, the crumple zones?" Marvin felt that with guidance these students could get through their barrier and successfully design a project.

While Marvin saw benefit to the teamwork that occurred in his classroom when the students were engaged in engineering design projects, he also saw some drawbacks. Marvin explained that every now and then he had a team that “really had to battle.” He said he had some rare cases where he had allowed teams to break apart and “on their own, do their own thing” because they could not compromise on a design. In these cases teamwork was not able to enhance the learning of some students. He mentioned as an example the situation with the three female students that sometimes “teamwork can be as issue.”

With regards to the three female students in his class who had motivation issues with physics throughout the school year, Marvin shared some of his thoughts:

> That first day, kind of, well, and again it is the end of the [school] year and I have already, like, given them a lot of extra effort to get them where they need to go. So, that first day I was more like, I’m just going to, if they want to not work then they are not going to work. And so I will let them fail. But then that second day, it seemed like when I worked with them and talked about the crumple zones and the slowing down of the frame and all that, and I actually helped them a little bit to get started. And then they kind of, I don’t know what happened there; they had this like “pwsst.” Light went off.

As a result Marvin noted that some students did not always start the engineering design projects with enthusiasm or a high level of engagement.

The last barrier to engineering that Marvin brought up was time. When he reflected on the implementation of the engineering design project he had wondered about making some changes or additions to the project for the following year. He agreed that he had not done some of those things because time had not allowed. For example he said he wanted to do some type of wrap up after the end of the second iteration but the barrier, "it was time."

Sally

Sally was finishing her sixth year of teaching. For those six years, she taught general physics classes as well as some astronomy classes. The general physics course was algebra based and yearlong. For the first time, that year she also taught a one-trimester class called applied physics. The school was an authorized International Baccalaureate (IB) World School that used the Middle Years Programme for its sophomore students and offered the Diploma Programme to all of its junior and senior students. The school housed grades 10 through 12 and was one of three high schools in the district. It was located in a middle-ring suburb. The school schedule followed a repeated six-period day. Sally's school had the highest level of diversity and highest percentage of free and reduced lunch students of the high schools in the district. The student body consisted of a total of 1,436 students: 13% limited English proficiency students, 76% students of color, and 62% students on free or reduced lunch (Minnesota Department of Education, 2012). Physics class was not a requirement for graduation from this school. The section of general physics observed, which was not part of the Diploma Programme, consisted of 24 students: 25% white, 75% students of color, 54% male, and 46% female. All but one of these students were seniors.

Engineering project overview.

Sally implemented a six-day engineering project in her general physics class. Classes were 55 minutes in length. The crumple zone project was the only engineering design project Sally implemented during this school year. This project took place at the end of the school year, during May and June of 2012. Previous to this time, Sally had completed a unit of study with her students on the topic of forces. Sally had implemented this specific engineering design project during previous school years with her general physics classes. The project was focused on the designing of a crumple zone for the front end of a cart. The goal was to design a crumple zone that produced the lowest amount of force on the cart after being rolled down a ramp and crashed into a wall. This year the data collected during the testing of the crumple zones were analyzed using video analysis. Sally explained that in the past they had measured the force of impact using force plates instead. The students were to conduct multiple iterations of the design process.

As a part of the IB Middle Years Program there was a design cycle that many of the students had used in other classes. This was not a design cycle specific to engineering but Sally planned to use it for this project because the students were familiar with it. The design cycle was used to structure the project and included the following segments: investigate, plan, create, and evaluate. These steps were included in each iteration of the design project.

The design project was placed in the context of car crashes. The product generated by the students was a completed “Crumple Zone Engineering” packet that was organized in the fashion of a formal science lab report. The packet required the students to explain their process and provide diagrams of their designs.

For this design project, students worked in self-selected groups of two to four members. The students were introduced to the project by watching videos of front-end car crashes. The supplies available for building prototypes included various types of paper, cardboard, and one foot of masking tape. The students were asked to create three different crumple zones and collect data for each one. Students collected data for the first two crumple zones by making a video of the crash and then analyzing the data. The final crumple zone was crashed using an accelerometer in order to directly measure acceleration. The results from the final crumple zones were judged against all of the class teams. The winning team of the competition created the crumple zone that produced the lowest amount of force.

The crumple zone project was placed at the end of the unit on mechanics, which included motion and forces. Previous to this project the students had gone on a field trip to a local amusement park where the focus was the measurement of g-forces. The experience the student had at the amusement park gave them an idea of what different amounts of g-forces felt like to their body. This related to the crumple zone project because the forces they calculated would also be in g-forces. Sally indicated to the students that the purpose of the engineering project was to help them "understand, kind of, a really practical way that forces are [in evidence] in their world." The theme of the project, shared with students, was "How safe is safe enough?" The engineering project was planned to cover the last six days of class for the school year. At the conclusion of the project, the students were to create a poster, which displayed their four crumple zones and the calculated forces each one had upon impact.

When the students had completed their four crumple-zone iterations, the plan was to have them make a poster that displayed their engineering process with information about each crumple zone iteration. Time ran out for the creation of posters but the class did have a competition with their final crumple zones. The group with the lowest calculated amount of force on their motion cart won the competition, which did not have any effect on their project grade.

Observations.

Sally's general physics class was observed for a total of six class periods. Each class period was 55 minutes in length.

Day 1. (Tuesday, May 29)

The classroom where Sally taught was centered facing an interactive whiteboard mounted on the front wall. Sally did the majority of her class-wide instruction standing near the whiteboard. All of the students sat on chairs at tables organized in front of the whiteboard. Behind and to one side of the tables were raised lab benches where supplies were made available and some students chose to do their design work.

As class began on the first day of the engineering project, displayed on the whiteboard was a picture of a car that has been in a front-end crash along with the title, "Crumple Zone Engineering" (see Appendix D). Sally displayed this slide at the beginning of each class for the duration of the project.

Sally told the students that on today they would begin their final project. She explained that they are going to be discussing car crashes and asked the students what they saw in the projected picture of a car. The students responded, "It was a crash. It was hit head on. The car is totaled. The back of the car still looks nice. The engine was destroyed." Sally asked the students if they thought the driver of the car had survived. The students noted the airbag had been deployed and they wondered if the driver had been wearing a seatbelt.

Sally asked the students “to imagine they have the best physics teacher ever and that she has decided to give every graduating senior a car, as long as they can show that the car is safe enough.” Students shared their ideas about how to show that the car was safe enough. They suggested looking at the CARFAX® website, looking at information from the State Farm and Progressive insurance companies, and looking up crash test ratings. Sally asked the students what features their car should have. The following responses were offered: good breaks, airbags, quality tires, adequate traction, seatbelts, good mileage, and a good engine.

On the whiteboard, Sally projected her proposed schedule for the project (see Appendix D). The schedule included an introduction to the project, student planning, designing and testing three crumple zones, the final crumple zone competition, creating a poster, and a quiz on the amusement park experience and the crumple zones. Sally walked through the schedule with the class. In the end, Sally had to modify this schedule because portions of the project were taking longer than she had anticipated. The modified schedule included only two trial crumple zones, instead of three, plus the final crumple zone for the competition. The modified schedule also did not include the creation of a poster due to time constraints.

Sally went on to ask students about what they had seen on TV about the testing of cars. The students mentioned crash test dummies and the dummies having measurement devices attached. Sally asked the students what the devices would be testing. The class decides that the devices are measuring g-forces. Sally explained that the number of g-forces measured could determine whether or not a person was able to walk away from a crash. She then asked the students what they thought was the maximum amount of g-forces that could be produced in a car crash. The students offered guesses anywhere from four to seventy-eight g-forces. Sally stated that people could survive in car crashes that got up to hundreds of g-forces. Sally asked the students what might make the difference and they replied it was related to the amount of time that elapsed from the beginning to the end of the crash.

The next part of the lesson focused on organizations that had done research on car crashes. Sally showed videos about vehicle safety from a number of different organizations, including the Insurance Institute of Highway Safety and the National Highway Traffic Safety Administration. After a video about safety devices in cars, Sally asked the class what the purpose of a seatbelt was. The students responded that it had to do with Newton's First Law and that the seatbelt applied the force to a bigger part of the body instead of just to the face.

Sally showed the students the NHTSA "Safecar" website (http://www.safercar.gov/Safety+Ratings). Sally asked one student in class what type of car she drove. She then looked on the Safecar website for the safety rating information for this car. The particular car chosen had good ratings. Another student begged Sally to look up his car. Each car was given four to six different ratings and some cars also had a video of the car being crashed. The car chosen by the second student did not have a video. The class then asked Sally to look up a car that had a video. Sally tried another car suggested by a third student but there was no video. She then looked up a Ford Explorer and there was a video of this car in a front-end crash. Sally showed the crash video and asked the students if the car looked good or bad and also where the sensors were located on the car. Sally then asked the students what happened to the hood of the car and the students responded that the hood had caved in. A student added that the hood caved in by design. Sally asked the class why a car would be designed like this and what would happen if the car did not crumple. The students responded that without the crumple there would be more g-forces. One student responded that the airbags in the car also acted like a crumple zone.

Sally next turned to some general questions for the class. She asked, “How do we want the inside of the car to be? Strong or not strong?” The students replied that they wanted it to be strong. Sally asked the students why they wanted it to be strong. The response came that they did not want to get crushed by the car. Then Sally asked, “How about the front of the car? Strong?” The students responded, “cushiony.” Sally next asked “How about the back of the car? Strong or squishable?” The response, “squishable.” “Why?” “So we don’t get whiplash.” Sally then explained to the students that they were going to design the front end of a car. They were not going to worry about the other parts of the car; the occupant compartment would be strong.

Each student was handed a “Crumple Zone Engineering” packet (see Appendix D). Sally told the students that they would be designing the crumple zone of a car and then asked them to explain the term crumple zone. The students responded correctly indicating that the crumple zone was in place to lengthen the duration of the crash. Sally asked the students to individually write in their packet a description of the problem or question that they were going to address. Students were also asked to write down any prior knowledge related to their problem. Sally asked for students to share their written problem and prior knowledge. Students described the challenge as designing a crumple zone to absorb some of the crash, that the front end needed to be flexible, they needed to use various materials, and they had questions about shapes to be used such as triangles. Sally told the students that they would start planning their designs the next day. The bell then rang and class was dismissed.

Day 2. (Wednesday, May 30)

Sally reminded the students what was covered in class the previous day and asked one student to describe the problem they were working on. The student responded, “to make a car safer by designing its crumple zone.” Sally asked the class how they would know the car was safer. A student responded, “reduce the number of g[-force]s an occupant would experience.” Sally asked the class what g-forces were. The students responded with ideas about force and change in motion. Sally concluded that g-forces were a measure of acceleration.

On the whiteboard Sally wrote the equation for acceleration, a = v/t (acceleration equals velocity divided by time), and pointed out to the students that they had worked with this equation in the past. Sally posed the question, “How can acceleration be changed?” The general class response was by either changing the speed or the time. Sally then asked which one of these variables they had control over during a crash. The students decided they could not control the speed, especially of another car. Sally asked if they could control the time and if so how would this be done. The student response was “in a time machine” and “by paying [closer] attention” to the surroundings. Sally then asked if they could control the time lapsing during the crash. She led them to the answer by talking about throwing something into a brick wall versus throwing it into a pillow. The connection was the made to the crumple zone of a car. Sally outlined the parameters; "You want the g[-force]s as small as possible and the time as much as you can so you slow [the car] down slowly."

Sally explained that they wanted the occupant compartment of the car to remain strong and the back and front of the cars to crumple. The crumple zones that the students built would be attached to the front of the motion cart. Sally held up a motion cart for the students to see (see Appendix D). Sally then outlined the constraints for the project. Students could use as much as they wanted of the following supplies: tag board, construction paper, graph paper, and paper towels. The crumple zone had size constraints and Sally showed the students a box with those dimensions, which the students could use to check the size of their designed crumple zone. The other constraint was that each group could use only a maximum of one foot of masking tape for each crumple zone.

Sally explained to the students that they needed an idea to try for their crumple zone because they could not just try everything. She gave the students two examples, "I think I should use cardboard because it is the strongest" and "It should be made out of triangles because they are strong." Sally gave the students two minutes to write some ideas down for their hypothesis in their packet. Most of the students wrote in their own packets, however, a few students asked their neighbors what they were supposed to be doing. At the conclusion of the two minutes, Sally announced that she was not going to ask the students to share their hypotheses because these were the student's "super secrets" that may help them to win the competition.

Sally then shifted the focus to variables and asked, "What types of variables will remain constant?" Student responses included: distance, type of crash, surface, no extra materials, atmosphere, speed, and how the cars were let go. Sally explained that to control all of these variables she was going to crash all of the cars into to same wall, at the same one-meter distance, at the same speed, on the same angled hill. Sally asked the students if this seemed fair and the students responded yes. One student asked how they would know if their car won. Sally responded to the student that it was a good question; they would be using video analysis and later a sensor. To the class, Sally posed the question, "what is the dependent variable?" She highlighted the responses related to force or the acceleration of the crash. These variables were what they needed to make as small as possible. Sally explained that the independent variables were those things to which the students could make changes for their crumple zones. Students were then given time to write these ideas down in the section of their packet labeled "variables."

Sally projected a design cycle diagram on the whiteboard. This design cycle was a part of the Middle Years Programme IB curriculum. The design cycle diagram is available in Figure 4.1. All of Sally's students should have been introduced to this design cycle at other points in their high school careers. Sally had added notes that pertained to this project to the design cycle diagram. The cyclical design cycle included four main areas: investigate, plan, create and evaluate. For each area Sally noted what the students would do when they reached that step. Sally told the students that at this point they had already done their investigating by knowing about forces and car crashes. She explained that the next step would be planning, and that would be done during this class period. The following day, the students would "create," or build. The last step in the cycle was to evaluate, and Sally told the students that this would take place when they tested their crumple zones. Sally reminded the students that they would be doing multiple iterations of this design cycle.

Figure 4.1. The Design Cycle diagram from International Baccalaureate, 2010, p. 7

Sally directed the students to form groups of two to four and start to plan their first crumple zone. Once groups had formed, the members began talking about ideas for their first crumple zone; ideas included rolling up paper and leaving air spaces. One group asked Sally to read what they had written. Sally did so and gave the group a positive response. Sally also managed the size of the groups by moving some students. She reminded the students she was looking for a crumple zone diagram in their packet to indicate they had completed the assigned tasks.

Group members were observed conversing with each other about the ideas they had for their crumple zone. One group discussed the possibility of using triangular shapes. One group thought this was a good idea and another member thought it was not. The member in favor of the triangles backed up his idea by talking about stability and flexibility. In the end, the group decided not to use the triangular shape and then moved on to discuss the benefits and drawbacks to the types of materials they had available. They decided that cardboard was too rigid to use for their design.

After some work time, Sally refocused the class and told the students they would need to pause their planning until the next day so that she could talk to them about the evaluation of crumple zones. She told the students she was going to demonstrate to the students how they would collect and analyze their data. She asked the students to open the program, LoggerPro, with which the students were familiar. Sally alerted the students to the possibility of this analysis process being included on their test at the end of the project.

The students were asked to open a file containing a video of a motion cart crashing into a wall. Sally showed the video to the students twice and then taught them how to watch the video in slow motion. She instructed that the first step in the analysis was setting the scale by outlining the length of the cart and then entering in the value of 0.38 meters. Sally explained to the students how to digitize the portion of the video where the crash took place. The result of the video digitizing was a position versus time graph. Sally told the students that this graph could be used to calculate acceleration, but that she was going to save those instructions for another class period.

Day 3. (Thursday, May 31)

Sally began class with some reminders about assignments that were due. She then told the students that during this class period they were going to build and then test their first crumple zone. This crumple zone would be the one the students had planned the previous day. Sally informed the students that they would need to be focused with their time during the period. Sally moved to the side of the room where there was a station filled with the supplies allowed for building crumple zones and reminded students about the supplies that were available. Sally also reminded the students of the size limit for their crumple zone. Finally, Sally reminded the students that they were limited to one meter of masking tape for each crumple zone and then directed the students to the area where the tape and ruler were stationed. Sally told the students they had 15 minutes of building time and then set them to work.

Many students moved toward the supply station and began obtaining materials. In some groups, the members communicated with one another about what materials they would use. Sally spent this initial time in close proximity to the supply station. She took a moment to place a student, who was previously absent, into a group. As groups began their work, Sally walked around the classroom and encouraged unfocused students to get involved with the project.

Sally set a timer on the whiteboard and announced to the students that they had 10 minutes left to complete their first crumple zone. Students were seen cutting paper to desired sizes and drawing shapes on the tag board. One group made a construction paper box and filled it with loosely packed crumpled paper towels. This group compared their crumple zone with the correctly sized box and determined their crumple zone could be longer. They decided to add on to the front of their current crumple zone by taping on lightly crumpled paper towels. Another group had built a pyramid-shaped crumple zone out of tag board. At the tip of the pyramid were accordion folded strips of paper. Sally checked in with this group and told them their design was "cool" but reminded them that there were size constraints and their current crumple zone was too big. Sally then announced to the class that she was going to come around and check to see that each group's crumple zone met the size limits. As Sally began this process she encouraged some groups to speed up their work process in order to have their crumple zone completed during the remaining time.

Two student groups were engaging in some competitive play. One group had completed their crumple zone and the other group was making fun of the design. They told the group that their crumple zone would just fall off of the cart. The first group responded by asking what the other group had accomplished so far. The first group pointed out that the other group had only cut a bunch of rectangles out of paper.

One by one each group brought their first crumple zone to the testing site. Sally videoed each crash and then gave the camera and a sheet of instructions to the group. The instructions outlined the steps for the students to follow in order to download their video to the computer. As groups crashed their crumple zones they responded vocally to the results. Some students were impressed and others were disappointed in the performance. As crashes occurred other students from the class were drawn to watch. Students laughed as crashes took place and the crumple zones were deformed.

Sally showed signs of frustration with some of the groups who were not completing tasks in the time allotted. Sally did quite a bit of running around the classroom throughout the period. After class was over, she took time to reorganize the materials used during class. Most of the students appeared to be involved in the project during class. None of the groups were observed with only one student doing all of the work. However, in some groups just two of the students were building and the others took a less active role.

Day 4. (Friday, June 1)

Class began with the students being asked to get out their "Crumple Zone Engineering" packets. Sally put the design cycle diagram on the whiteboard and reminded the students that they are working towards designing the "best" crumple zone. Sally asked the students, "What are the properties of a 'good' crumple zone?" Students from the class responded, for the crumple zone to crumple and to produce the least amount of g-forces. Sally told the students that in the hallway were posted crumple zone projects from another physics class. She suggested that the students look at these projects for ideas. Sally explained that the goals for the day were to analyze the data from the first crash, and then to build a second crumple zone and to be ready to crash it during the next class period.

Sally told the students to open LoggerPro on their computers and explained how to insert their video into the program. Sally checked with each group to make sure they had completed this task before she continued. Two groups were behind and Sally told them they needed to pay close attention. Sally explained to the students they would do three things to their video. She asked the students to fast forward their video to the crash. They were to find a frame where the motion cart could be seen clearly and insert a line that was the same length as the motion cart and mark its length as 30.8 cm (the length of the motion cart). Next, the students were to find the frame where the crumple zone first came into contact with the wall. Sally explained that the students were going to find a point on the car that was easy to identify to mark as the origin. Sally told the students she had chosen her point as the center of the back wheel of the cart. Sally circulated among the groups to check on their progress. Sally made a connection between the current project and a previous project that involved tracing where battery operated cars traveled. She explained that the students would do something similar except instead of tracing the path on the ground, they would indicate the motion on the computer.

Next, Sally showed students how to create a graph of their data. She asked the students if they were interested in the x or y direction; in other words, did the carts go forward and backward or up and down. Students responded that they moved forward and backward. Sally indicated that they should pay attention to motion in the x direction. Sally asked the students to think about their previous experience and predict what shape the graph of an object slowing down would be. One student shouted out, "parabola." Sally went through the steps of fitting a quadratic equation to their data. As Sally circulated the room some students were off task: chatting with each other, surfing the internet, head down on the table, and playing with a cell phone. Once Sally was convinced that all groups had their quadratic equation in place, she directed the students to their "Crumple Zone Engineering" packets where they sketched their position versus time graph and wrote down their equation.

Sally brought the class together to discuss the equation for the graph. She wrote the following distance equation on the board, $d = ½at^2 + v_ot + d_o$. Sally explained that to find the acceleration of the cart they needed to multiply the "A" value from their equation by two and then to convert the value into g-forces they needed to divide it by 9.8 m/s^2. The students did these calculations to determine their results. Sally pointed out the group with the smallest g-forces, 1.5. Sally then wrote the equation F=ma (force equals mass times acceleration) on the board. She told the students that the mass of the motion cart was 1.4 kg. Sally asked the students what the unit of force was and prompted that it was named after an “old dead guy.” A student responded, “Newtons.” Sally asked the students to do the calculations pertaining to their group data.

For the final 12 minutes of class, Sally told the students their goal was to reduce the number of g-forces and to plan and create their second crumple zone. Sally reminded the students that they needed to do the work required in the “Crumple Zone Engineering” packet and then set the students to work. Sally engaged with one group that was having difficulty with the computer analysis. She then circulated in the classroom and asked groups about their new plan and asked if they wanted more or less crumple in this second plan.

Groups tackled the second crumple zone in a variety of ways. Some groups did initial drawing and others did not. Some groups just start by building. Some groups appeared to have just one member doing the building. In many groups there was discussion about the benefits and drawbacks of different ideas. Some students stopped work early and Sally reminded them that they needed to have their second crumple zone built before the end of class. These students returned to work for the few minutes that remained in the class period. Before the bell rang, Sally asked the students to help with returning supplies.

Day 5. (Monday, June 4)

This was the beginning of the last week of school for the year. Before class started, some students were already gathering computers and building materials. Sally asked the students to take out their “Crumple Zone Engineering” packets. Sally explained that originally she had planned to have the students do a total of four crumple zones and to create posters of their work. She was now feeling a time crunch with only two class periods remaining. Sally made an adjustment to her plan; the students would create only three crumple zones and instead of making a poster, they would each turn in their “Crumple Zone Engineering” packets for a grade on this project. Sally reminded the students that they would have a test the next day. Sally explained that the students needed to have their third crumple zone, which would be entered in the competition, done for the beginning of the next day of class. The students began working; most were making final adjustments to their second crumple zone. Sally mostly played the role of facilitator during the class period. She answered a student’s question about saving videos to the computer. She restocked building supplies when a student mentioned they were low. She checked in on the progress of each group. One student had completed his crumple zone and asked Sally to which side of the cart the crumple zone was to be attached. Sally looked at the student and gave him some wait time. She asked the student if this was his second crumple zone and the student replied yes. Sally then asked the student some guiding questions to help him figure out where the crumple zone should be attached. The student was then able to attach his crumple zone to the correct end and put it on the ramp for testing. He sent the cart down the ramp as Sally captured the video.

Sally asked the class if there were any other groups ready to crash their second crumple zone. She did not get any positive responses. Groups were busy attaching crumple zones to the carts, completing the building of their second crumple zone, and writing information in their packets. A second group tested their crumple zone and as they watched the video the group members laughed at the deformation that took place. A third group tested. One student was overheard asking her group how to find the acceleration from the graph. The group members responded but a satisfactory answer was not given. The student then turned to Sally to find out how to calculate the acceleration. Sally reminded her that they needed to employ the numbers produced by the best-fit curve. Another group watched their video, with two other students looking on, and they laughed as they saw the crash. A student asked Sally what the units for force were and she responded with the answer. A fourth group tested their crumple zone. One group needed help with their data analysis so Sally reminded them of the meaning of all of the values that are generated from the best-fit curve.

The designs of the second crumple zones appeared to have evolved when compared to the designs of the first crumple zones. There was more accordion folding of the paper and more time and precision was put into the cutting and building. Some groups began to delegate jobs by having some members working on analysis while others were completing their packet. During this second iteration, a few groups were observed having half of their members working on the project and the other half off task.

For the next group to crash Sally taught one group member how to do the video recording with the camera and then allowed her to video their crash. Sally asked the group member to teach one person from the next group how to record the crash. This process continued and the groups became self-sufficient in their crashing. Multiple groups completed their crash with the second crumple zone. One group had built their third crumple zone and asked Sally if they could "test crash" their product before the competition. Sally replied that this was cheating and they would only be allowed to crash their crumple zone during the competition. With groups doing their own videoing Sally had a few minutes to input some grades into her computer. Her desk was located close to the crash site and she responded to questions when asked.

With 15 minutes of class remaining Sally talked with a group that was behind about time management. The group had yet to crash their second crumple zone. Only one group member was building the crumple zone so Sally suggested more than one person should do this work in order to speed the completion. Seven minutes later just two group members were working on the build and the other two members were talking about what they had done socially over the weekend. Another group asked Sally if they could just use their second crumple zone in the final competition. Sally explained that the expectation was for them to make three different crumple zones. The group said it was satisfied with the test results it had calculated for the second crumple zone. Sally asked them for the value of their g-forces and then encouraged them to work on a third crumple zone to decrease their number.

Day 6. (Tuesday, June 5)

This was the last day of the school year for all senior students: only one student would remain for class the next day. Before class a member of the group with time management issues talked to Sally, asking her if the one junior student in their group could work on the project the next day in class. Sally told the student that today was the last day to work on the project as the “Crumple Zone Engineering” packet needed to be turned in at the end of class. Sally told the students that they had five minutes to be ready to crash their third and final crumple zone. Some groups were ready to crash immediately while others scrambled to build their final crumple zone.

Sally announced that the crashes on this day would take place without the use of the video camera. Sally told the students she had been holding out on them and for this round of testing they were going to attach an accelerometer to their motion carts instead. Sally showed them an example graph of data from an accelerometer and told them how the data would lead them to the acceleration. Sally then began working with groups to crash their final crumple zone. She asked a student to record the acceleration results from each group on the board. The acceleration values ranged from 29.4 to 121.1 m/s^2. The group that had time management issues never made a third crumple zone and so they used their second crumple zone in the competition. Sally mentioned that the group would have a grade reduction because they did not complete the entire project. Students were observed celebrating or showing disappointment based on the results of their final crumple zone. Students verbally kept track of which group was in the lead in the competition.

When all of the results were in, Sally announced the winners of the competition. The group with the acceleration closest to zero had a value of -29.4 m/s^2. The wining team celebrated their accomplishment. The students were quick to point out which group had the least favorable result, -121.1 m/s^2. Other group members pointed out the ranking as 2^{nd} or 3^{rd}, etc.

After the competition was completed the students returned to their "Crumple Zone Engineering" packets to work on filing in the remaining information. Sally asked the students if they had a quadratic equation for the tests that took place today and the students responded no. Sally then asked why and a student responded that the black box, the accelerometer, did not give them an equation but instead just gave them the acceleration. Another student asked if it was acceptable to have a negative acceleration and Sally responded that the negative only indicated direction. Sally offered some guidance on the double bar graph that students were expected to create in their packet.

With 25 minutes of class remaining, Sally told the students it was time for the test. Sally asked the students to get a calculator and then spread out so there was only one student per table. Sally indicated that the students were not allowed to use their packet on the test. Sally handed out the test and read through all of the questions. The test contained questions written at two different achievement levels. Sally had labeled the lower level 1-2, and the higher level 3-4. The test had a total of two 1-2 level questions and two 3-4 level questions. The students were expected to answer all four of the questions on the test. The questions on the test can be seen in the document "Physics: Crumple Zone Assessment" in Appendix D. During the test, Sally circulated through the room picking up supplies and answering questions as needed.

The first student completed the test eight minutes after it had been handed out. Students turned in their tests and then went back to finishing their "Crumple Zone Engineering" packets. All of the students completed their test within 11 minutes. As students finished their packets they turned these in to Sally. As the class period drew to an end Sally wished all of the students well and reminded them she would see them at graduation. After the bell rang, six students remained in the classroom finishing their "Crumple Zone Engineering" packets. The last student left the classroom five minutes after the dismissal bell.

Interviews.

Sally participated in two interviews for this project. She was interviewed previous to the engineering integration into her classroom and then after the conclusion of the engineering project. The first interview was 36 minutes in length and the second interview was 33 minutes in length.

What is engineering?

Sally defined engineering as "trying to make something happen that you want to happen, and trying to do that in the most efficient or practical way possible." She continued, "So, not just trying to get something to happen but like having a, well first having a purpose but then having, like, criteria or trying to, trying to make is be as efficient or the best as possible."

Preparation for teaching engineering.

Sally earned a bachelor's degree in physics and then a master's of education degree in science education. When she was asked about what background she had in engineering or engineering education she spoke about experiences during her academic career, and about professional development she had done as a teacher. She explained that as a part of her undergraduate degree she had taken classes in engineering; she mentioned environmental engineering courses specifically. She indicated that she took these classes to earn elective credits required and to survey the different areas in engineering because at the time she was undecided about a career path. During her undergraduate years Sally had not yet decided on becoming a teacher.

While taking classes for her master's degree Sally said that some of her science education classes had a focus on engineering education. She clarified that she had opportunities to engage in multiple experiences related to engineering education. When Sally began teaching she remained connected to the university that had granted her both of her degrees. She became involved in professional development offered through the science education department. She remembered one specific training that was focused on Science, Technology, Engineering, and Math (STEM) integration.

Sally felt that the training she had, which was related to engineering education was sufficient. She enjoyed being involved in a variety of professional development opportunities. She stated, "I also hadn't turned down [professional development] opportunities and I've sometimes sought out opportunities to continue to improve my knowledge on that [engineering education]." Sally explained that engineering education was an interest of hers. She speculated, "If I hadn't necessarily been seeking those things out [professional development on engineering education], I don't know that … I would be including those things necessarily in my instruction just because I wouldn't have the resources of the knowledge as to how to do it or ideas as how to do it." Sally added that she found seeing other peoples' ideas were a great way for her to get ideas or inspiration for different classroom projects.

Addressing state standards.

The district for which Sally worked was in the process of changing all of their grading into standards-based grading. In the past couple of years they had worked on placing standards in classes. Sally explained that "The Nature of Science and Engineering" strand from the Minnesota K-12 Science Standards was placed into each one of the school's science classes. The current goal was focused on the standards but not necessarily all of the benchmarks within a standard. However, most of the science classes did not yet have engineering curriculum. The physics teachers were planning to have an engineering project during each trimester of the following school year. The current year Sally called a "rough draft" as they were trying to place standards and get projects into place. As a result, the only engineering project implemented for the current school year was the crumple zone project.

Sally was given a copy of "The Practice of Engineering" substrands and benchmarks and asked to indicate which benchmarks she covered in her general physics class. In relation to the five benchmarks listed within "The Practice of Engineering" strand, Sally indicated that she met all of the benchmarks to some extent in her general physics class. The one benchmark Sally believed she did not completely address was 9.1.2.1.3, related to the manufacturing, operation, maintenance, and disposal of engineered items (see Table 4.2).

Table 4.2

Sally's Implementation of "The Practice of Engineering" Benchmarks

Benchmark	Benchmark wording	Sally's implementation
9.1.2.1.1	Understand that engineering designs and products are often continually checked and critiqued for alternatives, risks, costs and benefits, so that subsequent designs are refined and improved.	Covered through implementation of multiple iterations of the crumple zone design project
9.1.2.1.2	Recognize that risk analysis is used to determine the potential positive and negative consequences of using a new technology or design, including the evaluation of causes and effects of failures.	Covered because the students had done multiple iterations of their design. The students were to evaluate each crash and work to understand the reasons for failure so that the next design could be better.
9.1.2.1.3	Explain and give examples of how, in the design of a device, engineers consider how it is to be manufactured, operated, maintained, replaced and disposed of.	Partly covered - connection made to each group creating multiple crumple zones. Sally said "fronts to their cars that are piling up and piling up. You know, you have to make a new one every single time." Recycle bins got full
9.1.2.2.1	Identify a problem and the associated constraints on possible design solutions.	Covered with the problem being "keeping people safe in their vehicle." Constraints included a size and materials.
9.1.2.2.2	Develop possible solutions to an engineering problem and evaluate them using conceptual, physical and mathematical models to determine the extent to which the solutions meet the design specifications.	Covered because crumple zones were tested and evaluated during implementation. The students used the results of that data analysis to determine "how effective that solution is, or how effective that design is."

Note. Benchmarks from Minnesota Department of Education, 2009

Influence of standards.

During the interview, Sally was asked her opinion on the effect of the recent Minnesota science standards that were focused on engineering. Sally stated that she had not implemented the crumple zone design project as a result of these most recent standards. She explained that in her department, "we did the project previous to the [implementation of the] standards." When asked if there had been an impact to her teaching based upon the STEM integration standards she responded, "No." She elaborated, "I feel like that is something that previously we have been trying to incorporate." As a result Sally did not feel that she needed to create something new for the standards because she was addressing them with her previous curriculum.

In regards to the next school year, Sally stated she was re-working some of her curriculum and planning to do one engineering design project per trimester instead of just one for the school year. She felt that doing more STEM integration projects would be "really engaging and motivating for our students." She was looking forward to having time during the summer break to work on the development of these additional projects.

Student Assessment.

Related to the assessment process for the crumple zone engineering project, Sally spoke about thoughts and reasoning in both of her interviews and also had documentation that was made available to the students. Previous to the implementation of the project, Sally stated that the student grades were not based upon the forces their designs produced. She said that the grading for this project was based on "their data analysis." She continued, "How are they using their data to come up with their next design and how are they looking at that in order to inform their work?" She also included in their grade communication, "like on how they present their poster." Sally said that in the science courses in her school "we use several different rubrics, different criteria we are grading our students on throughout the year." Sally explained that this was based on information from the International Baccalaureate program. In other words, Sally said she was grading based on "themes." Sally continued on to explain that her district was moving towards "standards-based grading." For each course, a certain number of standards would be addressed and students would earn a grade related to each standard.

During the implementation of the crumple zone project, Sally was observed collecting assessment data from each student. Each student turned in a "Crumple Zone Engineering" packet. At the back of this packet were two pages which each contained a rubric: Scientific Inquiry Rubric and Data Processing Rubric. In addition to collecting the packet to use for assessment purposes, Sally also gave the students an individual exam, "Physics: Crumple Zone Assessment." At the top of this document was written, "State Standard – Developments in physics affect society and societal concerns affect the field of physics."

After the implementation of the crumple zone project, Sally responded to a question about why she had given the students a test this year by saying, our district doesn't "want us to be grading students on group work. They want all of their work to be individual." Explaining how she achieved this while doing a group project she said, "This [the test] is my way of making an individual grade on a group project … they couldn't really do on their own." Sally also mentioned that she had wished she had the class time needed for the students to complete the poster portion of the project as she had intended. About the poster she said, "I like having them wrap everything up."

Reflection on the project.

In reflecting on the crumple zone project from this year, Sally felt the project was "good." She said that the project fulfilled one of her goals, which was "keeping the kids engaged through the end of the school year, the last few days." She shared her belief that this type of hands-on project kept the students more engaged than did traditional classwork. She pointed out that she felt this was particularly true at the end of the school year for senior students. Sally admitted that the project was definitely crunched within the time she had allotted. Overall, relating to the design project, she said that there were "things I was happy with and things I would have done differently."

After class one day Sally said that she felt during the beginning of a project she does a lot of telling the students what to do. She added that it did get better as they moved through the project. She gave the example of video analysis. This was the first time these student had experience with video analysis and so that required Sally to teach the students how to use this tool.

When asked what changes she had made to the design project this year, Sally responded "I did not really make any big changes, like to the project itself from what I had done the first time." However, as she reflected, she did note some changes she had made. One change was that this year she used the accelerometer to measure the acceleration of the final round of crumple zones whereas in years previous she had used the force plate to measure force. Another difference was that even though she had planned on the students building three trial crumple zones and then build a final one in the end, time allowed for the students do build only two trial crumple zones. In addition, at the end of the project this year, the students did not make a poster to "bring everything together." Again, this was due to time constraints. The one addition Sally made to the project this year was the inclusion of a test, which she had not done in the past.

Teaching strategies/philosophy.

When asked why Sally gave a test this year she responded it was because of the district's move to standards based grading. She explained that the district was saying, "They don't want us grading students on group work. They want all of their work to be individual." I asked Sally the reasoning behind this decision and she said it was to alleviate the issue of doing group work where "two kids do the project and two kids sit there and don't do anything" and yet they all receive the same grade. Sally expressed frustration with this issue in using group work because she felt that doing engineering projects should be a collaborative process. She explained that giving a test "was my way of making an individual grade on a group project that they did." In this way she felt she could assess the meeting of standards for each individual student.

Sally planned to use the crumple zone design project the following school year and hoped the project would "just go better overall." To do this she planned to have the students have experiences with the tools and technology used in the project previous to the beginning of the project. She explained that this year the students had worked with the graphing program but had not used the video cameras or done video analysis. She wanted the students to be "more familiar with the tools or more competent with them." She hoped this would shift the focus from learning how to use the tools to more about the engineering design process.

Sally felt that the poster portion of the project was important but she had merely run out of time to have the students create one. She believed the poster would be helpful for the students because it would contain all of the pieces of the project and it would be a way for them to "wrap everything up." Although the students completed the "Crumple

Zone Engineering" packets individually, Sally felt that the poster would give the students an opportunity to "process [the information] with the group or process with other people as well." She suggested some areas where the students could do this, the "conclusion, improvements you could make, how reliable was your data." Sally stated that it was "valid to have, like, collaborative conversations about it, because I think they get more."

The teaching methods Sally employed in her general physics classes was different than the physics class in which she had been in high school. She stated that high school physics class she took could be thought of as traditional. She explained this to be "do problems, do the odd ones out of the back of the book, take a test." She believed that if physics teachers observed her class, to them it "would not look like a typical class." Sally said that the physics class she taught "is definitely not like a traditional…, like, it is not at all like the physics class that I went into." There were two physics teachers at Sally's school; the other teacher was in charge of the other two levels of physics classes. She explained that one of these classes was an IB class and so the curriculum was very scripted. However, Sally said the honors level physics class was taught in a manner similar to how she taught the general physics class.

When asked how her teaching was different from a "traditional" physics class, Sally explained that to begin with the grading was different. Sally said that she had started "standards based grading" in her classroom. Instead of students earning grades on a particular unit of study, they earned grades related to a number of overarching standards. Sally gave an example of one standard on which she assessed the students, scientific inquiry and data analysis. She said that for assessments she used tests and lab reports. She explained, "Lab reports, those … are as important. The scientific inquiry and data analysis is [sic] as important in our class as the tests are. She gave another example of an assessment, one of her tests that year had just simply given the students the appropriate standard and told them to "explain this." She said the test was "a grading nightmare" but she likes how the test was very conceptual "for the purpose of being good at the physics and not as concerned about the math."

Sally was asked about any different teaching strategies she used when doing the engineering design project, compared to her regular teaching. She responded that the strategies she used in her regular teaching and in the teaching of engineering, "there's lots of it that's similar." During both her regular teaching and the engineering design project she did some direct teaching and then had the students working together. She said that during all of her teaching she really tried to have her students work on things together. She explained:

> I think that piece is important, like the teamwork and knowledge sharing is important. I do a lot of, like, try this stuff together with your group, put it on a white board and present it to the class. I try and have that be consistent throughout my teaching, so, there's a lot of like, kind of do something and then take some claim over what you think you know and then do you know it or not know it?

Sally believed that her engineering project could have contained more of this communication. She explained that in the past she had participated in engineering projects where each group had to present their findings to the group before they continued on to the next iteration. She gave example questions to answer. "What did you find out during this one? Was that good or not good?" Sally thought this would be a good addition to her crumple zone project; she could have the students share their knowledge with the whole class after the first or second iteration. Sally did mention that there might be a conflict between sharing ideas and competing for the best crumple zone.

Benefits and drawbacks of integrating engineering.

When asked what she felt about engineering education at the high school level, Sally responded that she thought it was “really useful.” She said, however, that she felt planning an engineering design project at a level appropriate for her general physics students could be challenging. She stated, “I think that the content isn’t always rigorous enough to allow for projects that don’t seem like they’re, like, fifth grade science projects.” She believed it was sometimes “really hard to find balance between there [the fifth grade science projects] and to find things engaging to the students.” Sally explained that these reasons led her to choose the crumple zone project. She realized that most of her students were 17-18 years old and that they were “all able to drive.” She felt that this connection between the physics concept of force and driving a car made this project “something that is applicable to them.”

During the interview Sally talked about some of the benefits and some of the drawbacks she had seen related to incorporating engineering into her physics classes. Her overall view was that there was benefit to putting engineering into her general physics classes even though the students in these classes were “not going to be an engineer after taking this class.” The belief that engineering design was beneficial to a wide range of students was why Sally had implemented it in her classes.

When asked why she included engineering in her class, Sally responded with two main reasons. The first reason Sally gave was, “I think it [engineering design] is super motivating for the students." She believed there was "a big group of students that really like this [engineering design] and can get engaged in it. You're building something and I can immediately see how mine works." The second reason was, "I really want my physics class to be very practical and I want my students to understand what the real world is like or what is happening in the real world based off the class they are taking." She continued that with the physics knowledge the students were gaining she wanted them to "understand how that really is applied in the real world and see situations where it [physics knowledge] really is useful for them." The motivation of the students and the connections they were able to make with the real world were the reasons Sally included engineering in her classes.

Sally shared some of the benefits that she believed that the students received with the implementation of engineering design. She thought that engineering "is a good place for them [the students] to be creative." She explained that in traditional physics classes students "do a lot of math problems." Sally felt that the engineering project allowed for students, who did not have strong math skills, "the opportunity to be successful in physics and to be engaged and to find value in the class." Sally shared that additional students in her class became engaged when they were working through the engineering project. She explained, "There's a group of students that, you know, are really good, like, math students and can be engaged no matter what we're doing in class but I think that there's definitely a different group that really likes the creative aspect or the design aspect [of the engineering project]."

With regards to the students being involved when doing engineering design, Sally believed that involvement increased. She said, "Then I think that all of the kids are responsible for doing things. I mean its really hard to sit back and say, 'Oh, I didn't do my homework' when nope, right now you are building something, like, you've got something to do. You can't just sit there and do nothing." Sally explained that the students' general response to the project was, "They really like it." Sally said, "I've always had kids really like it, get super engaged and, 'Oh, we are going to build this one next and it's going to do this and it's going to be great.'" When asked if she ever had students who did not become involved in engineering design she replied, "I don't think that I have had any that just, like, dropped out of it. So, some that still like choose certain parts that they want to do and then don't want to help, like, with the other parts that are not as fun." She agreed that examples of this would be students who wanted to build and crash but did not want to create a poster.

Sally thought that some of the motivation seen in her classroom when doing engineering projects related to the competitive aspect. The teams were competing with each other to design the crumple zone that produced the smallest force. Sally said that she believed of the students, "They like that challenge." Sally noted that during the project she observed some groups were being secretive with their designs. She said, "There were a couple groups that were, like, they had their bags up, like, all around the table and they're like 'Nobody can watch us when we crash this one.'" She also felt that "once somebody had the idea in their head [of what they were going to build next], no matter what they saw, they weren't going to steal somebody else's ideas." Observed during the class were numerous instances of competitive behavior.

While Sally found a number of benefits to implementing engineering design in her physics classes she also knew there were some drawbacks. Sally felt the biggest drawback was that engineering design "takes a lot of time." She explained that in her curriculum "there's a lot of things that take a lot of time and it's just hard to balance which, which ones do I select with which units." There was evidence of time being an issue in the crumple zone project because the time Sally had allotted for the entire project was not sufficient and in the end she had to modify the project to fit within the allotted time. Sally commented on the plans she was beginning to make for the next school year. She wanted to increase the number of engineering design projects done in class. In order to get this additional time, she was "trying to think of, like, how can I get my students to do more things. More like, how could I get them to do more outside of class so that we can do more inside of class?" Sally admitted that her students were not motivated to do physics work outside of class. She questioned if her expectations had limited what the students were willing to do outside of class but her knowledge that "if I expect it to get done, we will do it inside of class" came from years of experience with students not doing work outside of class time.

While Sally felt that it was beneficial for students to work together in groups, she also realized that group work did not always turn out the way she had intended. Sally mentioned one group where half of the members were working on the project and the other half were not. Sally agreed that group management could be a challenge. She said she needed to monitor "in the engagement pieces whose doing what, whose engaged." Sally reflected, "Ideally it would be great to have everybody doing it on their own or have teams of two or something like that, but then you run into, like, materials limitations and things like that." With the mention of materials Sally said, "the projects that we try to do are always just, like, minimal materials…We really try and be very conscious of, like, what we can do with some tag board that we can get from the office." The availability or funding for materials was another barrier. Sally explained that she worked around the barrier of limited funding for materials by designing projects that used inexpensive supplies.

Sam

Sam was a veteran physics teacher. He had been teaching in the same school district for the last 36 years. During the first 10 years of his career he taught physical science at the junior high level. He then moved to the high school level and taught chemistry for several years and for the last 24 years he had taught physics at the high school level. Recently, Sam spent one year as a teacher-in-residence teaching calculus based physics and physics for elementary teachers at a local university. The school at which Sam taught was a high school that housed grades 9 through 12. The location of the school was in a first-ring suburb. The school schedule followed a repeated six-period day. The student body consisted of a total of 1076 students: 4% limited English proficiency students, 27% students of color, and 29% students on free or reduced lunch (Minnesota Department of Education, 2012). Physics class was not a requirement for graduation from this school. The section of senior level honors physics observed consisted of 20 students: 90% white, 10% students of color, 55% male, and 45% female.

Sam had been working with a local oil refinery to implement an engineering design project in his physics classes for the last 23 years. He had received recognition for his implementation of these projects. A write up about his projects had been done in the local newspaper, Sam and his classroom had been on the news, and they had a visitor from the nearest national physics laboratory observe the project for a number of days.

Sam believed that "almost every parent in this district knows about this [project]…well, of the upper level students. They know about this and they want their student to be doing this."

Engineering project overview.

Sam implemented a five-week engineering project in his honors physics class. Classes were 55 minutes in length each day for five days of the week. This project took place at the end of the second trimester starting in February and ending in March of 2012. Previous to this time, the focus of the class was the study of mechanics. The engineering design project was designed in collaboration with engineers from a local oil refinery. The oil refinery staff volunteered to give engineering time to the physics class. As possible design projects, the refinery engineers offered examples of real engineering problems that had been investigated at the plant. Sam selected the proposed project that he felt was the best fit to implement in his classroom. The engineers then developed a "Request for Proposal" (RFP) document (see Appendix E). The RFP included a project schedule, an introduction, background information related to the need for the design solution, the project work scope, a list of deliverables, and an appendix which gave values of characteristics needed for the design. The refinery engineers then visited the physics classroom and presented the RFP to the students on the first day of the project. This year's project focused on the design and installation cost estimate for the building of a foundation to be used to support a new vacuum pre-fractionation tower.

The final product for this project was the writing of a two-page design solution proposal. Supporting this two-page proposal were explanations and calculations needed to understand the answer proposed. Along with the design, a budget was outlined for the proposed solution. In addition to the written product, each team had to prepare and deliver a presentation to the engineers that mirrored the proposal, but was similar to a proposal presentation that an engineering consultation firm might present to a client.

At the beginning of the project Sam divided the class into groups of four students using random assignment. These groups were intended to mimic an engineering consulting team. Each group had to designate a role for each student in their group: project manager, spreadsheet expert, bolt expert, and foundation expert. For the first two weeks of the project, groups were involved in lab work and discussion. The purpose of this time was for the students to gain experience with and learn about physics content that was applicable to the project: density, torque, pressure, elasticity and tensile strength. Subsets of each group performed three laboratory activities: “Deflection,” “Elasticity: Stress and Strain,” and “Force of Wind” (see Appendix E).

During the “Deflection” lab students investigated the relationship between force and deflection of a pole that was firmly planted in the ground. The product of this lab activity was the development of “a working formula that will predict this deflection for any size pole or tower.” During the “Elasticity: Stress and Strain” lab, students investigated the change in shape of an object when a force was applied. The experiment examined the elongation of a wire when a pull was applied to it. Students determined the elastic modulus of the aluminum wire used and then compared this value to the scientifically accepted value. Sam connected this lab activity to the engineering project by saying, “And that’s because the bolts, we have to calculate when the bolts will break.” During the “Force of Wind” lab students investigated the pressure produced on a surface due to wind. They examined surface area, wind velocity, and shape. With their results the students developed an equation to solve for the force.

The group's spreadsheet expert programed all of the calculations required to determine the results of each lab. In all three labs, students used their data to determine the value for a constant that was used in the development of a formula. For the "Deflection" lab the constant determined was the modulus of elasticity, which was used in an elastic deflection formula. For the "Elasticity: Stress and Strain" students determined the tensile strength of a wire. For the "Force of Wind" lab students determined an equation for the force on a sail and determined constants related to the area and wind velocity. Sam said that, "The equation they get from this one, they actually have to use in their solution. Whatever they come up with in lab, they have to use their equation and their constant that they have determined." Sam explained, "I always pick one of the labs and make them use it, kind of on purpose because otherwise you get several groups having the same answer."

In addition to completing laboratory activities during these first two weeks, both the foundation and bolt experts in each group were provided with some background information. Sam gave each expert an article from the refinery-engineering library pertaining to his or her required area of expertise. The students were given one week to read and understand the article. The articles contained terms that Sam anticipated the students would not understand. The students were to look up these terms. After the week given for individual reading, Sam met for one class period with a group consisting of all the bolt experts from the class. Students were not allowed to bring their articles with them for reference. During the meeting Sam asked questions of the group to make sure each person had sufficient understanding in order to be the bolt expert for their team. The same process took place for the foundation experts.

When all of the background research was complete, the designing of the foundation began. Sam had groups begin by filling out a "Problem Planning" sheet (see Appendix E). Groups were asked to define the problem and describe the anticipated product, list all of the information required to solve the problem, and list all of the equations needed. When completed, each group turned in their "Problem Planning" sheet and then received a sheet entitled "Solving the Problem" (see Appendix E), which contained an ordered list of steps to follow for solving the problem. This list included seven steps plus one optional step, followed by some calculation suggestions and an appendix section that contained reference information. The steps listed are as follows:

1) Find the forces of the wind at different levels for the vessel.
2) Convert forces to distributed forces.
3) Calculate the deflection using the maximum distributed force.
4) Size the foundation.
5) Check foundation for Overturning Moment.
6) Determine the number of bolts needed on the attachment ring.
7) Find the cost of the recommended foundation and your second option.

*Optional – Determine the thermal growth of the vessel.

Each group used this list as a guide as they began the process of building a mathematical model in the form of a spreadsheet.

Sam talked about the function of the spreadsheet program, "Because their final project has, is really only solvable by spreadsheet. It's too complex to not solve it, to try to solve it any other way." Sam explained that the students needed to input information about the tower and then input all of the variables. He talked about using the spreadsheet to make changes and see their effect. "We say what if we make the foundation this size. How is that going to change our torques and our…? How is that going to change the bolts? How is that going to change all of these things?" Sam said, "Once they get their spreadsheet built, then they can solve the problem and determine, ok, what's the best cost for the smallest footprint that we can make with our formulas?"

After all of the presentations had been made and the reports turned in, Sam planned a fieldtrip to the refinery. Sam stated his expectation for his students when on the field trip. "I thought the they [the students] should know there's lots of kinds of engineering… I am really trying to break free from that, engineering was making a foundation." The fieldtrip contained presentations from various types of engineers and a tour of the refinery. On the day following the fieldtrip Sam reflected with the students about their experience.

Observations.

Sam's honors physics class was observed for a total of 13 class periods. Each class period was 55 minutes, except for the last class period of the trimester, which was 1 hour and 45 minutes long. The fieldtrip was also longer in duration and lasted a total of five hours.

Day 1. (Week three of the project) (Wednesday, February 22)

Sam's classroom was physically divided into two areas. In the front was a demonstration table situated in front of a white board. Facing this were rows of individual student desks. In the back portion of the classroom were seven large tables, each surrounded by four chairs. Class always began with students in their desks but project work took place at the large tables.

Observations began following the background lessons described above. Day one began the third week of the project and students had begun working on the design portion of the project. When class started Sam encouraged the students to make sure they were following formats and showing their work. He told them that engineers must turn in "followable" work. In this specific project the student who had done the problem solving was to turn over their work to the spreadsheet expert. Sam also told them that being clear allows him to better help the groups when they run into difficulties. Sam then announced a meeting for the project managers. Sam noted that he meets with the project managers' group every few days. His purpose in doing this was to give guidance and make sure groups are on task. On this day, group members moved to their project work table but all project managers formed a circle of desks in the front of the room. Sam asked the group of project managers "How is it going?" and "Are there any questions?" He reminded the managers that during the last five minutes of class they should make sure that all work was organized in the group folder to turn it in so Sam could look at it. He reminded them that each person should be turning in something related to their work. Students would get any work turned in returned the next day with feedback. The students earned a score for daily work from these assignments. Sam told the project managers that he asked for daily work so could help them and look for mistakes.   Sam told the project managers that they should be assigning homework to group members and that the assignments should be reasonable and possible for one student to complete alone. Sam told the project managers that keeping people organized was their responsibility. The groups were allowed to work at their own pace but everyone had the same final deadline. Sam reminded the managers that at the very end each group needed to have two solutions – one recommended and one back up. He related this to the needs of the client who wanted a second choice if they did not like something (e.g. cost) about the primary design. The meeting was concluded and the project managers returned to their groups.

During the remainder of class on this day, Sam answered questions from individual students or groups. Sam was busy circulating throughout the class and was purposeful with his time. He did not let any one person monopolize his time. An example of one of his interactions started with Sam sitting down with a group. He checked what they had accomplished at this point. He told them he would give them *his* suggestion but reminded them that there is not just one right answer to this problem. Sam encouraged the students to use the appendix for further information. Sam asked which group member did the “Force Due to Wind” lab and told them they needed to convert the k value they determined into English units. During this time the students who were in this group were engaged in the conversation. Once Sam gave them some pointers he set the group to work. Sam then moved to help another group. During the work time the students were seen using the physics textbook, calculators, and the computers.

Towards the end of the hour Sam reminded the students that they should place all of their work into their folders and turn the folders in. The students worked right up to the end of the class period, some even asking questions of Sam after the bell rang. The students were expected to do homework for the project for the next day.

Day 2. (Thursday, February 23)

The class period started with announcements. Then Sam made a clarification for the students. He told them that the tank diagram was a bit misleading in that they were looking at the diameter of the tank skirt, not the tank itself. Sam admitted that he did not realize this until now. He also reminded the students to use significant figures in their calculations. The students were then released from their desks and moved to their group's large table.

Again on this day students were seen working on pieces of the design problem. Sam walked around the class asking groups what questions they had. During this time a student was seen looking at a page full of calculations. He stated that he needed to change one number and then go through all of the calculations again. Students were working on the computers using the spreadsheet program. Some students had done example calculations on paper and were now inputting this information into the spreadsheet to obtain multiple results. Students were seen referencing the tank blueprint (see Appendix E) that had been provided by the engineers. The blue print showed a cross-sectional diagram of the tank that was to be supported by the foundation the students were designing. The diagram included measurements, notes, and values that were needed for the design.

Students in one group were talking about the calculation of the force on the tank created by wind velocity. They were unsure at that point about what to do with this value. One student in the group asked, "Why don't we just lay the tank on its side? It would reduce the force from the wind." Another group member replied, "We can't because the tank requires gravity." Students were seen using reference sheets to find volume formulas for different shaped objects. Each group had to decide what shape they were going to use for their foundation.

Sam continued to move from group to group, answering questions. At one point he instructed two members of a group on how to input data into the spreadsheet in a way that it would recognize it in the desired fashion (adding $ to cell names). Once he gave this instruction he moved to another group. Another student asked him if the units for her torque value were correct. Sam responded to the student, "What do you think?" The student answered correctly. Sam then engaged the student in a conversation about why those units were correct. He told her that at the end of the calculations these units would cancel out. During the last few minutes of the class period Sam reminded the students to get their folders together and turn them in.

Sam explained to me that by the nature of this project, groups are all in different parts of the process at any given time. He said this meant he needed to personally have a strong understanding of the problem so he could quickly jump from helping one group to the next. Sam stated that at this point in the project the groups were really getting down to work. He said that they were just starting to put their solution together after the two weeks of background research. He noted that at some point, panic would set in. Some groups would struggle and need help outside of class time. He also noted that sometimes students began to cry. Sam said he did not think this was a bad thing because when a student got frustrated and cried, they then work past it. He believed that in the end the students realized they were successful in overcoming obstacles and in turn that built their confidence.

Day 3. (Friday, February 24)

For this class period there were no announcements shared. Sam reminded the students that they must turn in their daily paperwork with both a name and a date. He also reminded them that for calculations needing to be done multiple times, they should do one calculation by hand, know it is done correctly, and then use the spreadsheet to do multiple iterations. Students moved to their worktables, got out their work materials, and began working. Again for this day, students worked to problem solve through each of the tasks they had been given in the "Solving the 2012 Problem" outline. Sam walked around class and moved from one group to another answering questions.

Sam responded to a question from a student in one group. He wanted to make sure that the student understood the vocabulary word "overburdened." This word represented a concept that was used in solving the problem two of the groups members were working on at that time. The two students did not seem to have an understanding of the term and so Sam suggested that the foundation expert of the group look it up. Sam then left the group to this task. Sam moved on to help another group that was trying to process information from the blueprint. The students were trying to visualize how all the pieces of this project fit together. They needed this understanding in order to go forward with their calculations. The group was trying to determine what size bolts were needed to anchor the tank to the foundation. Sam helped the students understand the information that was given on the schematics. He then moved on to work with a third group. This group was discussing how to determine the size of the foundation. Sam highlighted that there was a minimum depth required but that the group could make the foundation as deep as they wished. One student jumped in to mention that the deeper the foundation, the more expensive it would be to build, and budget was a consideration for their project. In another group, students discussed different design ideas. One student mentioned the idea of just burying the tank, to avoid figuring out the needed depth of the foundation.

Sam's role during this class period was that of a facilitator. When students ran into a roadblock with their problem solving, they asked Sam for help. Sam did not appear to freely offer up information, but helped students to think through their problems using what they had learned and resources in the classroom. . Students were seen using their textbooks and articles for reference. Sam worked with one group to come to an understanding of the safety factors required for their design and then worked with another group that had a question about the foundation diameter. He asked which member was the bolt expert and then explained to this student how the pieces in the schematic fit together. Sam explained to the group that they must determine the diameter of the foundation. They had information to take into consideration but ultimately the group must decide. In addition to choosing the foundation diameter and depth, each group was also required to use the *k* value they determined in the "Force Due to Wind" lab. These factors resulted in different solutions from each group.

Students in the class mentioned that this work was difficult. After class, Sam told me that he felt he really needed to have self-motivated students for this type of project. When he tried to do a similar project with his regular physics students, he said not all of them could stay focused on the task. The majority of the honors physics students in this class were seen working on their project up until the bell rang each day. This was the last day of class for the third week of the project. Two days were missed due to a school holiday and a school field trip.

Day 4. (Week four of the project) (Monday, February 27)

Before class started Sam told me he was starting to worry about the time remaining for the project. He was concerned because there was the possibility of students missing class time due to a snow day or going to the state-wrestling tournament. Sam could not extend the project completion deadline due to the ending of the trimester. Sam was unsure of the timing of the project partly because the project given each year was different. He had never done the same project twice and some years students did not finish the project and had to just present the work they had been able to complete.

Sam began class once again asking for any announcements, and then told the students that it was "crunch time." He said that in three days the students should be at a point where they were putting together their PowerPoint presentation. This meant that by that time they should have determined their design solutions. Sam told the students that they needed to make a plan on how to finish the project. As Sam addressed the class, five honors physics students from Sam's other section entered and moved themselves to a back room. These students were present to work on the optional, or extra credit, portion of the project, which involved conducting an additional lab. When Sam had finished talking he went to the back room to help these students get started.

Students had moved to their worktables and begun working. Sam then set up a circle of desks he used to conduct another project manager meeting. Sam made a quick pass through the work groups to see if he could answers any questions, and then he called the project managers forward and asked them to bring their "Request for Proposal" that they had received from the refinery engineers. When the meeting began Sam handed out a sheet that listed options for bolts, including sizes and prices. The project managers were asked to deliver this to their group's bolt expert. Sam asked the project managers if they were feeling any pressure and the students answered in the affirmative. Sam told the students that feeling this pressure was good because it kept them involved in the project. Sam directed a comment specifically to one manager, whom he had identified to me as a much more creative type than the other managers. He asked her if she was ever nervous before going on stage. He then asked if she thought it would be good if she weren't nervous at all going on stage. Sam concluded to the group that some nervousness likely makes the performer do a better job. Sam then asked the project managers to find the sheet that listed the deliverables for the project and then gave them an additional sheet, which had more detailed information (see Appendix E). This new sheet told the students what was expected in their proposal and in their presentation. Sam then handed out example papers that had been turned in during previous years. He told the project managers that they may look at them but the papers could not leave the room. Sam walked through one example paper, telling the students that the paper gave them a general idea of what the final project looked like. Sam pointed out that these old example papers were from doing a different project, as the project itself was different each year. One manager then asked if students could bring in their own computers if they felt that they needed more than one computer per group. The classroom was fitted with one desktop computer per worktable. Sam answered that bringing in additional computers was acceptable. Then Sam collected the example papers and told the managers that the papers would be available at his desk. The meeting was adjourned and students were told to return to their work.

Sam took a brief moment to help the students from the other physics section who were working in the back room. He told them he could not give them much time because he was committed to his current class during this hour. The students in the back room told me they were working on finding the linear coefficient of expansion. This information was required to do the optional step of determining the thermal growth of the vessel.

Sam then began circulating within the class and helping groups with problems they were facing. One student asked Sam for the inertia moments for a hexagon and an octagon. This information had not previously been made available to the students. Sam went to his reference books in the room and looked for a value. He found values the group could use and passed these along. Other students asked questions, mostly related to the calculations or how to use the parameters given.

Observed was a project manager working with her group. She was communicating with a team member who would not be present for the group presentation. She outlined what was expected of him as a result. She then told the group that she was going to start assigning homework to each member every day. She told them that with this plan the work would not all pile up at the end. She explained that some of the homework would be rather straightforward.

Sam was working with a group that realized they had not included the torque from the wind in their calculations. Sam helped them wade through their analysis to find the information that was needed to calculate this. He began working specifically with one student who had done the other calculations. Sam told the student she was doing good things but just missed a few pieces. He had a very positive outlook. A few moments later the student said that this new information made so many things make sense. She said she was so confused before.

Sam announced that there were two minutes of class remaining. All of the groups were still working. He reminded them to get their work into the group folder and turn it in for the day. Class was over for the day.

Day 5. (Tuesday, February 28)

Sam began class with announcements and then turned attention to the spreadsheets. Sam highlighted that the spreadsheets were getting pretty complicated at that point. He suggested that students bring in their own flash drive in order to backup their files in order to protect the group from loss. Sam then told the students to go to work and they moved to their worktables. Again, Sam spent the majority of his time working from group to group to answer problems.

In one group the project manager was observed assigning jobs related to the writing of the final proposal to all group members. She asked one person to write a short paragraph stating the problem that had been given. She assigned another group member to write about the background of their fictitious engineering consulting company. Group members also needed to write about their own fictitious educational background and job history. A company name was also needed. The project manager asked the group members to email her these products by the end of the week.

This project was laid out as a competition among the various groups. In the end, the refinery engineers would choose a first, second, and third place design between the two honors physics classes. During work time in the class, students were instructed not to talk to members of other groups. The students worked only with their own group members and with Sam. At one point during this class period however, Sam noticed that a students was at another group's worktable. Sam blamed the student for "cheating" by stealing ideas from another group. Sam reminded the entire class that the groups were in competition.

Students were observed to have been doing a lot of explaining to each other. If one group member had figured something out, he or she shared it with other group members who needed to use this information. Group members were observed talking through different aspects of the project. When members got stuck they were often seen referring to the group expert pertaining to that particular aspect of the problem. Regarding the depth of the foundation, one student asked, "Wouldn't we want to go smaller because of cost?" The student was taking into account the budget constraint. He suggested to his group that he use the spreadsheet program to solve for depth. He wanted to get some results and from there choose a foundation size. He told the other group members that he needed them to give him formulas and values in order to program the spreadsheet.

I spent some time looking over the spreadsheets from one group. The group's spreadsheet had multiple pages, which they used to calculate values such as torque. One page was labeled "Wind on Tower" and contained nine columns with the following headings: *k*, height, area, *k*, shape coefficient, velocity, force, torque-b, and torque-f. Another page was labeled "Bolt Cost." This spreadsheet had columns for bolt diameter, number of bolts, tensile strength, torque, and weight. A student was observed typing values he determined on paper into the spreadsheet. The student was also writing formulas into the spreadsheet. After he input some data, the spreadsheet program produced all negative values for the number of bolts required. The student realized that these results were not logical, so he then talked to another group member about the calculations. The two students looked at the formula and checked the algebra. The original student found an error and made a change but the results were still negative. The group members decided to input the original equation into the spreadsheet without first simplifying it. They trusted that they were much more likely to make an algebra mistake than was the computer. The result was still not logical. The students then figured out that they needed to convert the units of their torque value. With this change, the spreadsheet produced reasonable results. The group then determined which appropriate bolt selection would result in the lowest cost.

When the student highlighted in the previous paragraph was asked how he became competent with the use of the spreadsheet program, he responded that he learned how to write formulas for the program in this honors physics class but also admitted that he knew some of it previously. This student was the spreadsheet expert for his group. He indicated that he had chosen to be the spreadsheet expert. Another member of his group said that none of the other group members had an issue with this choice, as he appeared to be rather proficient in this area.

As the class period came to a close, students finished up the tasks of the day, printed files, and placed work to turn in into the group folder. One student stayed after class to ask Sam a few questions and to make sure that her group had been turning in everything required. She told Sam she was trying to create a schedule for the group. She mentioned that her group members were not very interested in the schedule but she knew the group needed a plan in case they ended up needing to work together outside of class.

Day 6. (Wednesday, February 29)

Sam opened the class with announcements. He then talked to the class about estimating costs and using round numbers. He told them that they did not have to get so specific; they should think about significant figures. Sam then set the students to work. The students retrieved their group folders and moved to their worktables.

As the students were getting settled in, Sam gave me an example proposal report from a previous year. The group that wrote this proposal was doing a different design project than the students that were in class that day. The previous report was typed and formatted, as a proposal would be. The beginning of the report contained two pages of prose. This outlined the problem, the engineering company, the constraints, the basics of both a primary and secondary design, the specifics of the primary design, and an estimated cost. In the final paragraph the group made a recommendation for a solution and then supported this recommendation with results. Following these two pages were diagrams, graphs, spreadsheets, and example calculations. The report looked professionally done.

Sam maintained his practice of circulating throughout the class and providing assistance when asked. One student referred to a written report from a previous year. She noticed that the report had phone numbers listed. She asked Sam if this was required. Sam told the student that it was not required but that the group just decided to add them. He told her that in previous years groups have even made business cards and attached them to their report.

The students in one group were heard comparing their primary and secondary design choices. They noted that their primary design had a higher safety factor but also cost more. Their secondary design had a lower cost but did not have as large of a safety factor. The safety factor allowed for a margin of error in the design. The larger the safety factor, the more likely the foundation would perform within the conditions encountered during its use. The students showed an understanding of the trade off in cost for a higher probability of performance.

Students were observed doing troubleshooting in the process of designing their foundation. When students got results from their calculations that did not make sense to them, they went back through their work to look for mistakes. When members of groups came up with calculation results, there was conversation within the group to determine if the value seemed reasonable. One group was observed obtaining a result of 22 feet for a diameter. This value did not make sense because it implied that a large object was to be supported by a small object. The group members looked back through their calculations. They were unsure of the origin of one number. They voiced that they were sure they had not just "randomly come up with a number." The group members dug through their calculations pages and found the questionable number. They then rechecked how this number was determined. The students knew that there was no "right" answer to the design problem. They understood that at some points in the process they needed to make choices about what values to use. This was the case with this questionable number. The group members decided the number was reasonable. At this point they determined that this was not a problem with their result, however during their troubleshooting they discovered a calculator mistake in the final calculation. The student who made the mistake was embarrassed but quickly went back and fixed it. The group determined that the revised result was a more reasonable number.

There was now just four minutes left in the class period. Students were observed asking very specific questions of Sam such as, “For a square foundation, do they measure ‘diameter’ from the sides or the corners?” Sam announced to the class that “the pressure is on.” At the end of the class period students turned in their group folders containing the work they had completed during the period. Sam showed me an example spreadsheet product from one of the group folders. He told me that in the end the document is multiple pages with many columns. The students must turn this into a decipherable product. Sam told me that the groups had to determine what was important to keep and what was reasonable to remove.

Day 7. (Thursday, March 1)

This class period started in the same fashion as most. Sam asked for announcements, then questions, and then instructed the students to move to their worktables and begin work. As the students were moving, Sam shared with me a database he had created. He told me that a day or two before the presentations were to take place, the students would fill out the “Proposal Information 2012” sheet (see Appendix E). The proposal information sheet had places for a group to record pieces of information they used in the determination of their foundation design. This included the *k* constant calculated from the “Force of Wind” lab, the shape and dimensions of the foundation design, and the number of bolts. Information was expected for both the primary and secondary design. Sam said that he would take the information from these sheets and input it into his database. The output from this database gave Sam the answers the group should have determined if they had done all of their analysis correctly. Sam planned to give a printout of these results to each group so the members could compare.

Sam indicated that he used this information when he graded the proposals. He also mentioned that grading these projects was time intensive.

Sam spent the majority of the class period moving from one group to the next. He helped students troubleshoot by looking through calculations and indicating places where incorrect interpretations were made. Students were observed arranging information and calculations into a logical format in an attempt to visualize the outcome. Students displayed perseverance as they worked through the various steps.

One group manager talked through the requirements for the final proposal with his group. He assigned pieces of the proposal to group members that were currently not involved with some other piece. Some students mentioned that they had done research on their own since the end of the class period on the previous day. One member of a group indicated that he used Google to find some information pertaining to a result in which he had little confidence.

One group was observed discussing the size of their foundation. They knew they had to add to the foundation diameter in order to accommodate the bolts intended to secure the tank to the foundation. One group member suggested a foundation size. Another group member voiced his concern that this size was too big. The group discussed the additional cost to the project for the additional size of the concrete foundation. One student stated that he was concerned that they were overestimating the needed size and as a result the cost of building their proposed foundation would not be competitive with those from other groups.

Another group came to the understanding of the purpose of adding rebar to the concrete foundation. They discussed the implications of this change. They decided that the addition was not cost prohibitive and that the weight with the rebar was comparative to concrete alone. The group determined that the rebar could be added without affecting the entire system.

Sam mentioned to me that in his honors physics section that met earlier in the day, when class was over two students remained at their table and continued to work. They worked until the next class period started. Sam said he eventually told the students that they had to leave and go to their next class. Sam took this as an indication that it was starting to be "crunch time" for this project.

After class was over, Sam explained to me that one group had made a breakthrough by showing that they could use the spreadsheet to do multiple calculations and determine how the least amount of pressure could be obtained. He told me the students were very excited about this. He believed this was the last step in making a final decision. Sam said he could see the excitement of the students as the project came together.

Day 8. (Friday, March 2)

Sam once again began class by allowing time for announcements. He then indicated to the students that the rubric for grading both the proposal report and the presentation had been posted on the wall. Sam told the students that the presentations should be no longer than 15 minutes. Sam announced that he wanted to briefly meet with project managers and then set the students to work.

Sam met with the project managers in the front of the room. To each project manager he handed a copy of the "Proposal Information 2012" sheet, which he had discussed with me the day before (see Appendix E). He told the managers that he needed this sheet filled out and turned in to him by Monday or Tuesday, at least two days before the presentations were to take place. Sam explained what he was looking for regarding each value. On the sheet he had asked for the following regarding both the primary and secondary designs: formula used for force from air, shape, foundation dimensions, support shape, support dimensions, depth, total number of bolts in the ring, and the cost of one bolt. Sam reiterated to the project managers that the primary and secondary designs needed to be different, although not a completely different idea. He gave some suggestions for changes and some reasons why the refinery may choose one design over the other.

After the project manager meeting Sam circulated in the classroom answering questions from students. One group commented that all they had left to do was to check some calculations and then they were done with their design. They then needed to move on to writing their paper and building their presentation. Sam commented that this is the point that most groups should be at, with only two class periods left to work on the project. Other groups in the class were not yet at this point. He said that the weekend coming up (it was a Friday) was usually a big work weekend for the students. In the past many groups got together outside of school to work on their projects.

The project manager of another group was attempting to delegate tasks to group members. One member was not happy about what she had been assigned. The manager explained her reasoning; the person who did the calculations should also be the person to type them up. The manager asked another group member to type up all of the assumptions the group made during the design process.

I overheard a student working at a computer saying, “I don’t know why I didn’t learn how to do spreadsheets earlier; spreadsheets make the work so much easier.” She was using the spreadsheet to make multiple calculations. Two students were working together to write formulas for use in the spreadsheet. They double-checked their first result by using a calculator. They typed in a formula to the spreadsheet and it did not accept it. They found the error; they forgot a “+” sign, and made the correction. When one student saw the results, indicating the cost of excavation and laying the foundation, she commented, “That’s some expensive stuff!” She was impressed that the refinery client trusted her “engineering company” with such an expensive project.

One group was working on their company and member profile for their report. They were observed coming up with details and laughing. They were being creative while determining each member’s background, including schooling and work experience. One student suggested defining himself as an “engineer by day, rock star by night.”

At one point during the class period a student entered the classroom and asked to take two particular students out of class to take a theater picture. Sam allowed this disruption but the two students told the guest that they were in the middle of their work and they did not want to leave class. She indicated that she would come back later.

Sam announced to the class “they have less than five minutes left of class, even if it doesn’t seem like it because the hour has gone so fast.” Students began putting work from the day into their group folders. One project manager asked his group members what each one was doing for the project over the weekend. Then class was dismissed and the fourth week of the project came to an end.

Day 9. **(Week five of the project)** (Monday, March 5)

Sam began the new week with a request for announcements. He reminded the class that he needed two copies of the proposal from each group. One copy would go with the engineers from the refinery and the other copy Sam would keep to grade. Sam also talked about the projector set up available for the day of the presentations. Sam then prompted the students to move to their worktables. As students were moving, visible were a number of personal laptops that students had brought in for creating presentation slides.

After the weekend it appeared that most groups had finished their design work and were shifting focus to work on their proposals and presentations. Students in class were seen writing sample calculations, developing summaries of portions of the project, and putting spreadsheets together into one coherent document. Some students were working on drawing diagrams of their final design. Tools being used were compasses, rulers, and protractors. One student drew a side view of her group's foundation, consisting of two stacked rectangles. She labeled both the length and height of the diagram in feet. Another student drew a cross-sectional diagram of the side of the tank, which included a line for the inner wall and for the outer wall. Her other drawing was of a cross-sectional view from the top of the tank. The diagram contained multiple circles, each labeled. The student told me at home she did not have a compass available for her use, but instead she traced different sized bowls.

I spent some time looking through a group's turn in folder. One side of the folder was designated for turning in calculations work and the other side was for presentation and proposal segments. Each group received points for the work done on a given day.

The group was given suggestions based on the work they turned in each day. Students were also given points based on the individual work they completed. Sam said that grading the work in the folder each day was time intensive for him.

When the class period ended there was just one class workday remaining. Sam said he felt that all of the student groups were in a reasonable place. He felt the project was a good length this year, unlike some years when the groups did not finish that year's project and ended up presenting and reporting just on what they had accomplished to that point. Sam indicated that some years the design project ended up being more complex than in other years.

Day 10. (Tuesday, March 6)

This was the last class period for working on the project. Sam began with announcements and then told the students that they did not need to turn in anything in their group folders today. He explained that this was because the students would not see the folders again until the day of their presentations. However, on this day each group was required to turn in their copy of the "Proposal Information 2012" sheet. Sam planned to use the information from these sheets and his database to check the accuracy of each group's calculations. As the students moved to their work areas Sam noted to me that the students seemed stressed.

Students spent the majority of the class period absorbed in their work. Everyone was focused on completing some portion of the project. Sam was able to use some class time to continue developing the database he planned to use. He said he had not yet been able to get it to work. He needed the outputs for the next day when his other section of honors physics was scheduled to do their presentations. Due to a final exam schedule, the current section did not have class the following day.

On this day groups were not all at the same place in their projects. Some groups had created multiple slides for their presentations while other groups had not yet begun to work on their presentations. Throughout the class periods, students worked on pieces of the project. They also spent time communicating about who would do what, and when. Everything that was not completed in class on this day needed to be completed outside of class time.

One group manager was going through all of the pieces of their project with her group. She told the group members that she needed all of their completed pieces by the next evening so she could put it all together. She talked with one member about the list of pieces he had been assigned. Another group member did not appear very focused on doing work. When the manager went through her responsibilities, the student indicated she was done with her pieces. The manager then asked her for her diagrams. The student said, in contradiction with her previous statement, that she had not yet done the final diagram. The manager suggested she work on this during the class period. The student said she would draw them at home. The manager then glanced at some of the student's writing and made some suggestions on how to make it easier to understand. The project manager turned her attention back to the entire group and told them she needed an engineer biography from each person. The group members discussed ideas about their individual fictitious backgrounds including the college from which each had graduated. They were trying to make creative responses that had the potential to make other class members laugh. One member talked about having a background in building multi-colored rings and bright colored bolts.

Each student in one group had brought their personal laptop on this day. Each was working on a different aspect of the group's project. The first member was working with PowerPoint for the presentation. She made sure that each member had a complete biography page. Her own page indicated that she was the bolt expert for the group. The second member was writing prose for the proposal portion of the project. She was also helping the first member with wording for the PowerPoint slides. The third member was also writing prose for the proposal. She asked member two for help with language and for verification of values. Member two noticed that member one was playing with the slide layout for their presentation. She recommended that member one focus on getting all of the information onto the slides, since she currently had access to all of the members, and she could work on the layout when she was on her own. The fourth member of the group was working on organizing the final spreadsheet. He asked a question of the group, "How can you have a clockwise weight, versus a counter clockwise weight?" Some of the information in the spreadsheet was not making sense to him. He asked, "Weight is just down, isn't it?" Three group members started trying to figure this out. The students dug through their papers on which they had done all of their work. After referencing the appropriate papers they decided the values in the spreadsheet were correct.

In another group, three members were all sitting around one computer. Each individual member had been assigned to complete portions of the final project. The group manager asked the members to email their portions to him by the end of the evening. He planned to work on putting the PowerPoint together the next day.

One student asks about the point value for the different portions of the project. She wanted to know whether the presentation or the report was worth more. She did not get an answer from her group members. To get the information, she walked up to the rubric that Sam had posted on the wall. This told her how much each portion of the project was worth. Both the report and the presentation are the equivalent of one chapter test in their trimester grade. The daily work that they turned in via the group folder was counted as homework points, equivalent to two chapters.

With just five minutes of class left, groups were talking about how they were going to share information. In addition to the emailing referred to earlier, other groups saved files to individual's flash drives or planned to access the same documents using GoogleDocs. One group planned to meet together that evening at 7 p.m.

As class ended, each group turned in the "Proposal Information 2012" sheet with the values they had obtained. A student talked with another student about the tension in her group. When asked what she meant, she replied that not all the people in her group were currently getting along. She commented that it was all right; they were working it out. The second student reminded her that there was only a day and a half left before the project was done.

I commented to Sam that I noticed how all of the groups were at different stages of completion of their project. He responded that this was how it was each year. He commented that this project was probably the hardest thing these students had ever done together as a group. He stated that the project is difficult, partly because there were so many pieces that had to all come together.

Day 11. (Thursday, March 8)

This day was the final class period of the semester for this section of honors physics. With the final exam schedule, the class was 1 hour and 45 minutes long. Present in class were the two engineers from the oil refinery. They were present to observe the presentations and ask related questions. The engineers were both white males and appeared to be in their late twenties. Sam began class by handing out to each group a form to fill out. They were asked to indicate who was in the group and then specifically which group member worked on each portion of the report. While the students had about 10 minutes to fill out the form, Sam and the engineers met in the back room to talk over the logistics for the class period. Students filled out the form and then spent time making final adjustments to their PowerPoint slides and going over which member was presenting each part. A total of four groups were scheduled to present during the period; the fifth group had presented early due to a scheduling conflict.

Sam introduced the refinery engineers to the class and talked about their involvement. He mentioned that the engineers were volunteering their time to be at the school and to work with both sections of honors physics. Sam told the students that the engineers had been here twice before, were now here for the presentations, and would lead the class on a tour of the refinery in the future.

Sam had entered into his database all of the data collected from the students on the “Proposal Information 2012” sheets. He gave the engineers and me a printout of the results for each group presenting. The purpose of having this output was to compare these values with the values presented by each group.

The first group to give their presentation consisted of five members: 2 girls and 3 boys. Their initial PowerPoint page looked professionally done. All of the group members were dressed in typical everyday high school attire. The presentation began with one member explaining the problem they were given. They then pointed out some basic parameters of their primary design and their alternative design. They reported a cost estimate of $290,000 for completion of their primary design. The presentation, for which they had been given 15 minutes, was done in approximately four minutes.

After the first group completed their presentation, the refinery engineers asked some questions. First, clarification about some initial estimates was requested. Then the engineers asked the group what they felt was the hardest part of the project. The group replied that the hardest part was getting started. Because of their assigned areas of expertise, each group member brought different information to the group. This made communication between group members essential. The group explained that this communication piece was difficult.

When the engineers had finished asking their questions, Sam asked for some specifics about their results. At the end of the questions it had been a total of eight minutes since the group began their presentation. All group members had participated in the presentation. The presentation was basic and did not give a lot of details. As a listener I had difficulty following all that they were presenting to me. The information was given too fast for me to process it all.

The second group then stepped to the front of the room to give their presentation. This group had a total of four members: two girls and two boys. Three of the four group members were dressed in clothing suited for the workplace and the fourth group member was dressed in typical everyday high school attire. The group began their presentation by introducing each member. In this introduction they shared their fictitious educational background. One member then gave an overview of the project, including why a foundation was needed. The group explained that they had the option of making the foundation rectangular or circular in shape. One member presented the group's preferred solution. The PowerPoint contained a slide with a scale diagram of this solution. Another member did the same for the group's secondary design. During the presentation the group furnished the audience with results for the torque on the foundation and the vessel. They also gave results for soil pressure and explained why their design fell within the values of allowable pressure. One member then discussed the bolts the group had chosen. He referred to their deflection results. At the end, an estimated cost for their design was presented.

The PowerPoint slides for this group looked professionally done. The presentation included multiple numbers and equations and the group explained the reasoning for the equations and how they had come by their results. The presentation contained multiple diagrams that were drawn to scale. When the students were finished, the engineers asked this group some questions. "How did you decide between a square and a circular foundation?" The group responded that the decision was made based on ease of excavation and cost. The engineers then asked, "What calculations gave you the most difficulty?" The group indicated the deflection calculations were the most difficult. The presentation for this group had lasted approximately 10 minutes.

The third group was ready to begin their presentation. The group consisted of four members: three girls and one boy. Only the three girls were present in class today. The boy had a schedule conflict and as a result had just added his information to the PowerPoint. The presentation began with each group member introducing herself and giving her fictitious educational background. One member outlined the design problem they had been given. The group presented both their recommended and alternative solutions. The values the group presented for their solutions were different from the values calculated by Sam's database.

The engineers asked this group, "What was one thing you learned in this project?" The group responded that teamwork was a significant part of this project; different people had information about various parts of the project. The group manager indicated that organizing the group was a lot of work. Another member mentioned that she had to learn to work with people who were not necessarily her friends. When the presentation came to an end approximately nine minutes had lapsed.

The final group to present consisted of four members: three girls and one boy. The male student was not present due to a scheduling conflict. The members present were all similarly dressed in professional-looking outfits. Each group member was holding notecards. The presentation began with each group member introducing herself and providing her fictitious background. The backgrounds were somewhat silly but very creative. One group member then presented the design problem that was their task. She explained the need to design a foundation within the given constraints that would support a tower. The student who was absent was shown presenting his information in a video that had been imbedded into the PowerPoint. The group presented their two solutions; one solution had a circular base and the other solution had a square base. The group decided the square-foundation option was the best. The group presented all of their values and results. They stated that the design met all of the minimum safety factors that had been given. The final cost for the primary design was estimated to be $360,000. This was close to the value calculated by Sam's database, $375,000 (see Appendix E). At the end of the presentation the group displayed a diagram that showed the different layers of the foundation.

The engineers then asked questions. "With your recommended solution, how did you determine the diameter of the foundation?" The group responded that they started with the area of the base of the tank and then increased the size until it met the safety factor. The engineers then asked, "How did you know your spreadsheet calculations were correct?" The group said that for every type of result produced by the spreadsheet, they did a sample calculation using the calculator. If the two values matched they then expanded the spreadsheet to give the range of results needed. Finally the engineers wanted to know what was the most challenging part of the project? The response was that they worked with very complicated formulas. They felt they needed to double-check all of their values because the possibility of making a mistake was high. The group also indicated that it was challenging to work with all of the different people in their group. They had people who possessed different information and each member had his or her own different personality. The presentation ended after approximately 13 minutes.

When the last presentation was complete, Sam offered cookies and milk to the students in recognition of completing a difficult project. With their treats in hand, instead of drifting off into small groups, the class sat together as a large group and chatted. While the students were eating, Sam met with the two engineers. The engineers presented to Sam their results for the design of the same foundation on which the students had worked. Sam noticed that the large values of soil pressure calculated by the engineers were similar to the values determined by the groups. For other values, the engineers expressed some confusion as to where some of the numbers came from. There seemed to have been some confusion with the safety factor. One of the engineers said he would go back and double-check the values. The other engineer looked at the schematic of the foundation. He wondered why the sizes the groups had calculated were so small. They resolved to revisit the differences after the engineers had a chance to look through the proposals.

Day 12. (Monday, March 12)

This was the first day of a new trimester. Since the design project presentations, trimester grades had been calculated and a new schedule had been put into action. While this section of honors physics had many of the same students as during the first trimester, some of the students were previously in the other section of honors physics. The engineering teams that were in place during the previous trimester were no longer all together.

Sam began class by having students enter information in a new seating chart. Sam then asked the class for announcements. Brought up were the recent robotics, speech, and track team accomplishments. Sam then announced the schedule for the day, which included giving out trimester grades, returning the engineering projects, and doing some example problems. Sam called the students to his desk one at a time to show them their trimester grade.

Sam told the students that he was going to talk to them about the design project. He mentioned that the students would be going on a fieldtrip to visit the refinery in about a week and a half. He said that in the past the fieldtrip had been a wonderful experience. The plan was to have a number of different types of engineers, environmental, chemical, civil, etc., talk to the students. The engineers would go over what they determined was the "answer" to the design problem on which the students had worked. They would then talk about the results the students had obtained. The refinery would provide lunch for the students. After lunch the students would go on a tour of the refinery.

Sam explained to the class that the refinery did not generally allow high school aged students, or anyone for that matter, into the plant. It is a secure location, as required by federal regulations. Sam told the students that after the attacks of 9-11, the security at the refinery greatly increased. The year after the attack, the high school students were not allowed to visit. The following year the federal government gave permission for the high school students to once again visit. Sam explained that he would give a list of the students' names to the company; they would likely do a background check on each person. He told the students to imagine if something ever happened at the refinery. The result could shut down the 3-5 state area and the international airport as well. The students would need to bring photo identification with them on the day of the fieldtrip. A question was raised about a student who is a Russian citizen. Sam said he would need to check to see if there would be any issues with this student's admittance.

Sam engaged the class in a discussion about engineering. He emphasized that engineering was not always about building a foundation, as they did in class; engineers did all sorts of things. Sam told the students that the two engineers from the refinery had never worked on a foundation. Sam validated the students by saying that the project was challenging and it took a lot of time to get through. He pointed out that each person became a bit of an expert. He asked if it would take the students as long to build another foundation if given new information. The response was no, it would go much faster because they had done it once before. A person would become a bit of an expert in designing foundations. Sam told the students that the purpose of this project was for them to get an idea of what an engineer did. He assumed that when the students were first given the design problem, they had no idea how tough it would be to build a foundation. He reminded the students that this was a real-life project. This problem was not like the problems in the textbook where there is a one number answer. He indicated that in real life there might be more than one "right" answer.

Sam then shifted his focus from engineering to being an engineer. He asked the students if they now understood why engineers get paid so much. He said they work very hard. He told the students that they could have this type of job after earning a 4-year undergraduate degree. Engineers are not required to earn additional degrees. Sam compared this to psychology where people needed at least a master's degree if not a doctorate degree to get a job. With all of this education, psychologists are still paid less than engineers. Sam told the students he was not trying to talk them all into being engineers, but he wanted them to understand these options. Sam asked the students if any of them had siblings who were doing graduate work. One student indicated he had a sibling studying pharmacology. Sam explained that to become a pharmacist, a minimum of eight years of schooling was required. This is in comparison to engineering, which required only four years of schooling and both professions were paid similarly. Sam added a personal note indicating that an engineer's starting salary was equivalent to his own salary after teaching for 30+ years.

Sam then explained that many engineers advanced in their careers. Many did not stay in engineering jobs but instead moved into project management or to the business side of operations. Sam said it was important for people to understand the engineering side so they could become competent salespeople. Sam told the students that some of the engineers they would interact with during the fieldtrip would be engineers who no longer did engineering, but did other jobs.

Sam asked the class if anyone had parents who were project managers. He told the students they may have a better understanding of what their parent's job is like, or how they might feel at the end of a workday. He said this was true especially toward the end of a project when stress level runs high. Sam wrapped up his conversation by telling the students he hoped they enjoyed the project. He wanted them to realize all that they had made it through and accomplished. He hoped they grew.

Sam then switched gears for the class and moved to doing example problems. He told the students to get out their notebooks. He said that the new chapters were nine and ten: the topics in these chapters had been covered in the engineering design project. The topics included stress and strain. Sam related those ideas to the labs they did in preparation for the engineering project. He gave the students some equations and did example problems. Sam read the problem and then drew a diagram on the board. This particular problem had to do with the expansion of an object under pressure. When he had completed the problem he related it back to the engineering project, the part where they needed to be concerned about the pressure the pre-fractioning tank was exerting on the foundation. For the foundation, the pressure could not be too much or it would crack.

After the example problems, Sam handed out the results of the engineering projects. He told them about the output he had created using his database. The output was attached to each proposal. Sam told the students that the purpose of the database results were for him to know if the numbers the groups reported were on the right track. Students moved to the back tables to form their groups. As a group they looked through the grading. Some students blamed other group members when they saw where mistakes were made. The students asked questions such as, "Why was our foundation the wrong size?" One group asked about their pressure value. Sam told them he could not figure out exactly why their value was off. One student thought the results of her group's project were "sad." Three of the group members then argued about who did the parts correctly and who did not do as much work as the others.

Sam told the students that about three days before the end of the project he realized that he had misinterpreted the bolt numbers. He decided not to tell the students about the mistake, but instead to just have the students think about the bolts in the terms they were originally given. Sam said that this mistake was not their fault, but his own mistake. As a consequence, the values the students obtained were different that the actual values.

Sam communicated to me that he was happy with the reports. He told the students that they had done a nice job. The students then returned the reports to Sam and class was dismissed.

Day 13. (Wednesday, March 21)

This was the day Sam took the students from both of his honors physics sections on a field trip to the oil refinery. Present that day were 38 students: 15 male, 23 female, 34 white, and 4 students of color. The students loaded the buses at school at 9 a.m. The refinery paid for the transportation and for the lunch provided on this trip. The bus ride to the refinery lasted about 15 minutes. When the bus arrived at the refinery, each individual person had to be checked in, which involved photocopying his or her photo identification. When this process was complete all of the students were seated in a presentation room.

For the next hour and 45 minutes, the students were presented information from a number of different engineers. The first presentation was focused on refinery basics and was given by Jeff, who was a refinery strategic planner. Jeff told the students that he began working as a mechanical engineer. He asked the students what they wanted to know about engineering degrees. He showed them a chart with a list of different types of engineers and their starting salaries. Jeff then engaged the students in learning about U.S. refining industry facts. Students were given candy for correct answers. Part of this conversation shifted to a worldview on petroleum cost as it is related to supply and demand and connected to politics. Jeff talked about the crude oil imported to the U.S. from Canada via pipelines. Jeff explained that the refinery was built in 1954 to handle this type of crude oil from Canada. He said that the plant needed to be modified to match the properties of the crude currently being extracted. Jeff mentioned the potential environmental impact of oil sand mining and explained that in the mining areas the sand was replaced and new trees were planted.

Jeff walked the students through the process of oil refining that occurred at the plant. He told the students that the refinery processed 320,000 barrels of oil each day. The refinery received supply from both the north and the south. The product was distributed by pipeline, truck, and rail. This refinery alone produced 65% of the petroleum supply for three states. Jeff explained that they made an ultra low sulfur fuel. He then described the process of refining using density and boiling point. During the presentation the students appeared engaged in the topic. Sam pointed out to the students the different projects his classes had done as they came up in the presentation.

The next engineer to present had graduated from high school in 2004. Jason had a B.A. in mechanical engineering and was working at the refinery as a maintenance engineer. Jason asked the students what types of jobs engineers did. He told them that engineers could do just about anything. Jason explained to the students that for his job he did project and construction management. Jason described to the students what his job entailed: managing multiple aspects of a project, using technical and organizational skills, determining safety and environmental compliance, and planning a project schedule. Jason asked the students what the most important skill was for an engineer. The students gave many answers but Jason told them the most important was communication skills. Jason related this to the lives of the students, their need for communication and organization for school.

Jason told the students why he chose engineering as a career. He said engineering gave him a solid base on which to build his career. He also indicated that engineering allows possibilities for many job roles. Jason explained to the students that the company has an internship program. He said interns in this company work on real problems. He then talked about the benefits of doing any type of internship.

After a short break, another engineer talked to the students. Annie worked as an environmental engineer. She had both a B.S. and M.S. in civil engineering. She asked the group how many of the students wanted to be engineers. Approximately six students raised their hands. Annie asked these students what they knew about themselves that would fit well with engineering. Students responded problem solver, capable in math, good in science, and liked variety. Annie then told the students about the internship she did when in college and how it helped her decide what type of job she wanted to pursue. Annie mentioned that she now worked with the volunteer program at the plant.

Annie asked the students if they knew what an environmental engineer might do. The list created included: community advisory committee, regulators, work with the government, track waste, documentation for laws, regulatory interpretation, technical troubleshooting, planning buffer land, and helping the environment in the area around the plant. Annie told the students that she worked with air and waste. She worked on limiting benzene emission, limiting employee exposure, and leak monitoring. The students asked how many compounds had to be monitored and the response was approximately ¼ million. She asked the students if they had ever seen their override system in action. A flame at the top of one of the towers indicated the system was in use. She explained that the use of the override system had greatly decreased over the last decade. She told the students that the plant was leading the industry on environmental responsibility. Annie then talked about the use of technology at the plant. She mentioned that thermal imaging cameras were used to detect leaks. She showed a video of filling a car gas tank, taken with such a camera. The video revealed vapor escaping as the tank was filled. This lead to mention of the safety concerns related to using cell phones or smoking around gas stations.

Some of the students asked Annie what it was like to be a female in a male-dominated field. Annie responded that often she was the only female working on an otherwise all-male team. She also told the students that the company was actively recruiting females. Students then asked about the level of rigor present in college engineering courses. Annie responded that all engineering programs were rigorous but if students really applied themselves, they could make it through. Annie then mentioned her interest in the environment; she liked the aspect of her job that involved protecting it. Students asked about the number of hours Annie worked in a week and what level of flexibility there was in her work schedule. Annie said she works 40-50 hours per week and there was not much flexibility because the plant was ongoing in its production.

The final presenter of the morning was Chris who had earned a B.S. in chemical engineering. Chris talked through his career at the plant, which had included a number of different jobs. Chris explained that chemical engineers were a part of all departments at the plant. Chris said that currently he was working with technology in the plant, as a process engineer, and as an optimizer. He spoke about the creative portion of his job, seeing new ways to make things better or more efficient. He mentioned that in engineering safety must always be kept in mind. He indicated that his job came with a high level of satisfaction because the results of his work could be seen. One student asked what happened when a mistake was made. Chris responded that it depended on the mistake; there could be economic loss or a safety incident. He added that when consequences were higher, there were more checks and balances.

The morning presentations were then complete and the students were given a 40-minute break. During this time the people from the refinery provided lunch for everyone. Students were told that after lunch they would be given the opportunity to tour the refinery.

The group of students was split into two parts and each group was assigned a refinery engineer to lead their tour. The tour began in the central control room where the shift managers described the operating system. Students had an opportunity to listen to the operators explain what they were doing. The plant ran 24 hours a day and seven days a week cracking fuel. It was not easy to shut down the plant; the process took multiple days. Everything that happened in the plant was run from the computers in this room. The operators explained that most of them began working at the plant as an outside operator before they moved into the control room. Many of them had completed a two-year operator-training program. They each worked 12-hour shifts and their job provided them with a stable career.

The students then boarded the buses for a driving tour of the refinery. During the tour, the engineer explained the process that was taking place in each section. Students asked many questions, such as those that follow. What was the design function of the apparatus at which they were looking? What happened when there was severe weather such as a tornado? Why did the refinery have windsocks? What was the cost to build different portions of the refinery? How was the pressure contained within the system? Did anyone ever have to climb into the stacks?

A stop was made on the tour when they reached the actual pre-fractioning tank for which the students had designed a foundation. The students showed strong interest in looking at this structure in real life. All of the students moved to one side of the bus to get a better look. The students talked about shapes they used in their own designs, mostly rectangles and circles. They compared their shapes to the actual shape of the foundation, which was hexagonal. After seeing the size of the plant, the engineer told the students that he walked to most of his sites throughout the plant. As the tour came to an end, the engineer explained that one of the best parts of his job was that he was able to spend a lot of time outside.

When the tour was completed, the students were returned to the presentation room. The two engineers who had been working with the classes at their school were going to present the "winners." The engineers had taken a copy of each proposal after they were presented. They then took time to look through each proposal and determined to which team they would grant the bid.

The engineers began by explaining the scope of the project: design a foundation for a tower, calculate the expected tower deflection due to wind, specify bolt size and pattern, and provide a cost estimate for the instillation. There was also a bonus activity that involved calculating the thermal growth of the tower when it was filled with hot feed. The engineers walked through their own calculations and presented their solution. They then showed the students a picture of the actual foundation being installed.

The engineers explained their criteria for the selection of a winner. The first criterion was feasibility. Could it be built? Did the design fit within the constraints given? The second criterion was the accuracy of the results. Are the results close to optimal? The third criterion was related to the presentation and the report. Were the design and the cost clear? Was the presentation clear and understandable? Was the firm qualified for this type of work?

The engineers then announced the third place winners – Ferris Wheel Inc. They explained that the group showed a solid understanding of the constraints and the physical meaning of the equations. They also had a reasonable method for the thermal growth calculations. The second place winners were Engineers Under Pressure. The engineers explained that this group had excellent organization for their multiple iterations. Like the third place group they also showed a solid understanding of the constraints and the physical meaning of the equations. The first place winners were Prestige Worldwide Engineering. The engineers explained that this group's design was the closest to the refinery's proposal. The group had a great design and constructability analysis. They had used a hexagonal shape for their foundation. This shape had the benefits of an easier building of a form for the concrete pouring because straight boards could be used. However, the shape also optimized the circle-like shaping, which minimized size.

To close the day, the engineers then gave a "quiz" in which the students were asked to identify pieces of the plant from pictures. Sam then thanked the engineers for giving up an entire workday for the students. The students boarded the bus and returned to school.

Interviews.

Sam participated in two interviews for this project. He was interviewed previous to the engineering integration into his classroom and then after the conclusion of the engineering project. The first interview was 1 hour and 14 minutes in length and the second interview was 1 hour and 13 minutes in length.

What is engineering?

Sam defined engineering as the following,

> Engineering is solving a problem or developing a product using physics, essentially, and understanding physics. Although, you know how it is now in engineering, it isn't so much physics because you have a program that usually does it. But you need to understand the physics behind it or you can't solve the problems that come about with that solution, and that's the key.

Sam explained that he felt the focus on relationships between variables was very important. Engineers needed to understand different types of relationships such a direct, squared, inverse, or inverse squared. He added that "the engineer, I feel, needs to know and be able to solve these complex problems. They need to work together with other people well."

Preparation for teaching engineering.

When asked what type of background Sam had in engineering or in engineering education, he simply responded, "I have none." He explained that he began doing engineering projects in his high school physics classes about 23 years ago. At that time there was next to no engineering being done at the high school level. A local refinery that was hoping to send some of its engineers into local schools had contacted Sam. Sam went to an open meeting, which began his relationship with the refinery and was the impetus of doing engineering projects in his classroom.

Sam had college education in the areas of both chemistry and physics, but not engineering. However, Sam pointed out that "I'm a builder. I build cabinets and … I'm a person that builds stuff." Sam said he didn't realize engineering was an option until later, but he added that he was,

> one of those people in the basement when I was a kid, taking the motors apart. And I probably would have been an engineer in now-a-days but engineering wasn't even an option at Local State University in my day. And there were no engineering programs so I didn't even know what engineering was.

Asked how he had developed his understanding of engineering during his teaching career, Sam responded,

> Everything has basically been done on my own. I haven't done any classwork. I presented at several classes. You know, I have been asked to be a speaker at a number of things that are related to this [engineering projects in high school] because we have been, we've been written up in the paper, we've been on the news, and so on.

Sam added that his son had earned a degree in engineering and was now working for an engineering company. He said this gave him another perspective on what engineering was and what engineers do.

Addressing state standards.

Sam was asked about his understanding of where the new Minnesota State Science Standards related to engineering were placed in his high school's curriculum.

Sam answered that the engineering standards were met in his school's "Project Lead the Way" classes. These classes were offered through the Industrial Technology department and were not required for graduation. Sam relayed that currently "engineering is the big thing… [but] the administration thinks it's that course [Project Lead the Way] over there." With regard to his own classes he stated, "I know the engineering standards are placed in my class [honors physics]." Sam did not believe any other science classes were doing engineering projects. Sam then explained that his district had been working on a project where detailed course outlines were being matched to standards. Sam had done this for his physics courses. Sam indicated that he met most of the benchmarks in "The Practice of Engineering" in his honors physics course (benchmarks 9.1.2.1.1, 9.1.2.1.2, 9.1.2.2.1, 9.1.2.2.2). There was only one benchmark (9.1.2.1.3) that Sam said he did not cover in his honors physics course. This standard was related to the manufacturing, operation, maintenance, and disposal of engineered items (see Table 4.3).

Table 4.3

Sam's Implementation of "The Practice of Engineering" Benchmarks

Benchmark	Benchmark wording	Sam's implementation
9.1.2.1.1	Understand that engineering designs and products are often continually checked and critiqued for alternatives, risks, costs and benefits, so that subsequent designs are refined and improved.	Covered through implementation of foundation design project. "Well, of course we do that in honors, heavy into that."
9.1.2.1.2	Recognize that risk analysis is used to determine the potential positive and negative consequences of using a new technology or design, including the evaluation of causes and effects of failures.	Covered because the students had done multiple iterations of their design. The project included safety factors to minimize risk.
9.1.2.1.3	Explain and give examples of how, in the design of a device, engineers consider how it is to be manufactured, operated, maintained, replaced and disposed of.	Not covered – "Interesting, I don't remember that one. I don't know that one. I certainly am not doing that."
9.1.2.2.1	Identify a problem and the associated constraints on possible design solutions.	Covered with the implementation of the foundation design project
9.1.2.2.2	Develop possible solutions to an engineering problem and evaluate them using conceptual, physical and mathematical models to determine the extent to which the solutions meet the design specifications.	Covered because a mathematical model was produced and then tested in the foundation project

Note. Benchmarks from Minnesota Department of Education, 2009

Sam also mentioned that he met different engineering standards in his honors physics class compared to his general physics class. Regarding benchmark 9.1.2.1.1, related to design improvement, and benchmark 9.1.2.1.2, related to risk analysis, Sam stated that he met these benchmarks in his honors but not his general physics classes. Regarding benchmark 9.1.2.2.2, related to developing solutions to an engineering problem, Sam implied that he met this standard in his honors physics class. However, regarding his general physics class he said, "You know, I don't think in regular physics I do these. You know, I can say I do them, and I probably will say I do them when they ask me." Finally, regarding benchmark 9.1.2.2.1, related to identifying a problem and its related constraints, Sam felt he met this standard in both levels of his physics classes. He stated, "I think I do this in my regular [physics] class there, even in regular [in addition to honors]. We identify the problem and associated constraints and then we do possible solutions. So, I think I do that in a lot of labs. I mean that's kind of, that's the way we approach our lab, my lab in here. It just takes a lot longer to do it that way."

Sam believed that he met all but one of "The Practice of Engineering" benchmarks for the Minnesota State Science Standards in his honors physics class. However, while Sam felt he met some of "The Practice of Engineering" standards in his general physics class, he certainly met less in that class.

Influence of standards.

During the interview, Sam was asked his opinion on the effect of the recent Minnesota science standards. At the beginning of the first interview Sam stated, "Well, I wouldn't say that I have looked at the [engineering] standards and worried about it, but…" He continued, "That's been a minor point of my thing [engineering project]." However, later in the interview Sam explained more about his dealings with the latest Minnesota state standards.

Sam explained a process, called Eclipse, that his district was currently committed to putting into place. Sam described the process saying,

> Eclipse is a program that we [teachers in the district] are putting in all of our…, your course outline, detailed course outline, and then matching it to what standards, where it is covering what standards and then, and I have done all of that.

After mentioning that he had matched his course outline to the standards, he said,

> but it's not very important. I mean I have done it; I do it because I am told to do it. But it's all matched up in this class. In fact I am the only teacher in the school that's got it done.

Sam did not speak positively about the Eclipse program his district was implementing. In addition to matching his course outline to the standards, Sam had also written tests for each trimester that matched the standards. He said, "I have given them [standards based tests] once now and they've [the students] done terrible on them and, you know, it makes you feel like you haven't taught anything."

Sam clarified that he had matched both the curriculum for his regular and honors physics classes to the state physics standards. He admitted, "I don't think I'm testing the engineering standards." He explained that this was because he was giving the same test to both his regular and honors classes. Because he used the engineering project in his honors classes but not his regular classes he said, "I don't have the engineering standards covered very well in regular physics so it's not in there [the trimester exams] and that's why it's not in there." Sam explained, "I don't see why I need to write two tests because I have two different courses. I mean, I got enough problems getting the test to work…

It’s like everything else on this standards stuff. I mean, they [the state department] are not even sure what’s going to be on it [the state science test] yet and I’m supposed to write a [classroom] test for it.”

Sam gave his opinion about standards and the tests used to assess them. He indicated that his general belief was that he was not convinced that the latest standards were going to make a big difference. He was also not convinced that the standards, which he felt were pushing content, were not the best way to go. He said,

> Although once you get set into standards then you will have people trying to, teachers, especially teachers now-a-days, I feel bad for the young ones because they are being pressed so hard to accomplish these standards and if they don’t then their job is on the line, or their whatever is on the line.

Sam shared his frustration with testing standards. He said, “I don’t feel very positive about science [education] right now, where it’s going, at least in, from what I know.

Related specifically to the engineering standards, Sam was in favor of them. However, he commented honestly that he had been doing the engineering project for years because he felt it was a quality teaching strategy. He stated that he did the engineering project before the standards and now would do the project regardless of the existence of standards.

Student Assessment.

Previous to the implementation of the foundation engineering project, Sam explained how he intended to grade the project. “Well, for the first half of it, is traditional lab.” Sam asked the students to turn in three lab reports per team. One of the constants from their lab work was to be used in their design process. Sam explained that for the lab component of the project, "This is traditional grading." Sam said, "The grading for the, the proposal, the written up proposal, which all people have a part of, each expert is part of that, they get graded and that is one of their tests, one of their test grades." Sam continued to explain that the grading was both individual and team based. "There's points for the individual and there's points for the whole." Sam explained that with the students he compares the value of their final presentation as being equal to the value of one test during the term.

During the implementation of the foundation project Sam was observed collecting from each team, a folder containing the work that had been completed by each group member that day. Sam returned these folders to the groups the following day after making comments and assigning daily points. During class Sam told the students he was asking the students to turn in daily work because he wanted to help them, look for mistakes. To each group Sam gave a sheet titled "Proposal" which outlined the required portions for both the proposal and presentation for this project. Later Sam posted a list that included point values for each portion. As the project drew to a close, Sam asked each group to fill in values on a sheet titled "Problem 2012." He then input these values into a program that calculated the correct output values. At the end of the project, Sam provided these results to each group to judge the effectiveness of the spreadsheet model they had designed.

After the completion of the engineering project, Sam made a few comments about his grading practices. He mentioned that he had made many adjustments over the years he had been implementing this type of projects. The grading was based on daily work, lab work, proposal, and presentation. He said he did not start doing the daily evaluation piece "until probably 10-15 years ago." He explained he began this practice "to avoid parental issues [such as unfair group grading practices] because its nice to pull that [the daily grades] out when you've got a parent that's mad because their kid's … going to get an A- instead of an A."

Reflection on the project.

The current form of Sam's engineering design projects have required two decades of refinements. At the start of the relationship Sam has developed with the oil refinery, he was offered some engineers to walk around his classes and work with his students. At the time, Sam felt that the having the engineers present would be nice but that they would probably be "as much of a distraction as anything." Sam instead envisioned his students learning what engineering was and what engineers did. Sam made an initial proposal to the refinery suggesting the engineers help guide a project for the students where they were doing engineering themselves. The refinery agreed to work in this fashion and thus the engineering projects began in Sam's classroom.

Sam and the engineers worked together to present the students with a real-life engineering problem that had yet to be solved. The engineers visited the school and presented the design problem to the students. Sam recalled that during the first few years of implementation, the design project was much shorter than the current version, lasting four to five days. The projects were more conceptual and "we really did almost no math." Sam remembered the very first project involved moving a million pound vessel up the river to the installment site. In reality, this was a process that had already occurred at the refinery. The problem posed to the students was "how do you think they are going to get it [vessel] off the barge and up to the plant? And there is no, there's no truck, or something like that… you have to come up with some method. And to not sink the barge." Sam explained that during the first few years the students would "brainstorm in their group and decide on ideas of how to solve it and they would write that up." The students were asked to write a two-page report.

After doing these conceptually based projects for a few years, Sam developed the idea that the students should "do experiments, build the formulas they are going to use" in the design process. Since then, each year Sam determined the relationships the students would need to complete the project and then designed lab activities that allowed the students to build those equations. The students used these equations to mathematically calculate values needed to solve the overall design problem. Sam also decided it would be better if they worked on a project to which the refinery engineers had not yet determined a solution. Sam thought, "That'd be more fun." He felt that not knowing the solution at the start would allow for more creative thinking and would prevent him from guiding the students to the solution determined by the refinery. Sam agreed that this type of project was a lot more work but he believed "it was a lot of fun because I knew I, we were trying to solve something [that hadn't been done yet], and I still present it that way." During approximately 15-20 years the project grew into the current 5-week process.

On the evolution of the design project, Sam explained that he had added and removed pieces as he had gone along. He believed the project had "changed a lot." He said during one period he had each group write two papers but he "quit that just for the sheer work." He explained that after students completed their lab work Sam had them "write a lab report like you would in college." He said the reasoning for the lab report was to make the lab work more formal. The students needed to type their report and Sam suggested that doing that encouraged the students "to do everything carefully and correctly." Each student had to write his or her own lab report but the whole group worked together on one paper for the solution to the design problem. Sam said "but I quit that just because I got tired of correcting all those papers. And it always stretched it out so I almost had to go with six weeks… it's just too much time."

Sam admitted that during the last two school years the design projects he had worked on in class were not design problems for which the refinery did not have a solution. Engineers had already solved the projects and the product had been built. The reason for this was a time constraint for the engineers themselves. Sam wanted to continue doing new projects but the refinery engineers working with him preferred these already solved problems. New projects were more time intensive to work on than projects that had already been completed. To adjust, Sam still told the students the design project presented did not have a solution. In addition, Sam asked not to be told about the outcome while he was involved in the project with the students.

Each year Sam had worked on an engineering project with his honors physics classes. He said he had also done engineering projects in his general physics classes but "I haven't done it for a lot of years." He felt the projects were difficult for his general physics classes because it required the students to be self-motivated. He had found in his general physics classes that "People don't play their part." This was particularly destructive when each student was the expert in one area needed to complete the project. Sam explained that he had written some mini projects and used these instead in his general physics classes. Sam explained the mini project outline, "the engineers would present the problem, there would be a lab, … in going over the lab you would answer the problem." He said that the mini projects were short, intended to last three class periods, but allowed the students to experience "somewhat of the process."

When asked what changes he might make to the project for the following school year, Sam said that it depended on the refinery engineers. Even though he had worked with various other engineers in the past, he believed the two men who worked with him during this project would agree to come back the next year. He said that these two engineers were "more on the inclination to say, 'let's do one that we've already done so that we have, know the solution because it is just a lot easier for us.'" Sam said it was possible that they would choose a design problem that they had already worked on together and then "tweak it." He explained that he would probably say to the students, "we've done something like this in the past but there are some differences and, you know, there's some special problems in this one." Sam agreed that one benefit to doing a project where the product had already been build was that the students had the opportunity to see the result in real-life during the refinery tour.

During the fieldtrip there had been a presenter who brought in some connections between oil refining and politics. He spoke freely about his opinions on choices the President of the United States had made regarding oil pipelines. When asked about this presentation Sam explained that he had never heard such a political slant to one of the presentations in previous years. Sam said he talked to the students about this during class the day after the fieldtrip. He asked the students, "Well, where do you think he's coming from and what do you think it's about?" Sam explained to the students that their fieldtrip had come just a day or two after President "Obama said they were going to build a pipeline from Oklahoma down to Texas. They were going to accelerate the building of that." Sam asked the students, with this background on the new pipeline, "Now, why would he [the presenter] be upset? Let's think about it, you know, what's going on here?" Sam explained that the new pipeline would have economic impact for companies that owned refineries. Although not planned, Sam had ended up including politics and economics into the engineering project.

Teaching strategies/philosophy.

Sam shared some of his thoughts on his philosophy of teaching science and then about the strategies he uses in his teaching. Sam talked about his opinions on inquiry based versus standards based education. He said,

> I felt so good about science coming out [of college] as a teacher in the early 70s. You know, because it was inquiry, lab based kind of thing. And now it's content based and I don't see that that's going to solve, that's going to … I mean that's why we were so strong as a country. My opinion [is] that's why we were so strong as a country. We have people that were in this inquiry lab-based situation that came through there with that and they were really creative and solved problems. We're not the Japanese or the Chinese, broad term, where they like to take a thing and engineer it. But if you want to develop *new* things, anyway. I just think science, I just think science is, the process of science is being lost.

With regard to content, Sam explained, "I wouldn't push content at all, personally. I do content. I mean, we have to do content, that's a part of, you know you gotta [sic] do it but it's not, it's not where I think science is. Science isn't a bunch of facts."

Regarding the standards that Sam implied were forcing content he elaborated, "And the problem is we've got, in our society we're just going to push this further and further to where we get these people thinking that every time you say something it's a fact, and science doesn't, that's not what science is. He explained, "Science is process and a way to investigate things and our answers can change." He gave the following example, "You know, is there global warming? Well, yeah the fact I suppose is the measurements shows that, yes there is." However, Sam then asked, "Now what from there? What's the science?" He answered the question by saying, "The science is the process of studying that, trying to figure out what your conclusion is, but that could change. Twenty years from now, we'd be fine if it changed."

Regarding his philosophy on teaching science Sam concluded, "I feel really bad that we've lost that inquiry, be creative part, or we are losing it." He then suggested, "Now you could, I suppose you could kind of try to teach that content that way [inquiry based] but teaching that way. You don't get through nearly as much when you teach that way. I mean you, you really have to, you know, you have to sacrifice content when you are going to say, 'ok the student is going to learn through inquiry, or learn through investigation.'"

When Sam was asked what different teaching strategies he used during the engineering project compared to teaching other content or processes, he responded that his teaching strategies were not different in the two arenas. Sam explained, "I do a lot of lab work where I build the equations out. That's all the way through my coursework" including the engineering project. He said, "All my equations that we use in physics we always get from lab first, which has somewhat come out of this process [engineering process], rather than giving them an equation and then doing a lab with that equation." The one addition for the engineering project was that the students built equations and calculated constants during their lab work but then they had to use those to solve the engineering problem.

Related to students working together in his class Sam said, "I like teamwork. I like cooperative. I like them to help each other. You know, they work in groups of four in lab too…We are in lab, most every day, at least for part of the hour." While Sam explained that group work was a common occurrence in his class, he also clarified that the concept of having experts in each group was only put to use during the engineering project. During lab activities in the rest of the course he admitted that students worked together to collect data but that each student wrote their own paper. He compared this to the engineering project where students were dependent on others in their group in order to determine a solution. Sam explained that he gave each group member a specific role because "I'm trying to simulate the way a [sic] mini companies have to solve problems and that they have to be specialists in areas that handle certain parts of it." He explained that the students, "they have to work together and they each have their expertise. And you have to understand, kind of, what the other person is saying but you don't have to know all the details about that." Sam wanted the student to get a sense of how engineers, like his son, worked with others on a team to engineer a product.

Benefits and drawbacks of integrating engineering.

During the interview Sam talked about some of the benefits and drawbacks he had seen related to incorporating engineering into his physics classes. His overall view was that there was "great benefit" to putting engineering in his physics classes and that this outweighed the drawbacks. This was why he had done engineering projects in his classes for 23 years. He admitted that during that time he was asked by both parents and administration to justify the project and its importance. He had stood his ground and was able to convince others of the value of what he was implementing.

The most challenging drawback that Sam had faced was justifying the use of multiple weeks of class time to work through the design project. There was a trade off in the amount of material that was covered during a school year when time was spent doing engineering design.

Sam explained that the time used for engineering reduced the amount of physics content he was able to cover in a year. Commenting on a general view he said, "Teachers, physics teachers particularly, I think are, from my perspective, really focused on content and they don't feel they have time to do anything else, because we can't get far enough in our book otherwise."

Sam responded to the criticism of not covering enough content by talking about what he believed students should learn. He said, "In physics, it's how you solve a problem [that] is way more important than the content." Sam explained his view that "once you get about half way through [the textbook] they [the students] can probably do any chapter in there, if they're good I mean." Sam said that for him, "it's never been a problem giving up content… I never give up understanding for content." Sam supported his own belief by recalling that professors he had worked with at the local university had stated that they preferred students in their physics program who were able to solve problems compared to students who had been through programs that had covered a large volume of content. Sam believed that students "won't remember the content anyway but they may remember the process … and have that strength of solution." Sam was convinced that learning the process of solving problems was more valuable for the students than covering as much content as possible.

Sam realized that his view on process versus content was not aligned with the current legislative mandates where learning was being judged on the results of state tests. In terms of aligning with state standards and testing, Sam understood that his engineering projects were not geared towards pushing students to earn the highest test scores. Sam understood that his engineering projects closely aligned with the state standards on engineering. However, Sam believed at the current time that even though engineering was a part of the science standards, the state was not prepared to test students on it. In relation to standardized tests for engineering he wondered, "how do you test it? You can't test this traditionally." Sam showed frustration in aligning his curriculum with state standards and preparing his students for potential state tests. He shared that even though he inquired, he was not able to determine how the engineering standards were to be assessed. Regarding his communication with the state department of education he said, "but they won't even tell you [how the standards are going to be tested]. When I contacted them last year, I said, 'Well you know I can't really do this without knowing how you're really going to test on this.' 'Well, we don't have the test. We are working on that. We are not going to probably have it for a while.' And that's what I was told."

Another drawback Sam saw related to his engineering project was that it did not work well for students with a large range of abilities. Sam was confident with the design project's benefit in his honors physics classes. However, over the years Sam had gone back and forth about the value of these types of projects in his regular physics classes.

Sam said the difference came from a variance in commitment level and work habits. He believed that "You really need self-motivated people to take on this complex thing for a length of time because it takes them about four to six weeks of time to do this. And, you know, the regular student doesn't always keep that focus for that long."

Sam was sensitive about students being graded on group work they did in his classes. While the students worked in groups to do lab activities frequently, each student was asked to write their own papers on which they were assessed. With the engineering design project, the students were truly working as a team and were assessed together as a team. In relation to interdependence of students for their grades Sam said, "I always shy away from that anyway generally in class because you get a lot of problems with group work." As a result, for the engineering project Sam explained, "I do a lot of those things you saw to try to make them feel comfortable [working in a group], that everyone's being held accountable." Sam said, "It helps when you're in honors physics because they're all pretty hard workers anyway. You get into a lot more trouble when you're into regular physics because there you got people that just want to sit there. You do group work and they're just going to sit there for three weeks." "And then you get the one kid who is really responsible and they're just killing themselves trying to keep up." This work equity issue was one of the difficulties Sam had encountered in doing his design project.

Sam had received pressure from some parents and administration to change the honors physics class to an Advanced Placement (AP) physics class. Sam explained that he could not teach a class in which the entire AP curriculum was addressed and the engineering project was implemented, due to time constraints. AP courses were important to the school community. The school had been given an award based how many students had participated in AP classes. When asked why he thought parents wanted their kids to have AP classes, Sam responded, “They think they are going to save money.” Sam said at parent-teacher conferences parents often told him about all of the AP classes their child was in and how much it was going to save them. Sam commented, “I want to tell them that its probably not, but I quit doing that because nobody will listen to me.” Sam did understand that the very top students may advance their college careers with AP credits but for the vast majority of the students in AP classes the end result did not shorten their college career. Sam pointed out that students had to score appropriately on the AP tests and then the college of their choice had to agree to take the credits. The school had received a lot of recognition regarding the engineering project and Sam believed this was the reason he had not been forced to implement an AP curriculum.

Many of the students in Sam’s honors physics classes had expressed interest in becoming an engineer. While this was the case, many of the students “have no clue what that [being an engineer] means.” Sam understood that engineering was one of the main avenues a person could choose with a physics background. He explained, “My whole goal has just been for students to understand what they can do with it [engineering] and what it means to be one.” Sam believed that the best way to understand what an engineer does was to do some engineering. Sam said “By the time they are done with this project they know what it means [to be an engineer]. And some of them will go ‘god, I thought I wanted to be an engineer but I don’t want to be.’ And I said that’s some really good information.” Sam understood that many students planned to study engineering, but not knowing what it really was led them to drop out of a college program after just one semester. Sam knew that his program was beneficial because they had “an awful lot of our students go into engineering.”

During the most recent parent-teacher conferences Sam said there were three honors physics parents “that made a special trip to thank me for doing, or thank the school for doing the engineering project because it had changed what their son or daughter thought they wanted to do and how it had opened their eyes as to what it was. And they were so happy that that had happened.” Sam commented that many of his students who had this experience had gone into engineering.

Sam conveyed the need to understand engineering by saying “the goal is to have more engineers.” He believed he could help students comprehend more about what an engineer does. He felt that at the end of the design project that “they [his students] understand how complex these problems are” and that they “understand why engineers are paid a lot of money.” Sam explained that he had about 45 honors physics students in a class of approximately 300 students. He knew that only a portion of his students would become engineers. At the beginning of the school year he encouraged any of his regular physics students who were thinking about going into engineering to switch into the honors level physics class so they could have the experience of working on the design project. Sam said, that fall he had moved about four or five students from the regular to the honors level.

In addition to helping students understand what engineering is, Sam also wanted his students to understand “that [being] an engineer is a[n] avenue to just about anything you want to do in industry.” He said, “If you want to go into business, you’d be much better off getting an engineering degree than going and getting a business degree because you'll get a job and then you'll have an avenue to [business]." "You'll do a couple of years of engineering and then you'll end up going in the business side and you'll go sell stuff or you'll do whatever and you'll never do any more engineering but you'll be, you understand the engineering so now you can be involved in the product and development. It allows you to be just about anything you want to be in a company." Sam backed up his statement by talking about engineers he had worked with at the refinery. Only a handful of the engineers were still doing traditional engineering jobs whereas most of them had moved on to other types of jobs in the company.

While Sam had shared benefits of the project for students who were interested in engineering, he also saw benefits for the students who were not interested. He said, "I think its great for them to know how, what engineers do and what companies do because … they could, even though they don't think they are going to be, they could end up in something very similar." For students with career goals in the humanities areas he felt they should "know just what that [engineering] means, what that part of our economy" is based upon. In addition Sam felt that engineering skills transferred to many places because engineers "are problem solvers and you need that no matter where you are." He also felt that the project had the benefit of all his students to become more "comfortable with failure because a lot of smart students are not comfortable with failure in this country." He saw benefits of the project for all of his students.

One last benefit of the engineering project Sam touched on was about his own involvement. Even though the project was time intensive for him Sam said, "I know I really enjoy doing this a lot." He elaborated saying, "mainly because [each year] it's a new problem for me." Sam enjoyed new challenges. He explained that the project, "It's challenging for me so I have to learn a lot of stuff every year. I enjoy doing that." He understood that not everyone would feel this way, considering all of the time put into orchestrating a project like his.

Summary of Chapter 4

In this chapter each of the three individual cases were described in detail. Each case contained an overview of the engineering project implemented by the teacher, an outline of the classrooms observations that were made, and details about the interviews conducted with each of the three participating teachers. In Chapter 5, a cross-case analysis will be provided that makes comparisons among the three cases detailed in Chapter 4.

Chapter 5: Cross Case Analysis

In Chapter 4, the details of the observations and interviews of each participant were presented. An overview of each participant's background and situation is given in Table 5.1. In the current chapter a cross-case analysis is offered. The *Framework for a Quality K-12 Engineering Education* (Moore, Glancy et al., 2013), described in Chapter 2, provided structure for the cross-case analysis. The framework includes the following twelve indicators: Processes of Design (POD), which includes the three sub-indicators Problem and Background (POD-PB), Plan and Implement (POD-PI), and Test and Evaluate (POD-TE); Apply Science, Engineering, Mathematics Knowledge (SEM); Engineering Thinking (EThink); Conceptions of Engineers and Engineering (CEE); Engineering Tools, Techniques, and Processes (ETool); Issues, Solutions, and Impacts (ISI); Ethics; Teamwork (Team); and Communication Related to Engineering (Comm-Engr). The presentation of the cross-case analysis is organized using these 12 indicators (Moore, Glancy et al., 2013). Following this is a section on the cross-case analysis of the student assessment done for each of the projects.

Table 5.1

Overview of School Settings and Participants

Participant	School location	Type of school	School population	Free/reduced lunch	Students of color	Teaching experience	Educational background	Class observed	Engineering project
Marvin	Outer-ring suburb	Public charter high school grades 9-12	173	35%	9%	3 years	B.S. in physics M.Ed. in progress in 9-12 physics teaching	High school physics	Egg drop container
Sally	Middle-ring suburb	Public high school grades 9-12	1916	76%	62%	6 years	B.S. in physics M.Ed in 9-12 physics teaching	General physics	Car crumple zone
Sam	Inner-ring suburb	Public high school grades 9-12	1076	29%	27%	36 years	B.S. in chemistry M.Ed. in physics teaching	Honors physics	Pre-fractionation tower foundation

Indications of Quality K-12 Engineering within Engineering Design Projects

This study utilized the *Framework for a Quality K-12 Engineering Education* as a means to analyze the engineering design projects of the teacher participants. Table 5.2 provides an overview of the extent for which each of the projects addressed each of the indicators. The bold indicators are required for every engineering design project. The following subsections provide detail for each of the indicators.

Table 5.2

Overview of Analysis of Three Cases Using the Framework for a Quality K-12 Engineering Education

Indicator	Marvin	Sally	Sam
POD	✔	✔	✔+
POD-PB	✔	✔+	✔+
POD-PI	✔	✔	✔+
POD-TE	✔−	✔+	✔
SEM	✔−	✔+	✔+
EThink	✔−	✔	✔+
CEE	✔−	✔−	✔
Etool	✔−	✔	✔+
ISI	✔−	✔−	✔−
Ethics	✔−	✔−	✔−
Team	✔−	✔−	✔+
Comm-Engr	✔−	✔	✔+

Note. Required indicators are shown in boldface.
✔+ = high quality; ✔ = moderate quality;
✔− = weak quality

Process of Design (POD).

The POD indicator refers to the use of engineering design processes in the classroom. The *Framework for a Quality K-12 Engineering Education* separates the engineering design process into three fundamental parts: "Problem and Background," “Plan and Implement,” and “Test and Evaluate.” The paragraphs that follow contain analysis of the process of design introduced in the three cases. Evidence will be provided indicating how the teachers implemented the process of design in their engineering projects.

Each of the three teachers used an engineering design cycle to structure their project. All of the projects included multiple iterations: two for the egg drop, three for the crumple zone, and numerous iterations for the foundation. The design cycle was indirectly taught in Marvin’s and Sam’s classrooms, whereas Sally directly taught the steps of the design cycle to her students. Regarding the direct teaching of the design cycle, Marvin said he did not teach this to his physics students because in physics, he said; the process was “just more open.” During the egg drop project, Marvin’s students were taught the design process indirectly by working through the progression during their project. Similarly, Sam did not teach his students a specific design cycle. He explained this by saying, “It’s not an engineering class.” He stated, “You know, we are just solving a problem.” Sam believed that the students learned the engineering design cycle, “because they are learning how to do it, just by doing it.”

By contrast, Sally taught and used a visual representation of a design cycle in her crumple zone project. She showed the students this diagram multiple times during the project and used it to walk the students through the design process for the crumple zones. While all three projects allowed the students to apply the design process, only Sally explicitly taught the process of design. The direct use and discussion of the design cycle allows students to learn “the core elements of engineering design processes” (Moore, Glancy et al., 2013, p. 6).

Evidence exists to show that the teachers were very successful with the implementation of the POD indicator, as well as there being some room for improvement. All three of the teachers were successful in providing an opportunity for the students to apply the design process in a format that was iterative. However, Sam and Marvin could have improved their projects by directly teaching the students the engineering design process so that they could learn the core elements. Related to the projects being set in a realistic situation, Sam was very successful because he implemented an actual engineering project. However, Marvin could have improved upon this by making a stronger connection between the vertical egg drop and car crashes.

Problem and Background (POD-PB).

The POD-PB sub-indicator calls for the determination of a problem and attainment of the appropriate background knowledge needed to generate possible solutions to the problem. All three of the teachers identified and provided a clear design problem that engaged the students in the design process. Marvin's class was challenged to design a protective container for a raw egg. The container and egg were likened to a car and its driver. The container needed to land the egg safely after being dropped from the second floor balcony at the school. Sally's class was asked to design a scaled down crumple zone for the front end of a cart. The crumple zone was to reduce the amount of force imparted on the fictitious occupants of the cart when it crashed into a wall. Sam's class was asked to design a foundation for a vacuum pre-fractionation tower to be installed at a local oil refinery. While Marvin's and Sally's design problems were realistic, Sam's problem was an actual engineering problem that had been presented to the class by two oil refinery engineers.

Each of the three teachers put their engineering design projects into a real-life context so that the students could identify the need for engineering solutions. Marvin made a basic connection between car crashes and the egg drop containers. He showed videos of car crashes and discussed the reasons why occupants walked away safely from a crash. Both protecting the egg and keeping a car occupant safe required the same understanding that increasing the time for the crash resulted in a reduction of the force on the occupant. However, there was a disconnect in that cars tend to crash into vertical objects instead of hitting the horizontal floor, as with the egg container. Sally made a stronger connection between the crumple zone engineering project and real-life car crashes. Sally asked the students how they would determine if a car was safe enough. She showed examples and results of crash tests and discussed the reasoning for the success or failure of a particular design. Marvin's and Sally's projects connected to similar science concepts. However, unlike Marvin's project, Sally's project resembled, in miniature size, the real-life context of car crashes. Sam's foundation design project did not need to be put into a real-life context because it was an actual engineering design problem. The students were to design plans for the actual foundation, not a modified or smaller version.

All of the engineering design problems came with constraints. The primary constraint for Marvin's and Sally's projects was the materials available for the design. The students were given a list and quantity of materials available for the building of their prototype. Marvin introduced an additional constraint; "The egg must be able to 'breathe,'" meaning the observer must be able to see some part of the egg when it was in the container. In addition to the materials constraints, Sally introduced an additional constraint that limited the dimensions of the crumple zone. Similar to Marvin's and Sally's projects, Sam's foundation project gave the students a list of physical materials that could be utilized, which included the size. In addition, the students had to take environmental factors, such as wind speed, into consideration. Unlike the constraints for Marvin's and Sally's project, as well as the limitation of types of materials and the environmental constraints, Sam's students also had to consider cost. There was no upper limit placed on the cost of installing the foundation but students were asked to design the most cost-effective foundation.

All three teachers provided opportunities for students to gain the necessary background knowledge related to the design problem. Prior to the design project, both Marvin and Sally taught a unit focused on the applicable content. For Marvin this content was momentum and impulse; for Sally the content was force and acceleration. At the beginning of the engineering design project both Marvin and Sally used direct instruction, such as using car crash videos, to reinforce the content previously learned. Sally also built upon her previous unit that explored the concept of g-forces related to amusement park rides. Similarly, Sam placed his engineering design project following the completion of multiple physics units that prepared the students with the necessary knowledge of mechanics. Moreover, the first two weeks of the project involved students conducting additional lab activities to give them the opportunity to learn new physics content "that they'll need for this particular [engineering] question."

Related to the POD-PB sub-indicator, all three of the teachers identified the engineering problem for their students. None of the projects allowed for the students to formulate their own problem. Although this might have been difficult for the three projects observed, including this in some part of the students' engineering education would meet a different aspect of the POD-PB indicator. Additionally for the POD-PB indicator, Sam was the only teacher who included learning activities to gain necessary background knowledge. For his project the students not only did lab activities before beginning their design, but the results of those activities became imbedded in their mathematical model. Marvin and Sally could have improved their projects by adding a lab activity component, perhaps related to the properties of materials allowed for use in the prototypes. If the students had background information about the properties of the materials available, they may have been able to make more scientifically based decisions about what materials would be most valuable for their design.

Plan and Implement (POD-PI).

The POD-PI sub-indicator includes the students developing a plan for their engineering design and then producing a product. All three of the teachers provided time and encouraged the creation of a reasonable plan for a design solution. Marvin and Sally each started the brainstorming process with their entire class. They then asked the students to work together in teams to develop multiple solution ideas, evaluate the ideas, and decide on a plan. In Marvin's class, students were heard discussing the drawbacks and benefits of using a triangular shape, stating that it was "a structurally strong shape." In Sally's class, students talked about the pros and cons of the allowed building materials. One group decided that the cardboard available was too rigid for their design. Both teachers asked the students to draw their proposed solution on paper.

Sam also asked his students to develop a plan for their foundation design but provided guidance for this more elaborate design problem. The students began by completing the “Problem Planning” sheet in which they were asked to describe their end product and then make a list of all “the things you will need to determine to solve this problem.” Unlike Marvin’s and Sally’s design projects, which allowed the students to start with brainstorming, Sam’s project gave more structure to the steps required for the students to design their mathematical model, including a spreadsheet. However, like Marvin’s and Sally’s projects, Sam’s project asked that the students evaluate possible solutions, as seen by the requirement to design both a primary and an alternate solution.

All three projects required that the students make trade-offs in their design, related to the constraints. Marvin’s and Sally’s projects required the students to make trade-offs with the amount of materials used. In the egg drop project, the students could use any combination of the materials allowed. However, regardless of which materials or how many pieces of a given material were used, the students could not completely cover the egg with supplies. As the amount of supplies used increased, it was more difficult to leave portions of the egg exposed. In the crumple zone project, the students were limited in the amount of tape available but could use any amount of the other materials provided. However, regardless of how much cardboard or paper the students used in the design, the students could only design their crumple zone to a given size. The greater the amount of materials used, the more difficult it was to design the crumple zone within the allowable size.

The foundation project also required that the students judge the relative importance of the constraints. Unlike Marvin’s and Sally’s projects, Sam’s students did not have a limit on the amount of material they could use for the foundation. They did, however, have to design their solution to withstand the environmental setting in which the foundation was to be built. The trade-off the students needed to make was between the design parameters and the cost. For every portion of the solution design, the cost was a factor.

The three projects required that the students create some type of product. In Marvin's and Sally's projects the students built a prototype of their solution for each of the iterations. Marvin explained that for the egg drop project, the planning process and the prototype building process were not completely separate. He said that regardless of the stage in planning, once the students obtained their materials, "they want to get started building." He stated, "With the materials, ideas came." Sally also left room for the modification of plans during the building process. This is evident because the students were asked to draw an initial plan of the crumple zone and then to also draw the actual design they built. The result for both of these projects was a physical prototype of the design solution.

In Sam's project, the students did not build a prototype, but instead created a mathematical computer model. The purpose of this model was to test different design parameters in order to determine a primary and an alternative plan for the building of the foundation. The spreadsheet model created was extensive. Sam explained that the foundation project was "really only solvable by spreadsheet." He said, "It's too complex … to try to solve it any other way." All three teachers required that the students produce some type of product: Marvin and Sally required a physical prototype and Sam required a mathematical model.

The three teachers also had success, but left room for improvement, with the POD-PI sub-indicator. In each of the projects, the students were observed brainstorming ideas for possible solutions. However, the process through which students developed multiple solution possibilities and evaluated those possibilities was difficult for those outside of the group, such as the teacher or an observer, to follow. An improvement for all three of the projects would be to make this process more transparent to others by requiring that the students produce diagrams of possible solutions and write about the pros and cons of each solution. In this way, the students could explain how they determined the trade-offs they put into their design solution.

Test and Evaluate (POD-TE).

The final sub-indicator of POD is POD-TE, which includes the testing of solutions and the evaluation of those test results. All three of the projects provided the opportunity for the students to test their products. To do this, all of the students conducted experiments that had been designed for them. In both Marvin's and Sally's projects, the experiments were physical. For Marvin, the test was the simple dropping of the egg container from the balcony. For Sally, the test involved attaching the crumple zone to a cart and then crashing it into a wall. Sam's project did not involve a physical experiment but instead required the students to input values into their computer model, which then gave an output.

All of the tests produced data for the students. The level of analysis required of the data varied greatly among the projects. Marvin's project did not require analysis of the data produced. The egg drop provided the simplest result, the egg either cracked or it didn't. Sam's and Sally's projects required analysis of the testing results. The foundation mathematical model produced multiple pieces of data that related to the various parameters of the design. The analysis required by the students was to look at the results of the trade-offs they had made. For example, perhaps the output showed the least expensive solution but this solution did not quite meet the safety factors required. Sally's project produced a video file for the data as well as a mass and cart length measurement. Unlike Marvin's and Sam's projects, this data had to be analyzed both graphically and numerically. The students used a computer program to digitize the video and then create a graph of the motion. The best-fit curve of the graph provided constant values for a quadratic equation that allowed the students to calculate the force on the cart. The process was a bit different for the last iteration when the students used an accelerometer to measure the deceleration of the cart. Of the three projects, Sally's project required data analysis that related directly to the physics content being incorporated.

All three teachers asked their students to evaluate the results they obtained from testing their product. For Marvin's project the students did this in writing. The students were asked to answer these two questions. "What worked well last time and why? What didn't work and why?" For Sally's and Sam's projects the students were not required to write about their evaluation. Sally explained, "At the end of each design, if they were doing it correctly, they were, like, these are the good parts to this one. These are the not good parts." In Sam's projects the students needed to weigh the different output values and make decisions about what could be improved.

The students completing any one of the three projects were asked to use the evaluation they had done of their first test as feedback. This feedback was then used in a redesign of the product. In each project the students were to redesign their product at least one time in an attempt to better meet the design criteria. Evidence that this was happening can be seen in the results of the product tests for Marvin's and Sally's classes.

Marvin noted that the containers built in the second iteration of the egg drop were more successful than had those in the first iteration. The students realized that many failures came from the containers tipping over after impact, and for the second iteration measures were designed into the containers to avoid this. For the crumple zones, this evolution of the designs was evident by the increase in accordion folding of the materials. The students were asked to graph the force values obtained for each test to see the trend from each redesign. For Sam's foundation project, the use of feedback in the redesign was not as obvious. The students were able to complete as many iterations of their design as time allowed. When the spreadsheet produced an output, each group had to determine what changes could be made to determine the lowest cost of installation while still meeting all of the other constraints. All three of the projects allowed for the students to use feedback from their evaluation to improve upon their designs, although the process they implemented was not necessarily transparent to others.

Related to the POD-TE sub-indicator, each of the projects was successful at testing the product and evaluating the results. Although all the students tested their own products, they used a test designed by their teacher. An addition to the engineering education of these students could be a project in which the students designed the experiments used for testing. While all three projects required the students to collect data, Marvin's project did not require any analysis of this data. Adding data analysis, such as investigating a slow motion video of the crash, would improve the evaluation process for each prototype and make a stronger connection to the science content.

All three of the design projects met the POD indicator. Each project allowed the students to work through a design process, although Sally was the only teacher who explicitly discussed the design cycle process. The three teachers met the POD-PB sub-indicator by having a defined engineering problem that included constraints and was set in a real-world context. The teachers all provided opportunities for the students to gain background science knowledge before beginning to solve the design problem. All three teachers also met the POD-PI sub-indicator. The teachers facilitated students developing reasonable solutions for the design problems. The students had to take into consideration trade-offs between the various design constraints. Each project required the students to produce a product: a prototype for Marvin's and Sally's projects and a mathematical model for Sam's project. Finally, all three of the design projects met the POD-TE sub-indicator. The students performed experiments to test their products: the egg drop containers were dropped, the crumple zones were crashed, and the mathematical model was run. The testing of each product produced some data. Marvin's project did not require analysis of this data but Sally's and Sam's projects did require analysis. The final step in each project was for the students to evaluate the product they had produced. Students were asked to determine the portions of their designs that worked as planned and those that had failed. Overall, the design projects presented by each of the three teachers met each section of the POD indicator.

Apply Science, Engineering, Mathematics Knowledge (SEM).

The SEM indicator places importance on the interdisciplinary nature of engineering education at the K-12 level. Engineering requires the application of science, mathematics, and engineering knowledge. The engineering projects observed took place within the context of a physics classroom in which the students studied science concepts through an engineering design problem. The paragraphs that follow will provide evidence of how these three design projects required the integration of science knowledge in an engineering context. The integration of mathematical knowledge in an engineering context will not be addressed because the classes observed were specifically science classes. The integration of science knowledge will be investigated using the Minnesota Academic Standards in Science as an outline (Minnesota Department of Education, 2009).

All three of the teachers outlined their engineering projects within the context of science knowledge. Marvin connected the egg drop project to the topics of momentum and impulse. Sally connected the crumple zone project to the topics of force and acceleration. Sam connected the foundation project primarily to the concept of force. Each of the teachers implemented their engineering project following a unit of study on the applicable science concepts. As a result, the students were able to apply the science they had learned, to an engineering context. The design of each project dictated how much science content was required in order to develop an acceptable solution. Although all three projects were connected to science content, that does not guarantee that every student made this connection.

The egg drop and the crumple zone projects both addressed the benchmark 9P.1.3.3.1, which related to changes in society from advances in physics. In both projects, the teachers used the context of car crashes. They each showed videos of car crash tests that highlighted some of the results of the safety equipment being put to use. Both teachers focused on the idea of keeping the occupants of their vehicles safe during a crash. The students were able to identify the societal impact of car crashes through the context of the engineering design problem.

The foundation project did not directly address the same benchmark related to changes in society but instead addressed benchmark 9P.1.3.4.1 related to significant figures. The teaching of significant figures had been part of the physics curriculum earlier in the year. On more than one occasion during the project Sam referred to significant figures. He talked about estimating costs by using round numbers. He explained that when talking about large sums of money, the students did not need to estimate to the dollar. He told them they should "think significant figures." Neither Marvin's nor Sally's projects used the concept of significant figures.

All three of the engineering design projects addressed the benchmark 9P.2.2.1.2, related to forces and momentum. The units that each teacher taught previous to the projects focused on this content. The project then allowed the students to apply the science concepts they had already learned to the engineering problem. Marvin's project focused on momentum, with an extension made to the concept of impulse. During his instruction, Marvin frequently used the non-scientific term "give" to represent the concept of impulse. Sally's project, although using the same car crash context as Marvin's project, focused on the concepts of force and acceleration. The students were ultimately using the equation from Newton's second law, F=ma, to determine the force imparted on the cart. Sam's project also focused on the topic of forces. In designing the foundation, the students had to take into account all of the forces affecting both the foundation and the bolts that held the tower to the foundation. The project also contained other science content such as torque, pressure, elasticity, tensile strength, density, stress, and strain, many of which use the underlying concept of force. With three different design problems presented, all of the teachers focused their work on the same content benchmark related to force and momentum. However, each teacher focused on a different aspect of the benchmark and there were varying degrees to which the science content was implemented.

All three of the engineering design projects used the application of science knowledge in an engineering context. The egg drop and crumple zone projects addressed the benchmark related to the changes in society caused by developments in physics. The foundation project alone addressed the benchmark related to significant figures. It is interesting to note that with three rather different design projects, three focused on the same physics content standard, which is related to forces and momentum. While Marvin's and Sally's projects were set within the context of car crashes, Marvin's project focused on momentum and impulse and Sally's project focused on force and acceleration. With Sally's and Sam's projects, the context was different: a crumple zone versus a foundation. The same concept of force was used in both projects. Although these cases represent a very small sample, it is interesting to note that each one centered on concepts from the same content benchmark.

Evidence exists to show that the teachers were successful with the implementation of the SEM indicator, as well as there being some room for improvement. Each of the teachers required that students apply science content to solve their engineering problem. This was particularly true for Sam's foundation project. As a bonus in this project the students not only needed to apply science concepts, but mathematics concepts as well. This was apparent because the students were required to attach to their report example calculations for the formation of their mathematical model. As a group, the students had to understand the science and mathematics in order to produce their model. The application of science content was also apparent in Sally's project and again there was the bonus of including mathematical content. However, because Sally went through an example calculation with the students, it was possible that the students could have followed the steps from the example and not really understood the related science content. To improve her project, Sally could have challenged the students to do their analysis without the benefit of a step-by-step example. Marvin's project has the most room for improvement in this area. While the students were encouraged to use science concepts in the design of their containers, no mathematical concepts were included, even for analysis. It is possible that the students could have produced their design solutions by simply using trial and error. Marvin could have adjusted the project so that application of the science content was more central. He could have done this by asking the students to explain how they applied the science content of momentum and impulse during their design and evaluation phases. The addition of an explanation of the application of the science content may have been of value for both Sally and Sam as well.

Engineering Thinking (EThink).

The EThink indicator focuses on the idea that K-12 students should learn to think like practicing engineers. The first portion of the indicator specifies that students should be reflective thinkers who can learn from failures to ultimately lead to better solutions. All three design projects were devised to facilitate this reflective thinking. This is evident because each design project included more than one iteration. The students were expected to reflect on their results and apply this new thinking to their next design solution. Multiple iterations allowed the students to experience failure, gave them time to reflect on this failure, and then provided the opportunity to apply what was learned to the redesign of a better product. In the egg drop project, Marvin asked the students to complete two iterations. This was the first year Marvin had added the second iteration to this project. In the crumple zone project, Sally originally asked the students to complete a total of four iterations. However, due to time constraints Sally modified this to three iterations once the project was in process. In the foundation project, Sam did not specify the number of iterations required. At a minimum, the students were required to do two iterations because they were asked to develop a preferred and an alternative solution. Sam explained how the students used their spreadsheet models to run multiple iterations to determine an optimal solution. He said, "You put [into the spreadsheet] your information from the tower and then all of the variables that you can have change. We say, what if we make the foundation this size? How is that going to change our torques and … how is that going to change the [number of] bolts?" Through this process the students were able to determine the most cost effective parameters that met the problem guidelines. All three of the teachers allowed for their students to reflect on the failures of their previous design and use this information to present a better solution for the next iteration.

In addition to the EThink indicator expecting students to learn from failures, it also asks them to manage uncertainty, risk, and safety factors. Of the three engineering projects, only Sam's projects brought forth the concept of safety factors, while the other two projects did not. The "Request for Proposal" document from the foundation project asked the students to "Design a foundation to prevent overturning of [the] vessel with the following constraints: Safety Factor of 1.5 for empty vessel [and] Safety Factor of 2.0 for full vessel." When the design solutions were presented, frequent mention was made of the trade-offs that had been made between the value for the safety factor and the cost of the design. The use of safety factors in the foundation project indicates that the students were addressing uncertainty and risk in their designs. Both the egg drop and crumple zone projects did not ask the students to address these concepts.

The final portion of the EThink indicator expects students to engage in engineering ways of thinking, including creativity and perseverance. All three of the teachers spoke specifically about their engineering projects allowing students to think creatively. They all felt that allowing for creative thinking was one of the benefits of implementing engineering education in their classroom. With regards to this, Sally explained:

> I think it's a good place for them to be creative. I think a lot of students that, I mean, traditionally physics is just do a whole lot of math problems, at least the physics I went through is do a lot of math problems. And I think that really it [engineering design] gives lots of other students the opportunity to be successful in physics and to be engaged and to find value in the class.

Students working on each of the three projects were observed sharing creative ideas among team members. The creativity portion of the EThink indicator was apparent in each of the teachers' classrooms.

In addition to creativity, the EThink indicator also asks students to demonstrate perseverance. Perseverance was evident from students in each of the three teachers' classrooms. To begin with, all groups completed multiple iterations and did not give up after the first try. The students worked on these projects for multiple hours: three hours for the egg drop project, six hours for the crumple zone project, and upwards of 25 hours for the foundation project. There was evidence of students hitting roadblocks but then, with some guidance, being able to work past these. Sam gave the most notable reference to perseverance. He explained that in the past, some of his students became very stressed towards the end of the engineering project. He said that sometimes students “come in after school to get help and the tears start.” Sam believed that the tears were not necessarily a bad thing because “the student gets frustrated and cries and then they work past it.” He explained, “In the end they realized they were successful with overcoming obstacles, and this, in turn, built their confidence.”

The three engineering design projects investigated for this study all contained portions of the EThink indicator. All of the projects facilitated the students learning from failures to build a better solution by requiring multiple iterations of the project. Sam’s project was the only one that asked the students to work with safety factors for their design. Each of the teachers believed that the use of creativity was an important benefit of integrating engineering into their physics class. Finally, all three of the projects showed evidence that the students were persevering through the design project. Each of these design projects addressed multiple aspects of the EThink indicator.

Evidence exists to indicate that the teachers were successful with the implementation of the EThink indicator, but there is room for improvement. The students working on each project learned to use informed judgment through the process of evaluation and redesign. However, none of the teachers talked about the students using the engineering concepts they had gathered to become more informed citizens. The projects could have included making connections between understanding the engineering process and being an informed citizen. All three projects were also successful with providing opportunities for learning from failure. Each project required multiple iterations to encourage this. However, Marvin's project was not as successful in this area because it was possible that the students were tinkering instead of engineering. This was not as likely with Sally's project and for Sam's project it was not an issue. The EThink indicator also includes learning to manage uncertainty, risk, safety factors, and product reliability. Sam had the only project that successfully addressed this. The students had to design using safety factors, which brought up the ideas of uncertainty and risk. Marvin and Sally did not address uncertainty, risk, or safety factors. Sam could have made connections between the concept of safety factors with risk, uncertainty, and product reliability to improve the coverage of the EThink indicator with the students explaining the connections between the different concepts. Sally could have improved her projects to talk about risk, uncertainty, and safety by providing a threshold acceleration value to indicate the safety of the car occupants. Any further decrease in the acceleration value could have transformed into a safety factor for their crumple zone design. Marvin could have added in risk factors by having the students drop their egg containers from increasing heights. The safety factor could have been calculated by using a minimum threshold for success. For Marvin's and Sally's projects, the aspect of results replication could have been included to address product reliability.

Conceptions of Engineers and Engineering (CEE).

The CEE indicator places emphasis on K-12 students understanding the discipline of engineering and the job of engineers. The first portion of the indicator asks that students understand the big ideas or conceptions of engineering. The first of these conceptions is that a client drives the work of engineers. Sally's and Sam's engineering projects both had a client while Marvin's project did not. Marvin's egg drop project was set in the context of protecting occupants in a car crash. However, a connection was never made between the occupants and a client for the project. The connection instead was that the science of car crashes would also apply to the science of an egg drop container. Marvin could have easily included a client by talking about the needs of the occupants driving the design. However, as implemented, his project did not clearly include a client.

Unlike Marvin's project, Sally's and Sam's projects both had identifiable clients. The client in the crumple zone project was specified as the car occupant. In the "Crumple Zone Engineering" packet it states, "Your job is to design a crumple zone for the front end of a car which will help to keep the occupants of the car safe." Sam's foundation project also contained a client. In the "Request for Proposal" document, the introduction indicated to the students that the oil refinery "is installing a new crude pre-fractioning tower as a part of their Crude Capability project. [The oil refinery] requests your consulting company to provide a design for a foundation for this vessel along with an estimate for installation." The oil refinery became the client for which the students were designing. Both the crumple zone and foundation projects had an identified client.

The CEE indicator lists the second engineering conception that the students learn, that engineering involves working within constraints. The students would have come to this understanding through the design process. All three design projects required the students to work within a number of constraints. Both Marvin's and Sally's projects allowed the students to work from a specified list of materials; the students were not free to choose any materials they liked. Marvin's and Sally's projects placed number limits on some of their supplies, such as 30 craft sticks or one foot of tape. Sally's project also had a size limitation for each crumple zone. Sam's project involved environmental factors, such as the force produced by wind gusts. Limitations were also introduced based on the materials used in the projects, such as the shearing point for the bolts. In addition, Sam's project had safety factors as one of its constraints. Finally, the foundation project asked the students to produce the most economical foundation that met the rest of the constraints. All three of the design projects gave constraints that the students had to manage during their design process. Through the management of constraints, the students would have understood that constraints are a major factor in the process of engineering.

The final engineering conception listed in the CEE indicator asks that students understand that no design is perfect. Through the design process, the students discovered that they could make their products better. The inclusion of multiple iterations in each project allowed students to improve upon their previous design, hopefully giving them a better performing design with each successive trial. At the end of each project there were some designs that performed better than other designs. While the students may have gotten a sense of the best design in the class, none of the teachers referred to individual solutions as *the* answer. For Marvin's project the students either passed or failed with their design. For Sally's project the design performances were put in rank order, according to the acceleration value. For Sam's project, the oil refinery engineers chose a design they felt was best. In all three design projects, the students were not left with a sense of finality for the last designs tested.

In addition to understanding the big ideas or conceptions of engineering, the CEE indicator also asks that students begin to understand the profession of engineering, including engineering disciplines and their pathways. Marvin and Sally stated that they had not included this aspect in their design problems. However, Sam's project included multiple instances of teaching about the engineering profession. The most obvious part of the foundation design project that related to engineering as a profession, was the introduction of two working engineers into the classroom. The students were able to see and interact with the engineers, as well as receive feedback from them about their designs. Sam designed his project with teams that he likened to small engineering firms. The students had different areas of expertise, much as engineers working together on a project would have. At the conclusion of the project, Sam said to the students, "The purpose of this project was for you to get an idea of what an engineer does, the process." The final piece of the foundation design project was a field trip to the refinery. The first part of the day involved presentations by a number of different types of engineers. Each engineer told the group about their educational background, the type of engineering they did, and what their job entailed. Present were the following types of engineers: mechanical, maintenance, civil, and chemical. The engineers answered questions from the students about their backgrounds and jobs. While Marvin's and Sally's projects did not include the topic of engineering as a profession, Sam's project included interaction with two working engineers and presentations by various types of engineers.

Finally, the CEE indicator asks for students to learn specifically about the diversity, job prospects, and expectations of the engineering profession. Again, with this portion of the CEE indicator, both Marvin and Sally did not address this idea with their design projects. For Sam's students, the majority of this information was delivered during the engineer presentations on the field trip. Engineers mentioned a high level of work satisfaction, the challenges of being a female in a male dominated career, and gave an indication of salary levels for various types of engineering. Sam spoke seriously to the students about the benefits of beginning a career as an engineer. He told the students "engineers often advance in their career. Many do not stay in their original job but move into project management or the business side." With these various pieces, Sam's implementation of the foundation design project included talking about the engineering profession as a whole, while this topic was not covered by Sally's or Marvin's projects.

All three of the design projects addressed some aspect of the CEE indicator. Sam's and Sally's projects had a client for their design project whereas Marvin's did not. All of the projects had constraints, which allowed the students to understand this big conception of engineering. All three also allowed the students to discover that no design solution is perfect. Sam was the only teacher who talked about engineering as a profession in terms of disciplines, pathways, diversity, job prospects, and expectations.

Evidence exists to show that the teachers were successful with the implementation of the CEE indicator, as well as showing evidence that there was some room for improvement. This is the indicator where the teachers should strive for the most improvement in their engineering curricula. As a result of the fieldtrip, Sam was successful in introducing his students to a variety of engineering disciplines, giving students an idea of what engineers do, and bringing up some of the job diversity issues. Marvin and Sally included very little of this indicator in their projects. Sam could improve his project by being more direct in his coverage of the topics in the CEE indicator. Marvin and Sally need to add this component to their engineering curricula. Mentioning what type of engineer would be working on projects like the one they were doing in class could be a start. Doing some research about the different types of engineers and the pathways to these jobs would also be beneficial. It is also important that all of the teachers add conversations to their project about the current diversity levels within the engineering field.

Engineering Tools, Techniques, and Processes (ETool).

The Etool indicator asks that K-12 students learn and implement different techniques, skills, processes, and tools as professional skills that engineers use. The techniques portion of the ETool indicator was met by Sally's and Sam's design projects but not by Marvin's project. The techniques used in Sally's project were those of video capture and video analysis. In Sam's project the techniques included: using the "simplified method," from the "Bolt Information" handout, to determine the size and number of bolts required; using the "method of superposition," also from the "Bolt Information" handout, to determine the amount of deflection at the top of the tower; and following the "generalized design steps," from the "Foundation Design" handout, to design their foundation.

The ETool indicator next lists skills as an area in which students should become familiar. All three of the design projects included the students using different skills. To begin with, all three projects asked the students to produce drawings or diagrams of their design. The foundation project also asked the students to decipher a schematic drawing. In both the foundation and the crumple zone projects the students were asked to use the skill of converting units. These projects also asked the students to use the skill of solving algebraic equations. The egg drop project did not ask the students to either convert units or solve equations. Additionally the foundation and crumple zone projects required the students to use computer programs to perform tasks. For the foundation project, the students made use of the Excel spreadsheet program to build their mathematical model and the JMP Statistical Discovery program to analyze data. For the crumple zone project, the students used Logger *Pro* to analyze data. Finally, the foundation project was the only project that asked the students to use the skills of finding the average of a list of numbers and the skill of using significant figures.

Next in the ETool indicator is the expectation that students will use tools to make their work easier. All three projects required the students to use tools. The egg drop and crumple zone project allowed the students to use tools to build their prototypes, such as scissors. Instead of using tools to build prototypes, the foundation project used tools, such as wire cutters, vernier calipers, and protractors, during laboratory activities and for the drawing of diagrams. The foundation and crumple zone projects required the use of calculators, computers and a network for saving and analyzing data. The egg drop project did not require the use of computers or calculators. The crumple zone project was the only one that required the students to use a video camera, the FlipShare software, and an accelerometer as tools. The use of these tools was important to successfully complete the design projects.

The final expectation in the ETool indicator is that students use various processes. The indicator gives examples of these processes: manufacturing, production, and universal systems model. None of the engineering design projects observed contained pieces that fit within the processes portion of the ETool indicator.

All three design projects encouraged students to use some of the techniques, skills, processes, and tools outlined in the ETool indicator. Techniques were used in both Sam and Sally's projects but not in Marvin's project. Skills, such as drawing, were used in all three projects. Tools were also used in all three projects and ranged from scissors to computers. None of the design projects required the students to use processes as defined in the ETool indicator.

Evidence exists to show that the teachers had some success with the implementation of the ETool indicator; however, there was also room for improvement. All three of the engineering projects had the students using tools and skills. The common skill used in the projects was that of drawing a solution. Although this was included in each project, Sam's drawings were required to be to scale. This is a change that could easily be made for both Marvin's and Sally's projects. While Sam and Sally both included the use of techniques in their projects, Marvin did not. If Marvin's project were changed to include video capture, as mentioned with the POD-TE sub-indicator, this would facilitate the collection of more data, the analysis of which could inform redesign decisions. None of the projects included the use of process. This could be added by including the concepts of manufacturing or production, particularly in Marvin's or Sally's projects. This would allow the students to think beyond the designing of just one crumple zone, to the process of putting this design to use in the production of cars.

Issues, Solutions, and Impacts (ISI).

The ISI indicator is centered on the societal problems that we face. The intent is for students to understand the impacts of their solutions on the related context, and understand the impacts of the context on their solutions. All three of the teachers stated that the topics in the ISI indicator were not a focus of their engineering design project. However, some pieces related to the indicator could be found in each of the projects. All three of the design projects were set within a societal context. For the egg drop and crumple zone projects the context was car crashes and for the foundation project the context was a working oil refinery. Both the egg drop and crumple zone projects can be classified as impacting the societal context of vehicle occupant safety. However, the safety aspect of the occupants is more closely related to the Ethics indicator and so it will be discussed in that section of this chapter. The societal impact of car crashes on vehicle occupants was the only context to which both the egg drop and the crumple zone projects could be connected.

Unlike the egg drop and crumple zone projects, the foundation project related to multiple impacts of, and on, the solutions to the context. The societal and global context of the project had an impact on the design. Petroleum recovery and distribution is a worldwide concern, which gives it a political aspect. During the presentations by the engineers, the issue of supply and demand was related to the work that was done at the refinery. One of the presenting engineers explained that the refinery supply now came mostly from oil recovered by fracking. The engineer was very passionate about the politics that affected the distribution of refinery products.

While all three projects related to the societal context of their solutions, the foundation project also related to the environmental and economic contexts. The environmental context had an impact on the design solution. Multiple environmental factors had to be taken into consideration. Included in these was the wind speed of the area, the geology and climate of the site, and the properties of the soil. The economic context also had an impact on the design solution. The purpose of the tower installation, for which the students were designing a foundation, was to produce more desirable light products from the heavy Canadian crude that was delivered to the refinery. If the less expensive heavy crude could be refined into the light products, the profit margin would increase. With profit being the motivation for this project, the students were also asked to design the most inexpensive foundation that still met the design requirements.

The foundation design project also related to the impact of the design solution on the environment. During the engineer presentations, the protection of the environment was a topic of discussion. While the specific environmental impact of the foundation was not addressed, the environmental impact of the refinery, as a whole, was discussed. The impact of the fracking process that recovered the oil was explained to be minimal. The environmental impact of the refining process was also addressed, including all of the emissions management programs that were in place. The foundation project was well situated within the working of the oil refinery, which connected to a variety of contexts. The foundation design project was not occurring in isolation.

In addition to the impacts on and of the various contexts, the ISI indicator also asks students to learn about current events and contemporary issues. All three of the design projects were related to contemporary issues. The egg drop and crumple zone projects were related to the contemporary issue of transportation. The foundation project, within the context of an oil refinery, was related to the contemporary issue of energy supply. The hope is that the relationship of these design projects to contemporary issues will bring about awareness, for the students, of the problems that exist within our society.

All three of the design projects met some portion of the ISI indicator. Each project was placed within a real-world context. Marvin's and Sally's projects were the least connected to the ISI indicator. These projects were related to the societal context of car crashes and vehicle occupant safety. The foundation project had a much stronger connection to the ISI indicator. The project was set in the context of an oil refinery. This put the design project within the societal context of supply and demand of a critical resource, which made the process political. The foundation design solution was also dependent on both an environmental context, such as dealing with wind, and an economic context, creating the greatest profit margin. The oil refinery setting allowed the students to learn about some of the environmental impacts of the refining processes, and how they were being managed. Finally, all three design projects were linked to a contemporary issue, either transportation or energy distribution. So, although none of the teachers focused on the ISI indicator, each of them met at least some portions of it.

Evidence exists to show that teachers were being successful with the implementation of the ISI indicator, as well as there being some room for improvement. All of the projects were focused on contemporary issues. However, none of the projects were connected to current events. This leaves room for an addition to these engineering curricula. If connected to the observed projects, Marvin's and Sally's projects could easily be tied to a current event. For example, a local car crash could be investigated through newspaper reading. Adding the reading of an article about oil use in the United States or about the current debate on oil fracking would make a connection to current events. These connections to current events would allow the students to build an awareness of real problems. Sam's project was intended to make connections to a global, economic, environmental, and societal context. Sally and Marvin made a connection to the societal context through the use of car crash videos. An economic context could be added by talking about the cost of car crashes in terms of property damage and medical bills.

Ethics.

The Ethics indicator states that K-12 engineering education should include exposure to ethical considerations, which are integral to the practice of engineering. Each of the three teachers indicated that the ethics of engineering had not been a focus of their project. In the paragraphs that follow, evidence is given of how portions of the Ethics indicator were present in each of the three projects.

All three of the engineering projects addressed the portion of the Ethics indicator about safety. As mentioned during the analysis of the ISI indicator, both Marvin's egg drop and Sally's crumple zone projects were grounded in the idea of keeping a passenger safe. The safety aspects of these projects fit within the portion of the Ethics indicator related to the safety of those using a product. Both Marvin and Sally showed videos to their classes that made comparisons between crashes with and without safety equipment, such as seatbelts and airbags. The teachers talked with their students about the science and purpose of the crumple zone of a car. Both Marvin and Sally's design projects focused directly on the safety of those who would be using their product.

Sam's foundation project also contained safety aspects related to the Ethics indicator. However, in this project the safety was related to those affected by the product. In designing the foundation, students had to take into consideration the safety of those who would be working around or near the pre-fractionation tower. The foundation and bolts attaching it to the tower had to be designed well enough that the tower would remain upright during various environmental conditions. The two safety factors, given as constraints for this project, can be thought of as giving the design a margin of error. Safety was also mentioned during this project when talking about the oil refinery as a whole. The students were told the refinery was a secure facility, with limited access, to prevent destructive acts. The students also learned that the refining process as a whole could be dangerous, considering the mix of fuel, air, and explosions. The safe operation of the refinery, with all of its engineered pieces, was important to all those who could be affected by a disaster, particularly the employees. With the foundation project taking into consideration the safety of the tower, it is apparent that all three of the engineering projects were linked to the safety aspect of the Ethics indicator.

The foundation project was the only one of the three projects that addressed another component of the Ethics indicator, integrity. The first way in which the students were asked to demonstrate integrity was a result of the different roles given to each member in a group. For each role, students were responsible for understanding different knowledge and performing different tasks. This meant that there was interdependence among the students on an engineering team. The students were required to display integrity in terms of being an active and knowledgeable participant in their group. Students were also asked to show integrity within their classroom engineering community. The engineering teams were in competition with each other. This meant that students could not discuss their problems or ideas with members of other teams. Sam reminded a couple of students caught “cheating” that they were expected to act ethically.

Although ethics had not been a focus for any of the design projects, each one showed some link to the Ethics indicator. All three of the projects were concerned with the safety of either those using the product or those being affected by the product. The foundation project was also concerned about the integrity of students within and between engineering teams. Other aspects of the Ethics indicator were not found in any of the design projects, including designs working consistently and the rights to intellectual property.

Evidence exists to show that teachers had some success with the implementation of the Ethics indicator, as well as there being room for improvement. Sally's and Marvin's projects had strong connections to the ethical concept of safety, as this was the problem for which they were designing a solution. Sam's foundation project also contained safety aspects and, in addition, the concept of integrity. None of the teachers stated that they had planned to directly address the ethics portion of engineering. This definitely leaves room for improvement for all of these projects. A component about the ethical use of resources could be added to each project. In addition, a discussion about governmental regulations related to each project could be added. For Marvin and Sally, the addition of building duplicate prototypes, as mentioned with the EThink indicator, could provide an opportunity to discuss the ability of each product to work consistently. For all of the projects, an improvement could be made in covering the Ethics indicator if the topic of intellectual property rights was included.

Teamwork (Team).

The Team indicator centers on the students being able to work together in an effective manner. Working together requires students to contribute, collaborate and compromise. All three of the teachers made teamwork a foundation of their engineering project. They all spoke positively about the benefits of the use of teamwork for their engineering projects. For example, Sam said, “Half of my focus in this project is to teach them [the students] how to work together in a group on complex things.”

Each teacher allowed for the formation of teams near the beginning of their engineering project. Marvin chose to have groups of two, Sally groups of two to four, and Sam groups of four students. Marvin and Sally allowed the students to choose their own team members whereas Sam assigned groups randomly. For each of the design projects, all members of a team had to work together towards a common goal; each team produced one collective product.

While all of the teachers expected each student to participate as a contributing team member, Sam’s team strategy had more structure to facilitate this occurrence. Sam assigned a role to each member of a team: project manager, spreadsheet expert, bolt expert, and foundation expert. Each role required the gaining of different knowledge and the performance of different tasks. Each member of a group had to be involved because the roles were interdependent of each other and were required for the creation of a satisfactory product.

During observations in each of the classrooms, there was evidence of team members working together. Students demonstrated collaborative work. For example, with the foundation project students often relied on other group members to help troubleshoot problems, such as the spreadsheet returning results that indicated a negative number of bolts was required for the design. The students in all three classrooms were also observed to make compromises between group members. For example, during the second iteration of the egg drop project, one team member said, “I really don’t want to scrap the old idea.” The team decided they could compromise by starting from the old idea and using new ideas to modify it.

With collaboration and compromise being observed during all three design projects, this is not to say that the teamwork always went smoothly in each classroom. Some teams were more effective than others. Some team members spent significant time off task. However, each teacher structured his or her design project to include teamwork. All teams worked toward a common goal and each student was expected to be a contributing team member. Sam’s team strategy was different than Marvin’s and Sally’s, where students were allowed to choose their own groups. Sam formed groups randomly and then each team member was given a specific role. All three of the design projects addressed various aspects of the Team indicator.

Evidence exists to show that teachers were being successful with the implementation of the Teamwork indicator, as well as there being some room for improvement. While all three of the teachers structured their projects by having the students work in groups, Sam was the most successful with this aspect. Sam’s addition of individual roles for team members provided very positive results. This structure allowed for individuals to be held accountable for their participation in the work of the group. Marvin’s and Sally’s structure for teamwork had room for improvement. Allowing the student to choose their group members certainly added a different dynamic to their group work, compared to if the students had been assigned to groups. In Marvin’s and Sally’s classes there was more evidence that all members of a group were not pulling the same weight when compared to Sam’s class. To improve Marvin’s and

Sally's projects, more structure should be added to their groups and perhaps group members should be assigned randomly.

Communication Related to Engineering (Comm-Engr).

The Comm-Engr indicator requests that K-12 students learn to communicate engineering ideas and designs in a manner similar to those of practicing engineers. All three of the design projects contained a portion where the students were asked to communicate in a manner similar to practicing engineers. Communication related to engineering was most complete in the foundation design project and only minimally addressed in the egg drop project, with the crumple zone project falling between these two.

All three of the design projects asked the students to do some technical writing to explain the process they went through and the solution they determined. The egg drop project required the least amount of writing, with only the "Egg Drop 2.0" sheet being filled out. The three questions on this sheet asked the students to reflect on their first iteration. In doing this, the students may have used scientific terms. The crumple zone project asked for more extensive written communication. The students were required to fill in the eight-page "Crumple Zone Engineering" packet where they were expected to give technical answers. This packet was structured similar to a laboratory report using the scientific method and as a result required the use of scientific content. While the foundation problem put to use some question/answer sheets to guide the process, the technical writing required of the students was a formal written design proposal. The proposal included two pages of writing in which the students were to describe both their primary and secondary solutions.

For each project, the audience for the technical writing required was someone with background knowledge in the topics being addressed. For all three projects, the audience for the writing was the teacher. None of the projects asked the students to write in a manner aimed at being understandable by the layperson, as presented as an option in the indicator. The foundation project had an additional audience other than Sam, the teacher. The students were asked to direct their proposal to the two refinery engineers who had been involved in the project. The students knew that while Sam was giving them a grade for the project, the engineers were comparing design proposals and choosing one to which they would "award" the contract.

All three of the design projects also required that the students provide pictorial representations to communicate their ideas. The "Egg Drop 2.0" sheet asked the students to "**Draw** your solution and **describe** what the pieces of the device are meant to do." The crumple zone project asked the students to produce multiple drawings, including drawings of an original design, the prototype before testing and the prototype after testing for each crumple zone. The foundation project required that the students provide both a top and side view schematic of their primary foundation solution, drawn to scale. For the foundation project, these drawings were to be included in both the written proposal and the group presentation.

The crumple zone and foundation projects also required the students to include symbolic representations as part of their reports. Using the Logger *Pro* software to produce graphs of the data created the symbolic representations required for Sally's project. The students were asked to sketch these graphs in their "Crumple Zone Engineering" packets. The students used the information from the best-fit curve of each graph to create another symbolic representation in the form of a distance equation. Values from this equation were used in an equation to calculate the acceleration. These equations were also to be included in the "Crumple Zone Engineering" packet. The foundation project required the use of the JMP Statistical Discovery program to produce graphs during the laboratory activities conducted near the beginning of the project. The students were required to provide these graphs in their laboratory reports. As a part of the design proposal created by each team, multiple symbolic representations were required. The students were required to include example calculations for each of the steps in the design process. The students were also to include a printout of their spreadsheet, showing all of the numerical values. Unlike the crumple zone and foundation design projects, which required the students to provide symbolic representations, the egg drop project did not include this requirement.

Both Sam's and Sally's projects planned to have the students create presentations to share their design process and solution with others. Sally originally planned to have the students create a culminating poster that would display each team's process and solutions. Sally had a poster exemplar as part of her teaching materials. However, time ran short for the crumple zone project and Sally removed the poster portion of the design project. Sam, on the other hand, did require the students to create a presentation. The presentations created by each team were produced using a slide-show format. The presentation included information about each group member, the two design solutions, and a detailed explanation of the primary solution. These presentations were given to the class, including Sam, and the refinery engineers.

It is of interest to note that of the three projects, Sam's engineering design project required the most elaborate form of communication. As written in the Comm-Engr indicator, engineers are expected to write client reports. The design proposal required as a product for this project most accurately mirrors products produced by practicing engineers. The design proposal not only included a problem statement and descriptions of both the primary and alternative design solutions, it also asked the students to give background on their fictitious engineering company and the team members who worked on the project. In addition, the design proposal required the students to provide background information, such as calculations, that supported the design decisions they had made.

All three of the design projects met some portions of the Comm-Engr indicator. Each teacher required his or her students to use technical writing to explain the process they went through and the solution they developed. This writing was all produced for an audience that had background knowledge related to the project. All three design projects also required the students to produce some type of pictorial representation, such as a drawing of their design. Additionally, Sally's and Sam's projects asked the students to produce symbolic representations, such as a graph of the data. While both Sally's and Sam's original project outlines included the students producing presentations of their work, Sam's project was the only one that actually had the students give these presentations. While all three of the design projects required the students to meet some portions of the Comm-Engr indicator, Sam's project, which included the writing of a design proposal, most completely met all of the aspects of the indicator.

Evidence exists to show that the teachers were successful with the implementation of the Comm-Engr indicator, as well as there being some room for improvement. Sam had the most success with the communication that took place during his project. The products that the students were asked to produce were similar to the types of projects practicing engineers would produce. In addition, the students not only had to produce written but also verbal communication related to their results. Sally would have better met the Comm-Engr indicator if she had provided time for the students to create the posters as she had planned. These posters would have provided an opportunity for her students to organize and present their work in a fashion more aligned with engineers, compared to the packet they had completed. Sally also mentioned that in the future she would like to add, between each iteration, a verbal presentation portion to her project. This would also be an improvement. Marvin's project allows for the greatest amount of improvement for this indicator. A first step for Marvin would have been requiring the students to complete and turn in the evaluation sheet they were given. The project should also include a final communication piece. The students should present their work and findings to others. There are many different options for Marvin to better meet the Comm-Engr indicator and putting this into place would increase the impact of the project.

Student Assessment

All three of the teachers provided their students with a grade or a score for their engineering project. For Marvin and Sam, a portion of the student's grade was based upon the success of the prototype or mathematical model that was produced. Marvin graded based on the degree of cracking in the egg. Sam graded based on the accuracy of the students' mathematical models' output compared to his own model's output. Unlike

Marvin and Sam who took prototype performance into consideration for grading, Sally did not base student grading on performance of the crumple zone prototypes.

The three teachers implemented a range of assessment practices. Marvin's assessment strategy was the most basic with points being based on prototype success and student participation. It did not appear that Marvin used the "Egg Drop 2.0" handout for grading purposes. Sally's assessment strategy was more complex and was based on the completion of the "Crumple Zone Engineering" packet and the taking of a test. For grading purposes for the packet, Sally used two rubrics; one was based on scientific inquiry and the other on data processing. The test was graded based on correct responses to the questions. Sally had two questions on the test that indicated a C or B grade and two questions that indicated a B or A grade. Grading of the tests was not based on points but on a holistic score.

Sam's assessment strategy was the most complex of the three teachers. Each student earned grades based on daily work, lab reports, the group proposal, and the group presentation. Sam gave each student points for class work that was completed each day. He explained that he graded the lab reports in the traditional manner in which he graded all lab reports throughout the term. The proposal and presentation were given a group grade, which was based on point attainment related to a list of requirements. For each student these grades were melded together and included in the term grade, as was any other unit. Sam definitely had the most complex assessment system with the greatest number of pieces when compared to the other two teachers.

Finally, all three projects included a competitive aspect. For Marvin's students, those prototypes that successfully protected the egg were praised and shared with other classes. For Sally's students, a tally of forces that impacted the test car in the last test was ranked on the board and one group was declared the "winner." For Sam's class, the refinery engineers evaluated each proposal and announced a first, second, and third place.

Summary of Chapter 5

In this chapter, a cross-case analysis was presented for the three engineering design projects investigated. The cross-case analysis was structured by using the *Framework for a Quality K-12 Engineering Education.* Each of the twelve indicators in the K-12 framework was addressed. All three of the design projects met each one of the indicators on some level. However, some projects met various indicators to a much greater extent than other projects. Successes and places for improvement in the projects, including their assessment, were given. In the chapter that follows, a discussion of these results will be given, along with implications of the results and areas for further research.

Chapter 6: Discussion, Implications, and Recommendations

The research question that guided this study is: How, and to what extent, do physics teachers represent quality engineering in a physics unit focused on engineering? To answer this question, in Chapter 4, a case study was provided for each of the three teachers observed for this project. These case studies offered a detailed account of how each teacher implemented an engineering design project in their physics classroom. In Chapter 5, a cross-case analysis of the three cases was provided using the *Framework for Quality K-12 Engineering Education* (Moore, Glancy et al., 2013) as the guiding theoretical framework. The cross-case analysis described evidence for each of the twelve indicators from the K-12 engineering framework, as well as the project assessments, to compare and contrast the engineering implementation of the three teachers. In this final chapter, the quality of the implementation related to the indicators for quality K-12 engineering education and the assessment of the projects are discussed. Then, based on the study findings, implications for teachers, schools, teacher educators, and policymakers are presented. Finally, recommendations for future research are outlined.

Summary of the Cross-Case Analysis

In Chapter 2, the *Framework for Quality K-12 Engineering Education* (Moore, Glancy et al., 2013) was introduced. Each of the key indicators from the framework were outlined and supported using the literature. While the K-12 engineering framework requires all twelve indicators to be present in order to have quality K-12 engineering, it does not require each indicator to be present in each individual engineering project that constitutes the entire curriculum. Rather, the goal is that all of the indicators in the K-12 engineering framework will be addressed during each separate grade band (K-2, 3-5, 6-8, 9-12).

To define quality K-12 engineering education at the individual classroom unit level, the twelve indicators were placed into three groups. The first group contained the three indicators considered most central to engineering and engineering education: POD (POD-PB, POD-PI, POD-TE), SEM, and EThink. The second group included the indicators important to the development of students' understanding of engineering: CEE and ETool. The third group contained the four indicators that promote important professional skills used by engineers: ISI, Ethics, Team, and Comm-Engr. In Chapter 2, I suggested that every engineering unit or project contain all of the three indicators deemed most central to engineering and engineering education. The reasoning for this is that without meeting these indicators, a project can merely become a craft or tinkering project, rather than an engineering design project. Indicators important to the development of students' understanding of engineering are not required in each project but will increase the authenticity of projects. Of the indicators that promote important professional skills used by engineers, the ISI and Ethics indicators are also not required in each project. However, the Team and Comm-Engr indicators are required for each engineering project in order for it to be considered quality. Engineering problems are usually solved by a group of people, and as a result the Team indicator is required for every project. The Comm-Engr indicator is required because students must be able to communicate their thinking in order for others to understand or assess their process. This classroom level application of the *Framework for Quality K-12 Engineering Education* provides criteria for discussing the quality of the engineering projects implemented by the teachers.

Marvin, Sally, and Sam included the components of the indicators central to engineering in their engineering design projects. Each teacher implemented their project by having the students work through an engineering design cycle. Each project had a design problem that contained constraints and was connected to science background knowledge that the students had obtained in a previous unit of study. Each teacher asked the students to create a plan for a design solution and then create a product in the form of a prototype or mathematical model. In each class, the students tested their product and were encouraged to evaluate the results and apply the findings to a subsequent design.

In addition to each teacher using an engineering design cycle (POD) as the basis of their project, each of the teachers encouraged the application of science knowledge to the design process (SEM). However, the application of science knowledge was not of the same quality level for each teacher, as will be discussed in the next section. Along with the application of science knowledge, each teacher encouraged their students to think like practicing engineers (EThink). This was in evidence because each project provided multiple iterations that allowed the students to learn from their failure. Each teacher also spoke about the ability of their students to engage their creativity during the design process.

The remainder of the indicators were present to different levels but not all of the teachers included all six of the remaining indicators. With regard to the two indicators important to the development of students' understanding of engineering, all of the teachers included, to some extent, the ETool indicator but only one teacher (Sam) included the CEE indicator. None of the teachers stated that they had intended to include in their project portions related to the CEE indicator. However, Sam's implementation of the foundation project, which included a fieldtrip to the oil refinery, did include portions of this indicator. Each of the teachers implemented the use of more than one of the components of the ETool indicator. For example, in each of the classrooms the students used tools. However, the quality of the implementation related to the ETool indicator varied among the teachers. The quality component will be discussed in the next section.

Teachers also did not include all of the four indicators that promote important professional skills used by engineers. The ISI indicator was lightly touched upon by each teacher, but none of the projects effectively situated the impact of their solutions. However, each project involved a context that could be identified as a contemporary issue. Only two of the teachers provided a cursory inclusion of the Ethics indicator. This is because their design context involved product safety. In these cases, however, the Ethics indicator was only implicit in the context and not explicitly discussed. Each of the teachers employed both the Team and Comm-Engr indicators in their implementations. All of the teachers structured their project such that students worked in teams and were expected to communicate information related to their project. However, for each of these indicators the quality of implementation (discussed in the next section) varied widely among the three teachers.

Discussion

The *Framework for Quality K-12 Engineering Education* was developed for, and originally applied to, state science standards related to engineering. The standards were assessed using the indicators to code the presence of components of engineering education (Moore, Tank et al., 2013). However, the current study is the first time in which the K-12 engineering framework has been used to explore the implementation of engineering education at the classroom level, and in particular at the unit level. The sections that follow provide a discussion of the major findings of this research. The findings are related to the connections made between the practices of three high school physics teachers with the K-12 quality engineering framework and with the assessment processes used within the engineering projects.

Quality of engineering implementation.

The three engineering design projects observed did not represent overall high-quality engineering education. Each project incorporated portions of the three indicators central to engineering, as well as some of the indicators related to understanding engineering and using professional skills, as described in Chapter 5. However, the reasons the implemented projects were not of high quality included not addressing or insufficiently addressing required indicators. In the following paragraphs, the quality of the engineering design projects will be discussed. The discussion will be organized using the three groups of indicators as explained below.

As outlined in the previous section, summary of the cross-case analysis, not all of the indicators in the K-12 engineering framework are required for every engineering design project. The indicators were placed in three groups: central to engineering and engineering education, important to the development of students' understanding of engineering, and promote important professional skills used by engineers. Five of the nine indicators are required for every quality engineering design project; the three that are considered central to engineering and engineering education and two of the indicators that promote important professional skills. In keeping with the original order of the K-12 engineering framework, which has been used throughout this paper, the five indicators required for quality engineering education are not discussed in one group but rather are discussed in the order in which they appear in the framework.

Indicators central to engineering education.

Previously mentioned, each of the engineering design projects addressed, to some extent, the three indicators central to engineering: POD, SEM, and EThink. However, the quality of the implementation varied among the projects. In addition, each indicator cannot be assessed as a separate entity as there is overlap between the indicators. In the sections to follow, the implementation of the indicators central to engineering will be assessed.

Engineering design cycle.

An engineering design process is an important component of quality engineering education. This is in accordance with Brophy et al. (2008) who wrote that an engineering design cycle is central to K-12 engineering education. The findings suggest that there are different ways in which teachers include engineering design.

The data show that for students not only experience with an engineering design process is important but also important is the formalization of the design process. Crismond and Adams (2012) identified K-16 student design performance starting with the “beginning designer,” who has little or no experience, and building to the “informed designer,” who has some formal training in design (p. 743). The authors state “beginning designers design in haphazard ways…[and] treat design as a set of strategies to be done once in linear order” (Crismond and Adams, 2012, p. 769). However, “informed designers do design as an iterative process…[and] use design strategies multiple times in any order" (Crismond and Adams, 2012, p. 769). The goal for K-12 engineering education is to move students towards being an "informed designer." In this regard, the teachers in this study did this by structuring their projects using an engineering design process.

While all three of the teacher participants allowed their students to experience an engineering design process by working through it using an engineering problem, only, Sally explicitly helped her students recognize a design process. This direct instruction on the engineering design process can provide for formalization of the process, whereas implicitly teaching the process lessens the likelihood for students to understand the engineering design process. The experience of an engineering design process without the formalization may leave students at Crismond and Adams' (2012) "beginner designer" stage. However, understanding engineering design allows students to move toward Crismond and Adams' (2012) "informed designer" stage.

Engineering design problem: Context and trade-offs.

This study suggests that there are multiple ways in which teachers can implement quality engineering design problems, which need a meaningful and engaging engineering context and should require trade-offs between competing constraints. Brophy et al. (2008) stated, "The instructional challenge is identifying engineering contexts that are accessible to learners, [and] difficult enough to be interesting" (p. 372). The three teachers in this study met this instructional challenge to varying degrees. Each of the projects had an engineering design problem that was set within a real-world context, one in which the students could understand the problem within their world experiences.

However, one of the teachers, Sam, used an actual engineering design problem that had been posed to professional engineers. Another teacher, Sally, used an authentic engineering design problem, one that would not be presented to professional engineers but was true to the process and intent of engineering. Both of these teachers had engineering design problems that were of high quality in that they had contexts that were accessible to the learners. The third teacher, however, had a disconnect between his engineering design problem and its context; he asked the students to design a container that was to sustain a vertical impact, whereas most car crashes involve horizontal impact. In addition, the egg drop project was never given a client for whom the teams worked. A quality engineering design problem should be appropriately set in an engineering context and should be framed by the needs of a client (Moore, Glancy et al., 2013).

Constraints are important in an engineering design problem as they provide the limits on the solutions that can be developed. Garmire (2003) states, "that all [engineering] designs are compromises" (p. 22). All three of the teachers had constraints included in their engineering design problems. However, having constraints as a part of an engineering design problem does not necessarily require students to make trade-offs. Of the three teacher participants, the data show that only one specifically required trade-offs between constraints. This particular project required a trade off between building plans and installation cost. For the students, every design decision they made had to factor in the effect that the proposed solution had on the cost. The goal for the project was to have a design for a foundation that met all of the building requirements within the given constraints but required trade-offs to minimize the use of financial resources.

Requiring students to make trade-offs between different constraints increases the quality of the engineering design problem.

Physics content knowledge.

Quality implementation of engineering education requires students to articulate and justify their design plan rather than building a solution through trial and error (Chandler et al., 2011). This justification involves the application of science content knowledge to the engineering problem, as Apedoe et al. (2008) indicated, engineering design requires students to “use and extend their knowledge of science and math” (p. 455). In addition, they state that students engaged in engineering design “learned more in their scientific content knowledge compared to learning in their traditional classrooms” (Apedoe et al., 2008, p. 455). Without the application of science or mathematics knowledge, a design project may be reduced to a craft project. Each of the three design projects used physics content as the background knowledge. However, the quality of the application of science knowledge varied among the projects. Marvin’s egg drop project was the most problematic in this area. The intent was that students would apply their understanding of the concept of impulse to the design of their container. There was no data analysis required for this project, so the students were not required to apply their knowledge of impulse. It was possible to complete the entire project via tinkering and never employ physics content knowledge. In contrast, Sam and Sally designed engineering projects that required students to apply physics concepts to the problem. For example, the crumple zone project required that the students use knowledge of force and acceleration concepts in their data analysis.

Expressing thought process.

Each of the design projects required that the students design and test multiple iterations of their solution. This type of implementation provided opportunities for the students to think like engineers (EThink) and apply science knowledge (SEM). Engineering education is noted to unleash creativity and motivate deeper thinking, as well as to encourage learning how to sift through large amounts of information to determine what is pertinent and what is extraneous, and to push beyond determining only a single answer (Carlson & Sullivan, 2004; Kelley, 2009). However, the data show that the intent for students to think reflectively during the test iterations, and what the students actually did, was not aligned. The different design projects produced varied evidence of the students thinking reflectively, applying physics content knowledge, and learning from failure. The reflection between iterations needs to be explicit, thus forcing students to verbally, or in writing, reflect on and refine their designs. The application of science knowledge and sharing of thought processes could have been improved for all three of the projects. This aspect of the projects ties closely to the communication portion of the design process, as will be discussed in another section.

Indicators for understanding engineering.

While the POD, SEM, and EThink indicators should be incorporated into every engineering design project, those indicators related to the development of students' understanding of engineering are not necessary for a quality engineering lesson. This section of the K-12 engineering framework contains two indicators: CEE and ETool. With a desire to maintain an adequate supply of engineers within the United States, it makes sense that K-12 students should understand the pathways available to become engineers.

What is engineering and what do engineers do?

The data show that the three participant teachers generally did not address the conceptions of engineering and engineers in a meaningful way. Educational research shows that K-12 students generally have a poor understanding of what engineers do (Cunningham et al., 2005; Cunningham & Knight, 2004). Understanding what engineering is and what engineers do (CEE) as well as what tools are used by engineers (ETool) is important for all high school students, in order to become informed citizens. It is of particular importance to those students anticipating further study in engineering. The level to which the three design projects addressed these concepts was of minimal or basic quality. In particular, two of the teachers did not specifically include information related to the CEE indicator in their projects.

To address CEE meaningfully teachers should provide instruction to promote the understanding of the engineering discipline. This includes concepts such as the work being driven by the needs of a client, the existence of multiple solutions, and general knowledge about the engineering profession. Sam's foundation project focused on the engineering profession to a greater extent than the other two projects, but still with moderate quality. The inclusion of a fieldtrip to the oil refinery, that included presentations by different types of engineers, allowed the students to get an idea of what different types of engineers do. In addition, Sam's design project required that the students use a variety of techniques, specific to the related engineering field, and skills to determine their solutions. Students likely completed this project with an understanding of what engineers do but the extent of their learning in this area is unknown. In order to increase the quality of this implementation of CEE, Sam could have included an assessment piece to determine what understandings of the engineering profession his students had gained.

Indicators to promote important professional skills used by engineers.

The final section of the K-12 engineering framework contains those indicators that promote important professional skills used by engineers. The indicators in this section of the K-12 engineering framework are: ISI, Ethics, Team, and Comm-Engr. The content of these indicators is not specific to engineering education, but overall quality K-12 engineering education for students is not complete without addressing each indicator.

Engineering related to the larger picture.

Real engineering problems begin with a need. While some engineering projects appear to be relevant only to individuals, it is important for students to understand that engineering solutions are also relevant to society as a whole (NRC, 2009). Students should "understand engineering in the broad context in which engineering is actually practiced" (Kelley, 2009, p. 7). The two indicators that cover this concept are ISI and Ethics. Although ISI and Ethics are not required in every engineering design project, they are required once during each grade band, and so investigating the ways in which the three participant teachers addressed these indicators is of value. As a group the teachers did not successfully address either the ISI or Ethics indicators. The data show that these areas of the framework were not a priority for any of the physics teachers.

The implementation of the ISI and the Ethics indicators by all three teachers was very basic. For ISI, loose connections can be seen between each of the projects related to a societal context and to contemporary issues. Related to Ethics, each of the projects contained aspects about safety but did not fully address the concept of ethics within the engineering process. Sam's was the only project in which the Ethics topic of integrity was addressed. None of these projects fully addressed the inclusion of their design project within a larger context related to issues or ethics. On the other hand, the ISI aspect could be added to each project. However, the lack of a link between these three projects and these two indicators does not detract from the projects as a whole. A reminder, the expectation is not to include each of the indicators in every engineering design project, but to include them in every grade band. The ISI and Ethics indicators could be added to these design projects but they also could be included in other engineering design projects that are a part of these students' grades 9-12 science education.

Working together.

Engineering is rarely done by an individual alone. As a result, the implementation of teamwork in K-12 engineering education is logical and Team is one of the required indicators. Each of the teachers structured their projects for the students to work together in teams. The data show that teamwork can be arranged in a variety of ways and that teacher organization and management of the teamwork correlates with the effectiveness of the group work. Teamwork encompasses a large range of ways in which people work in groups, but the benefits of cooperative teams in classrooms is well researched (Johnson et al., 2008). The three projects resulted in teamwork being put to use at various levels.

Sam's teamwork structure can be compared to that of cooperative learning. Johnson et al. (2008) state that in order for students to work together cooperatively, two of the requirements are positive interdependence and individual accountability. Sam's structure provided both: positive interdependence based on individual group roles and information, and individual accountability based on the grading of individual daily work. Marvin's and Sally's teamwork structures cannot be considered cooperative learning because they did not require both positive interdependence and individual accountability. However, they both structured their projects for the use of teamwork. The K-12 engineering framework does not require cooperative learning but does require the use of teamwork, which employs interpersonal skills.

Communicating learning.

The data from this study provide evidence of the value of having students communicate design, process, and justifications for their solutions. Selingo (2007) indicated that students involved in engineering education should learn the valuable skill of communication. Each team of students in this study was asked to communicate their work through written language. Even though Comm-Engr is a required indicator for a quality engineering design project, the data show that the engineering communication required by the students varied greatly between the projects ranging from formal proposals and presentations to a basic worksheet that was optional.

The communication expected of the students needs to be made explicit. Therefore, teachers should ask students to communicate their reasoning for making decisions to someone outside their group, perhaps the teacher. This outside person should be able to read or listen to this reasoning and find a logical path from beginning to end. For example, in Sam's project the students were required to develop two solutions, but in their proposal and presentation they had to provide reasoning why one solution might be chosen over another. Communication can also take the form of mathematical analysis such as shown in the foundation project. The real purpose of communication in engineering design projects is for students to reveal their process, their thinking, and the reasoning as to why they chose their solution. This communication allows students to share with their teachers the process through which they have come. The teachers can then use this communication for assessment purposes. Assessment will be a topic addressed in a following section.

Assessment of student work.

As presented in the literature review in Chapter 2, empirical evidence exists indicating that engineering education can increase conceptual understanding in secondary science (Klein & Sherwood, 2005; Apedoe et al., 2008; Ellefson et al., 2008; Svarovsky & Shaffer, 2007; Chiu & Linn, 2011; Schnittka & Bell, 2011). The *Framework for Quality K-12 Engineering Education* does not directly address the topic of the assessment of engineering design projects. However, to determine what understandings students have developed during the implementation of an engineering design project in the classroom, teachers must assess student learning. The data from the three cases show that each of the three teachers assessed the work performed by students in very different ways. The findings indicate that the assessment component of the engineering design projects was not clear in purpose or method.

The assessment observed in the three cases revealed a different approach by each teacher: Marvin's assessment process was the most basic, Sally's was intermediate, and

Sam's was the most multifaceted of the assessments. The purpose of the assessments fell into three categories: effectiveness of the prototype (Marvin), assessment of science content knowledge (Sally and Sam), and assessment of engineering process understanding (Sam).

The findings indicate that while assessments were used, the purpose of the assessments given for each project was not clear. Regarding success of the prototype or mathematical model, Sally and Sam both conducted a competition between student groups, but in no way were these results reflected in grades on the project. All three of the teachers indicated that they intended for their students to apply or learn science content knowledge as a result of their engineering design project. Marvin's assessment did not assess this application of content. Assessment of the understanding of the engineering process was only included by Sam and was revealed in group proposals and presentations.

The results of this work related to student assessment indicate that teachers need to determine their purpose in implementing engineering design projects in their classroom. The two major purposes centered on the application or learning of science content knowledge and the understanding of the engineering process. Assessment tools should be designed according to their intended purpose. Perhaps initial engineering design projects in a given grade band should be assessed more comprehensively with respect to the engineering process. Once this process is understood, future engineering design projects can be assessed more comprehensively with respect to science content.

Implications

The findings of this research have implications at the teacher, school, professional development, and policy levels. At the teacher level, this research implies that developing and implementing a quality engineering design project requires significant knowledge and much work. It is evident that it is not easy to create a quality design challenge, and it is even more difficult to make a connection between that challenge and the science content. Teachers should become aware of the *Framework for Quality K-12 Engineering Education* (Moore, Glancy et al., 2013) and similar works that outline requirements for quality K-12 engineering education. Teachers should include the five required indicators (POD, SEM, EThink, Team, and Comm-Engr) in every one of their engineering design projects. These indicators should be implemented and assessed at a level that results in quality engineering education. Engineering design projects should: be structured using an engineering design process which students can experience and formalize, require the use of science content as an integral part of the project, and promote students to think and problem solve in manners similar to those of practicing engineers. In addition, teachers need to plan and manage effective teamwork practices and design a strategy so that students explicitly communicate their reasoning and understanding throughout the project. This study also implies that the assessment of engineering design projects is complex. The student assessments used by teachers in the classroom need to be well thought out, keeping in mind the purpose(s) of the engineering implementation. The purpose of a given project may focus on the application or learning of science content knowledge or on the understanding of the engineering process.

Teachers need to allow for adequate attention to the designing and implementation of assessment tools for engineering design.

This research implies that teachers cannot implement quality engineering education, particularly at the high school level, by including just one engineering design project in their curriculum. It follows that at the school level, across grade bands, science teachers will need to work together to include all aspects of quality engineering education in their science curriculum. Because every indicator cannot feasibly be included in each individual engineering design project, and engineering standards are delineated in grade bands (Massachusetts Department of Education, 2006; Minnesota Department of Education, 2009), coordination is required. With four of the nine indicators in the *Framework for Quality K-12 Engineering Education* (Moore, Glancy et al., 2013) not being required for every engineering design project, planning needs to take place to determine in which grade level or with which projects these additional indicators will be addressed. Engineering education needs to become a thread that is woven through the science curriculum at the school level.

At the professional development, or the teacher preparation level, this research implies that designing or implementing quality engineering education is not a simple task. The *Framework for Quality K-12 Engineering Education* has the potential to guide the work of pre- and in-service teachers. Teachers will need to become aware of what pieces are required in every engineering design project. They will also need to learn what constitutes quality implementation for a design project. Quality lessons will need to be modeled for new teachers and for in-service teachers new to this area. Teachers will need to become familiar with ways in which to implement the indicators that are not required for each project and be provided guidance on curriculum planning across grade bands. With engineering education becoming a priority at the K-12 level, there is much education needed to bring all science teachers to the level where they can implement quality engineering education.

A final implication of this work is related to educational policy, specifically to standards. For two of the three teachers observed, the engineering design project observed was the only engineering experience their students would have in their high school careers. Additionally, at the schools for those two teachers, the physics classes observed were not required for graduation. While these two teachers were able to connect their engineering projects to state science standards related to engineering, the result was still that a large portion of the students from these high schools were graduating without having a high school engineering education experience. This is in a state in which there are engineering standards as a part of the K-12 state science standards. The implication is that regardless of required state standards in engineering being in place, some students are still not receiving engineering education. As more and more states are considering adding engineering to their state science standards, attention from policymakers and school administrators is needed in order to provide teachers opportunities to understand both the intention of the standards and the pedagogies involved in implementing them.

Recommendations for Future Research

As engineering education at the K-12 level gains ground, research in this area is still needed. In this study the implementation of three engineering design projects was observed and analyzed using the *Framework for Quality K-12 Engineering Education.*

Future research into the application of this K-12 engineering framework at the classroom level is still needed. The current study focused on engineering education in high school physics classrooms. This scope needs to be broadened to include other high school science subjects as well as science at the K-8 level.

In this work, the area of assessment as it related to the implementation of an engineering design project was investigated. Although assessment was not outlined in the framework for K-12 engineering, it is an important aspect of classroom engineering education. The results showed that student assessment was not consistent among the teachers nor was the purpose of the assessment always clear. From interview data, it is apparent that these three teachers found assessment of the engineering projects difficult. The purpose, methods, and effectiveness of student assessment related to engineering design projects needs further research.

The *Framework for Quality K-12 Engineering Education* was used as a theoretical framework for this research. The framework represented quality K-12 engineering education. As this work was the first time in which the framework was used to investigate the implementation of engineering design projects in the classroom, there is value in continued research related to the framework. In particular, research is needed in the area of teacher education related to the K-12 engineering framework. How will teachers interpret the framework and how will they put it to use? How can designers of professional development related to K-12 engineering education use the framework as an effective tool for teaching science teachers about the requirements for quality K-12 engineering education?

Finally, it was of interest that all three of the physics teachers had implemented engineering design projects in their classes before the introduction of required state science standards related to engineering. In the interviews, the three teachers provided reasons as to why they had decided to include an engineering design project that was not related to the state standards. When discussing the individual state engineering standards, the teachers could match the majority of the standards to the projects they had implemented. However, it was obvious that they had not designed or modified their current engineering curriculum to meet those standards. Further research needs to be conducted on the reasons why physics teachers have chosen to implement engineering education in their classes as well as on how they are implementing engineering. Hopefully the results of this work could help instill in teachers of other science disciplines the value seen in implementing engineering design projects.

The field of K-12 engineering education research is growing. While standards have been put into place, there is still much to discover and to develop related to this area. It is hopeful that the findings presented here will help others determine how to best encourage K-12 science teachers to implement quality engineering education in their classrooms.

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Appendix A

Interview Protocols

Interview Protocol – Pre-Observation
Engineering Education in HS Physics
Jennifer Kersten

Introductory Remarks:
Thank you for taking the time to talk with me today. This interview will take approximately 45-60 minutes. I am doing interviews with current high school physics teachers. The purpose of this study is to look at components of engineering education implemented in the current high school physics classroom. I am doing this interview to collect data as a part of the research I am doing for my dissertation. The information collected here is not to judge your abilities as a teacher; I am collecting information to gain an understanding of the various methods and levels in which engineering education is implemented. (Include IRB specifications and requirements. Obtain signed consent.) You may stop the interview at any time if you decide you no longer wish to be a part of this study.

Main Questions:

1. Please share with me some background information about yourself:
    - What is your teaching experience? How many years total? How many years at your current school? In what capacity? How many years of physics teaching?
    - What is your personal educational background?
    - What, if any, background do you have in engineering/engineering education? Degrees? Courses? Professional development? Reading? Family members?

2. Tell me about your familiarity with "The Nature of Science and Engineering" strand that is apart of the MN academic science standards that went into effect for the 2010-2011 school year. Pay particular attention to the substrands "The Practice of Engineering" and "Interactions Among Science, Technology, Engineering, Mathematics, and Society." (Have available a print out of MN Academic Science Standards, show after initial answering of question.)
    - Do you know where these standards have been placed in your schools' 9-12 science curriculum? Explain what you understand about their placement.
    - Do you know how students meet these standards? Explain classes, projects, etc.
    - Do you meet any of these standards in your physics class? Which ones? How do your students meet these standards in your physics class?

3. To the best of your ability, explain to me in your own words what engineering is.

4. Tell me about the projects (project based learning) that are part of your physics

curriculum:

- What are the projects? What is the purpose of the project(s)?
- Do students work on projects individually or in teams?
- What content material is connected to the project? How/Are students asked to explain the content associated with the project?
- Who are the students creating the project for? The teacher? A client? A competition? Themselves?
- Does the project include a design segment before any building begins? Explain. Is the designing written down on paper?
- How is the successfulness of their product judged? Teacher grade based on rubric? Results of a competition? Fellow student input?
- Are the students allowed/encouraged to make adjustments/updates to their project before final judgment? (Iterations?)
- Design cycle?

5. If interviewee appears to have engineering education background:
    - Why do you include engineering in your physics class?
    - What benefits do you see to including engineering education in your physics class?
    - How do the students respond to engineering activities?

6. What do you think about engineering education at the high school level?
    - Useful? Not well placed in science/physics? Teacher training has been adequate/not enough?
    - What information/support would you personally be interested in having available?
7. Is there anything else you would like to tell me about your teaching, inclusion of projects, use of engineering education?

Interview Protocol – Post-Observation
Engineering Education in HS Physics
Jennifer Kersten

Introductory Remarks:
This interview will take approximately 45-60 minutes. Again the purpose of this study is to look at components of engineering education implemented in the current high school physics classroom. (Include IRB specifications and requirements. Remind teacher of signed consent obtained previously.) You may stop the interview at any time if you decide you no longer wish to be a part of this study.

Main Questions:

1. Tell me you thoughts about the unit/project that you just taught and I observed.
2. A framework for quality K-12 engineering education has been developed. I observed evidence for the following points being addressed during your teaching. Do you agree that these points were a part of the curriculum delivered? Why or why not? I did not observe the following points in the curriculum. Did I miss them? If so, explain to me how or when these were addressed. If not, is there reason why they were not included?
    - Application of Science/Engineering/Math knowledge
    - Processes of design – engineering design cycle
    - Conceptions of engineers and engineering
    - Engineering thinking
    - Engineering tools
    - Teamwork
    - Issues, solutions, and impacts
    - Ethics
    - Communication – in engineering and in education
3. Do you feel any of the points that are a part of the framework do not apply to K-12 engineering integration? Do you feel there are points missing from this framework?
4. Do you feel you used any different teaching strategies when integrating engineering compared to teaching other content? Explain
5. What advantages for the students do you associate with the integration of engineering in your physics curriculum? What barriers?
6. How have the Minnesota science standards related to engineering guided your instruction in physics? Have they made changes to your curriculum? Do you believe this activity I observed meets all of these engineering standards for grades 9-12? What else might you do differently to meet these standards?
7. Is there anything else you would like to tell me about your teaching, inclusion of projects, use of engineering education?

Appendix B

Observation Protocol

I. Background Information

Teacher Name: ___________________________

School: ___________________________

Class: ___________________________

Date: ___________________________

Start Time: ___________________________

End Time: ___________________________

Observation Number: ___________________________

Number of Students in Class: ___________________________

White: _____ Students of Color: _____ Male: _____ Female:_____

II. Detailed log of classroom observation

Time	Observation Notes

Appendix C
Egg Drop Design Project

Egg Drop Project 2.0

Team:

What worked well last time and why?

What didn't work well and why?

How do you plan to address the problems from last time?

Draw your solution and **describe** what the pieces of the device are meant to do:

Appendix D

Crumple Zone Design Project

Tentative Plan:
1/2 day - intro up through reading the graph
1 day - show video analysis of spring plunger crash, students create own video of spring plunger and analyse crash. Most finish with this.
1 day - hand out packet and have them start on process of design. Some groups started to build first crumple zone.
1 day - Continue
1 day - continue A few groups finished 3 designs, most did not.

Issues

Sometimes video in logger pro is just white with no image. Switching computers usually fixes this.
Increase length of crumple zone to around 15 cm to increase chance of getting 3 data points during collision.
Have groups start the poster around day 3.

Crumple Zone Engineering

Schedule

Tuesday: Intro, hand out packet, finish planning pages
Wednesday: Demonstrate how to analyze from spring cart, start design #1
Thursday: Finish Design #1 Analysis, Work on Design #2
Friday: Design # 2 Analysis & Build Design #3
Monday: Build Design # 3 & Posters
Tuesday: Quiz, Competition (Crash #3) & Poster Project Due

Crumple zone background information

http://www.iihs.org/

Vehicle Research Center tour

http://www.iihs.org/video.aspx/info/vrc

2009 Chevrolet Malibu and
1959 Chevrolet Bel Air in
40 mph frontal offset crash

http://www.iihs.org/video.aspx/info/50thcrash

http://www.nhtsa.gov/

http://www.safercar.gov/

NHTSA research

http://www.youtube.com/watch?v=gMZE337Nodw

Crumple zone
goes here.

Investigate - Minimize forces on the car in a crash with a crumple zone attached to the front of car. Crumple zone must fit in a 15 cm x 9 cm x 5 cm box, be made with supplied materials and less than 1 yard of tape.

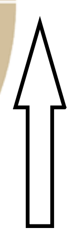
Evaluate - Crash the car with crumple zone. Draw and label after crash. Use video camera and Logger Pro software to analyze crash.

Plan - Design a crumple zone. Draw and label before building the crumple zone.

Create - Make the crumple zone. Draw and label actual design.

Investigate - Minimize forces on the car in a crash with a crumple zone attached to the front of car. Crumple zone must fit in a 15 cm x 9 cm x 5 cm box, be made with supplied materials and less than 1 yard of tape.

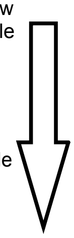
Three designs are created to learn and improve on your design. The final design will be used in a competition against other teams crashed against a force plate to determine winner.



Plan - Design a crumple zone. Draw and label before building the crumple zone.

Create - Make the crumple zone. Draw and label actual design.

Evaluate - Crash the car with crumple zone. Draw and label after crash. Use video camera and Logger Pro software to analyze crash.



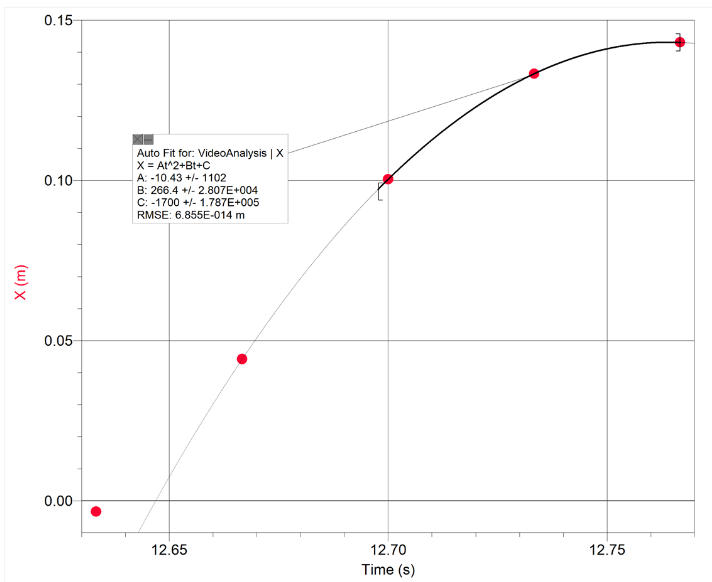
Video Analysis with Logger Pro

Car crash into wall. m = 1.4 kg

Equation

$d = d_0 + v_0 t + ½at^2$
$d = ½at^2 + v_0 t + d_0$
$1/2a = A$
$acceleration = 2A$

- What is the acceleration for this crash?
- What is the net force during the crash?



Video Analysis with Logger Pro

Example using spring bumper on cart

Logger Pro
Insert > Movie
Set Origin
Set Scale
Add Point (for whole motion)
Graph - select X for y-axis
Drag box around points for collision only
Analyze curve fit - Quadratic
Record equation

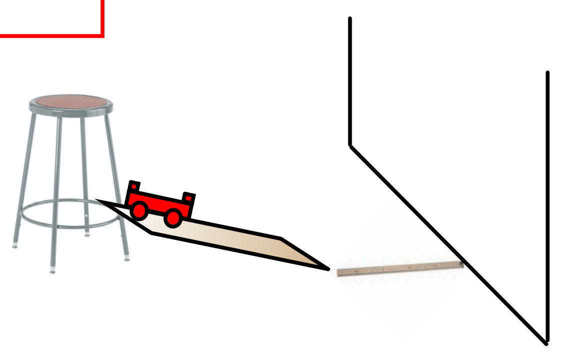
Plan - Design a crumple zone. Draw and label before building the crumple zone.

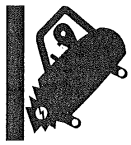
Create - Make the crumple zone. Draw and label actual design.

Evaluate - Crash the car with crumple zone. Draw and label after crash. Use video camera and Logger Pro software to analyze crash.

Equation

$d = d_0 + v_0t + \frac{1}{2}at^2$
$d = \frac{1}{2}at^2 + v_0t + d_0$
$1/2a = A$
acceleration = 2A





Group Members:

Crumple Zone Engineering
What is the safest design for a Crumple Zone?

Your job is to design a crumple zone for the front end of a car which will help to keep the occupants of the car safe. In order to keep the passengers safe the Crumple Zone must absorb as much of the force of the car crash as possible. The Crumple Zone that wins will be the one where the crash has the smallest force.

Design Restrictions:

- Crumple Zone must fit into a 15cm long X 9cm wide X 5cm tall box
- Each Crumple Zone must use less than 1 foot of tape
- Each Crumple Zone must be taped to the front of the car

Products:

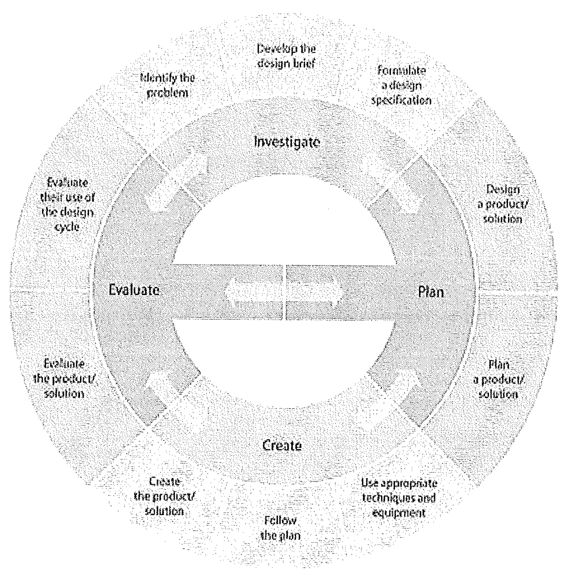
- You will be graded on Criteria D & E (See attached Rubrics)
- You will create a poster to display your work
- The crumple zone that creates the lowest Force on impact wins!

Description of the Problem/Question: (What is the purpose of this investigation? What is it that you will need to do to win? What are important parts to remember when trying to solve this problem?)

Initial Knowledge: (What do you know about crumple zones and car crashes? How will you use this knowledge in designing the safest crumple zone?)

Hypothesis: (What will be the characteristics of a crumple zone that will keep the passengers the safest by having the smallest net force? Why do you believe this?)

Variables: (What are the Independent, Dependent & Controlled variables?)



Design #1 Data

Plan: Draw and Label Plan for Crumple Zone

Actual Design: Draw and Label Actual Design for Crumple Zone

After Crash: Draw and Label Crumple Zone after crash

Data

Mass of Cart:

Graph Equation:

Acceleration of Cart:

Force on Cart:

Sketch of Position vs. Time Graph:

Design #2 Data

Plan: Draw and Label Plan for Crumple Zone (What makes this design better than #1?)

Actual Design: Draw and Label Actual Design for Crumple Zone

After Crash: Draw and Label Crumple Zone after crash

Data

Mass of Cart:

Graph Equation:

Acceleration of Cart:

Force on Cart:

Sketch of Position vs. Time Graph:

Design #3 Data

Plan: Draw and Label Plan for Crumple Zone (What makes this design better than #2?)

Actual Design: Draw and Label Actual Design for Crumple Zone

After Crash: Draw and Label Crumple Zone after crash

Data

Mass of Cart:

Sketch of Position vs. Time Graph:

Graph Equation:

Acceleration of Cart:

Force on Cart:

Final Design Data

Plan: Draw and Label Plan for Crumple Zone (What makes this design better than design #3?)

Actual Design: Draw and Label Actual Design for Crumple Zone

After Crash: Draw and Label Crumple Zone after crash

Data

Mass of Cart:

Acceleration of Cart:

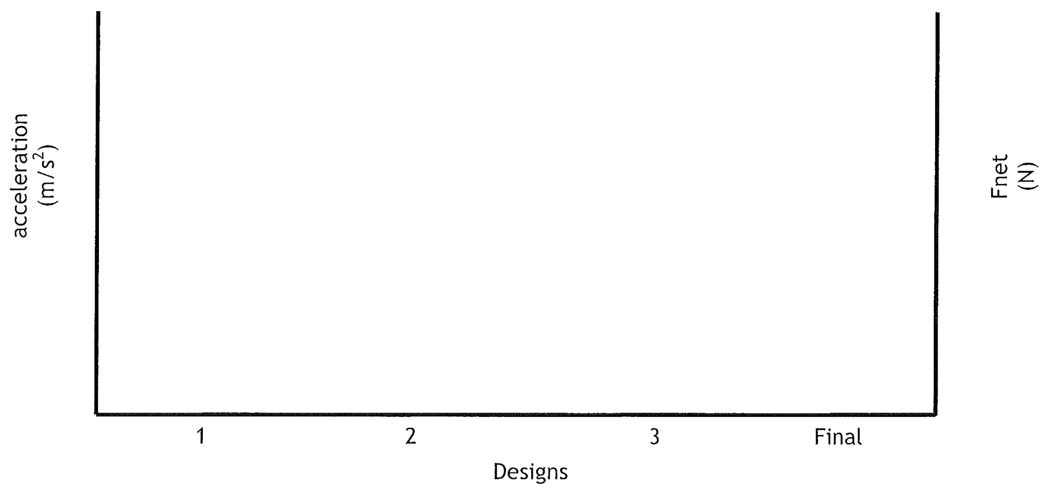
Force on Cart:

Data Table:

Design Number	Acceleration (m/s^2)	Force (N)
1		
2		
3		
Final		

Graph:

Force and Acceleration for Crumple Zone Designs



Trends/Patterns/Relationships: (What noticeable or surprising features do you see in your data? What information do you see in your data to help you know which crumple zone is the best?)

Reliability of Data: (How accurate are your measurements? How well did you make your measurements?)

Conclusion: (What design did you test that was the best? What about how the design was made that made it the safest? What scientific reasons make these characteristics of the crumple zone the best?)

Improvements: (What would you change next time about the plan or procedure?)

Area(s) for further research: (What else could you experiment with to improve the safety of your car? What other materials could you bring in to create a safer crumple zone? What other science would it be helpful to know to make a safer car?)

D: Scientific Inquiry Rubric

	IB Descriptor	Task Specific Modifications
0	The student does not reach a standard described by any of the descriptors given below.	☐ Does not fall in any of the higher categories.
1-2	The student attempts to define the purpose of the investigation and makes references to variables but these are incomplete or not fully developed. The method suggested is partially complete. The evaluation of the method is either absent or incomplete.	☐ **Define Purpose:** Talks about the question you are trying to research or why are you doing this experiment/answering this question. ☐ **Identify Variables:** Identifies a few of the variables; independent variable, dependent variable and controlled variables. ☐ **Method:** Describes some of the steps that you are going to do in your lab or lists some of the materials used. ☐ **Reliability, Validity, Improvements, and Further Investigations:** Includes 0 to 2 of these with minimal detail in explanations.
3-4	The student defines the purpose of the investigation and provides an explanation/prediction but this is not fully developed. The student acknowledges some of the variables involved and describes how to manipulate them. The method suggested is complete and includes appropriate materials/equipment. The evaluation of the method is partially developed.	☐ **Define Purpose:** Explains the question you are trying to research and why are you doing this experiment/answering this question. ☐ **Hypothesis:** Describes hypothesis and explains why you believe this (using correct scientific vocabulary). ☐ **Identify Variables:** Identifies some of the variables; independent variable, dependent variable and controlled variables. ☐ **Method:** Describes the steps that you are going to do in your lab and how you are going to change each variable, and lists materials used. ☐ **Reliability, Validity, Improvements, and Further Investigations:** Includes a discussion of at least 2 of these with some detail.
5-6	The student defines the purpose of the investigation, formulates a testable hypothesis and explains the hypothesis using scientific reasoning. The student identifies the relevant variables and explains how to manipulate them. The student evaluates the method commenting on its reliability and/or validity. The student suggests improvements to the method and makes suggestions for further inquiry when relevant.	☐ **Define Purpose:** Explains in detail the question you are trying to research and why are you doing this experiment/answering this question. ☐ **Hypothesis:** Describes hypothesis and explains in detail why you believe this (using correct scientific vocabulary). ☐ **Identify Variables:** Describe with details independent, dependent and controlled variables. ☐ **Method:** Describes in detail the steps that you are going to do in your lab and how you are going to change each variable. Describes equipment used. ☐ **Reliability & Validity:** Describe using details if your measurements are correct and accurate and if your method actually works to answer your question. ☐ **Improvements:** Explains in detail what could you do to make your lab more reliable or valid if you were to perform it again? ☐ **Suggest Further Investigations:** Describe what the next experiment you would perform or question you would want to answer and explain why.

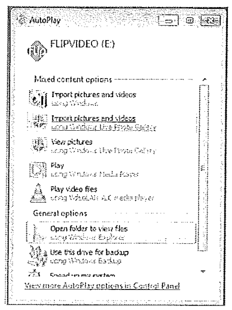
E: Data Processing Rubric

	IB Descriptor	Task Specific Modifications
0	The student does not reach a standard described by any of the descriptors given below.	☐ Does not fall in any of the higher categories.
1-2	The student organizes and presents data using simple numerical or diagrammatic forms and draws an obvious conclusion.	☐ **Data Table or Graph:** Contains either data table or graph, maybe missing up to 3 important features of the image ☐ **Conclusion:** Conclusion is stated
3-4	The student organizes and transforms data into numerical and diagrammatic forms (tables, graphs) and presents it using appropriate communication modes. The student draws a conclusion consistent with the data.	☐ **Data Table:** Data table with important variables included. Missing 1 of the following: labels, units, complete data. ☐ **Graph:** Graph with X-Axis Independent Variable, Y-Axis Dependent Variable. Missing up to 2 of the following: Axis Labels, Units, trendline, equation ☐ **Conclusion:** Conclusion is stated and agrees with your data
5-6	The student organizes and transforms data into numerical and diagrammatic forms (tables, graphs) and presents it logically and clearly, using appropriate communication modes. The student explains trends, patterns or relationships in the data, comments on the reliability of the data, draws a clear conclusion based on the correct interpretation of the data, and explains it using scientific reasoning.	☐ **Data Table:** Includes labels, units, all variables correctly in table. ☐ **Graph:** Appropriate graph with X-Axis Independent Variable, Y-Axis Dependent Variable, Axis Labels, Units, trendline, equation. ☐ **Trends, Patterns and Relationships:** Discusses in detail observations from data in graph. ☐ **Reliability:** Discuss in detail how well the data was measured. ☐ **Conclusion:** Clear, correct, and a detailed answer to question that is based on evidence from data. ☐ **Scientific Reasoning**: Discuss using detail and "book knowledge" how your conclusion matches up with the scientific and real world understanding.

Flip Camera with Logger Pro instructions

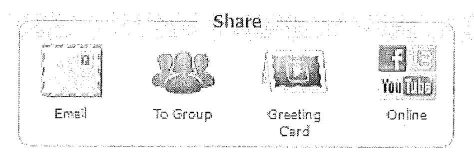
Plug camera into USP on lap top

Ignore and close this:

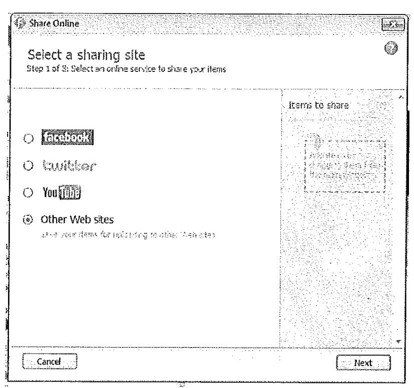


Open FlipShare application

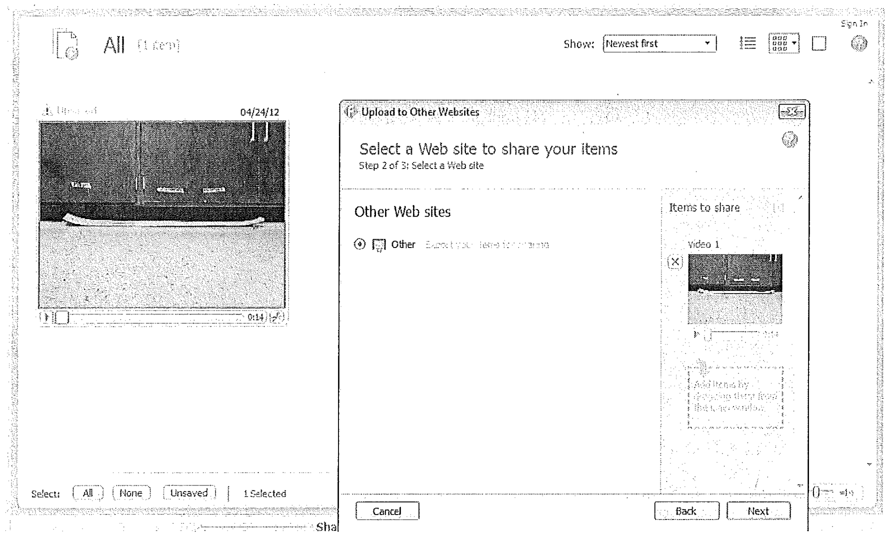
Click Share Online:



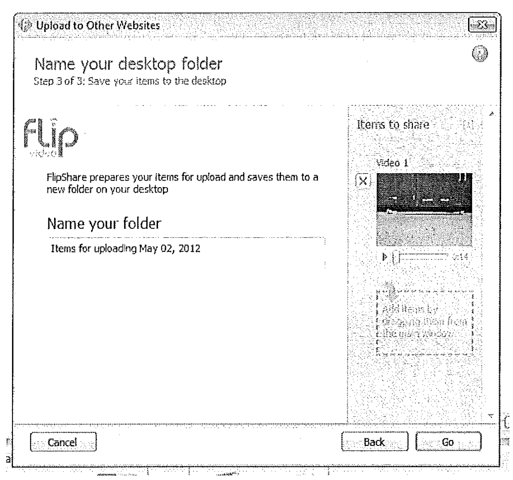
Check Other Web sites and click next:



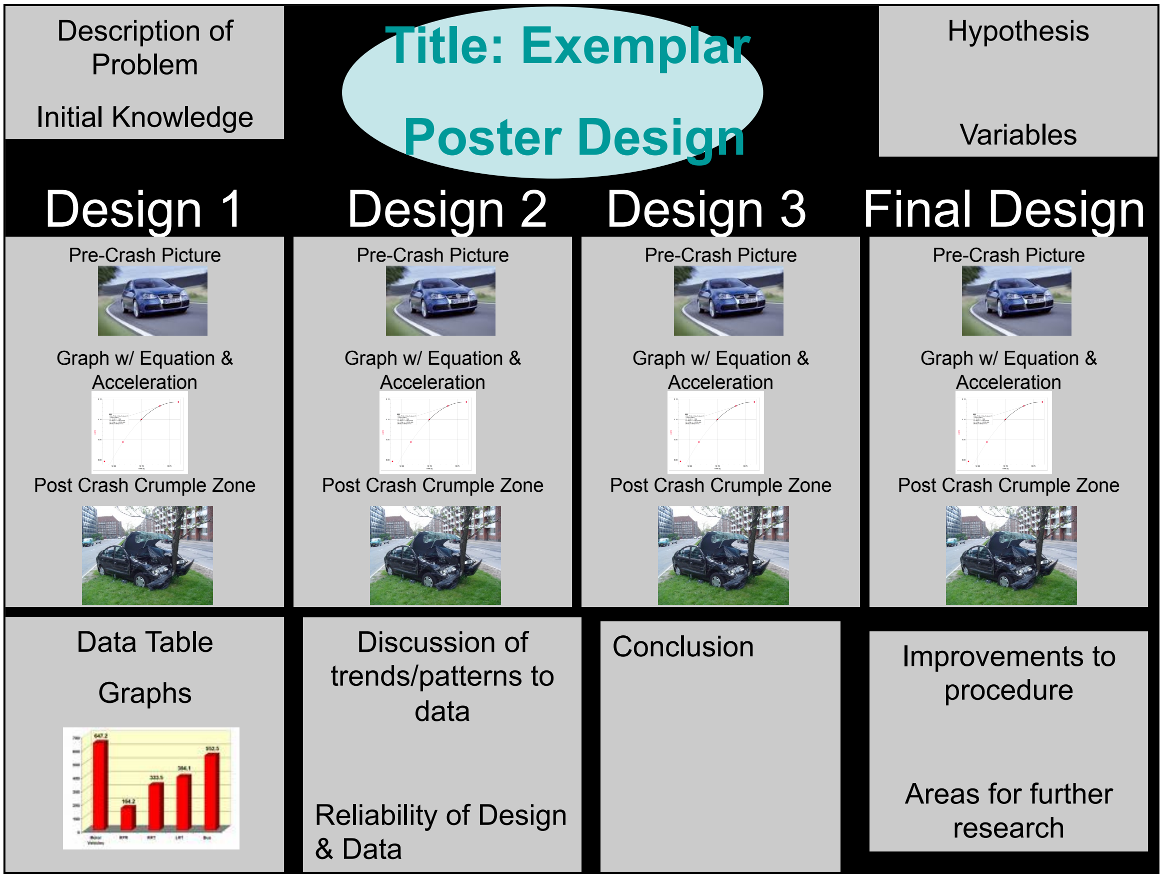
Check Other Web sites again and drag your video into the Items to share window. Click Next:



Keep the name assigned to the folder or change it. This will show up on the desk top. Click Go:



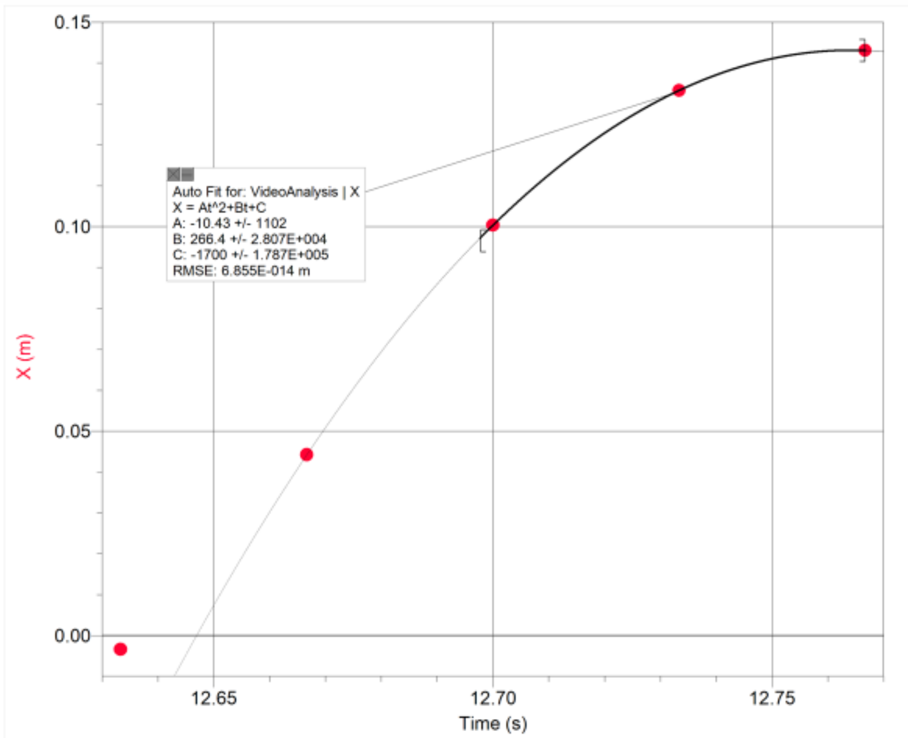
Open Logger Pro and use Insert>Movie.


Description of Problem
Initial Knowledge
Title: Exemplar
Poster Design
Hypothesis
Variables
Design 1
Design 2
Design 3
Final Design
Pre-Crash Picture
Graph w/ Equation & Acceleration
Post Crash Crumple Zone
Pre-Crash Picture
Graph w/ Equation & Acceleration
Post Crash Crumple Zone
Pre-Crash Picture
Graph w/ Equation & Acceleration
Post Crash Crumple Zone
Pre-Crash Picture
Graph w/ Equation & Acceleration
Post Crash Crumple Zone
Data Table
Graphs
Discussion of trends/patterns to data
Reliability of Design & Data
Conclusion
Improvements to procedure
Areas for further research

Physics: Crumple Zone assessment Name ____________________

State Standard - Developments in physics affect society and societal concerns affect the field of physics.

Achievement Level	
3-4	5-6
1) The goal for acceleration during the crash in the crumple zone project should be: a) Large b) Medium c) Small Describe (give a detailed account) your reasoning for this answer.	1) The goal for time during the crash in the crumple zone project should be: a) Large b) Medium c) Small Describe (give a detailed account) your reasoning for this answer.
2) Using the video analysis graph on back, find the acceleration for the 1.4 kg cart. Show your work. $x_f = ½a(\Delta t)^2 + v_i(\Delta t) + x_i$	2) Using the video analysis graph on back, find the force for the 1.4 kg cart. Show your work.



0.15
0.10
0.05
0.00
X (m)
12.65
12.70
12.75
Time (s)
Auto Fit for: VideoAnalysis | X
X = At^2+Bt+C
A: -10.43 +/- 1102
B: 266.4 +/- 2.807E+004
C: -1700 +/- 1.787E+005
RMSE: 6.855E-014 m

2

REQUEST FOR PROPOSAL

25V-55 Crude Vacuum Prefractionation Tower

Proposal #: 12-25V55

Date: January 23, 2012

CONTACTS

Dan	651-438-1783
Mike	651-480-3859

SCHEDULE

Project description presentation	1/23/11
Return visit by project member(s) for questions	2/15/11
Submit proposals and present recommendations	3/7/11
selects proposal and Control Room tour	TBD

INTRODUCTION

is installing a new crude pre-fractionation tower as part of their Crude Capability project. requests your consulting company to provide a design for a foundation for this vessel along with an estimate for installation.

BACKGROUND

is an oil refinery that produces various products such as gasoline, diesel fuel, jet fuel, asphalt, propane, butane.

The Process

is expanding its capability in an effort to produce more light products (gasoline, diesel, and jet fuel) in the Minneapolis market. The heavy Canadian crude that processes typically produces a high volume of asphalt and petroleum coke (similar to coal). This project focuses on installing a Vacuum Pre-Fractionation (VPF) tower. The VPF tower will allow to lower the pressure and recover more light products from the asphalt.

The Market
Crudes are referred to in two basic categories, sweet (lighter, less sulfur content, less acidic), OR sour (heavier, high in sulfur, more acidic). Heavier, sour crudes can be purchased at a lower cost. Refineries need special equipment with specific metallurgies to refine heavy, sour crudes into usable products.

The Bet
is implementing a capital capability project to enable them to run heavier, sourer crude through their units. The bet is that if crude can be purchased at a lower price and refined to the same quality end product, profit margins will increase.

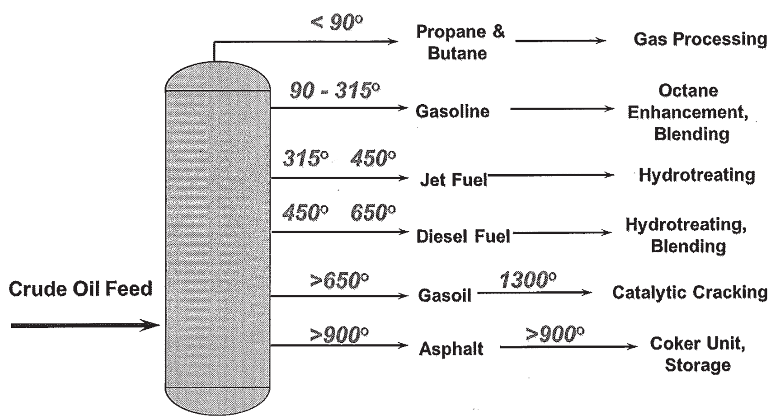


Fig 1 – General Process

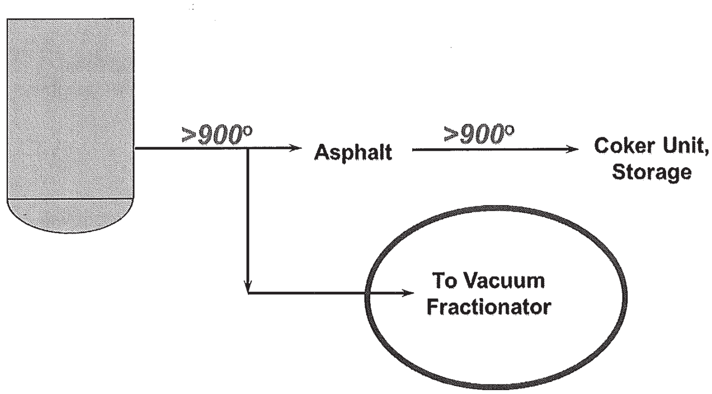


Fig 2 – Additional capability by adding Vacuum Pre-Fractionator

PROJECT WORK SCOPE

1. Design a vessel foundation to support such a structure to withstand winds and other forces common to the area and that will fall within the design parameters.
    - Foundation design to include material of construction and anchor detail between vessel and foundation
2. The system shall not include any consideration for additional piping, pumps, or valves. All equipment parameters shall be considered adequate for the new design.
3. The cost estimate shall be determined using the data located in Appendix 2.
4. Design a foundation to prevent overturning of vessel with the following constraints:
    - Safety Factor of 1.5 for empty vessel.
    - Safety Factor of 2.0 for full vessel.
    - Do not exceed soil bearing strength.
5. Examine overall effects of the wind on the tower and its foundation (i.e. – deflection).

DELIVERABLES

Please provide (2) copies of the proposal, 1 for , and 1 for Mr. Olsen.

The Consultant's design proposal shall consist of the following:

1. Consultant's Company Name, team members, referenced Request For Proposal number.
2. Provide the Company's background and team member's qualifications.
3. A brief problem statement.
4. Identify all assumptions used in the design
5. A list of alternatives considered and a short description.
    - Clearly identify your recommended alternative
    - If more than one alternative is considered then a cost benefit analysis should be conducted to determine the best single option.
6. The results of all calculations must include units (e.g. feet, pounds, ect…)
7. A detailed description of the recommend solution, including:
    - Foundation design and achieved factor of safety.
    - Evaluate wind load on the vessel (lbf) and the overturning moment (ft-lbf)
    - Bolting size and quantity
    - Expected deflection of the vessel due to wind (in or ft)
    - Any additional assumptions made.
    - A total cost estimate for the installation (round the total to the nearest $1,000)
8. Bonus work – How much vertical thermal growth would you expect in this vessel?

Proposal write up should be concise (two or three typed pages, maximum) and look professional. Please attach pertinent illustrations, figures, and data as appendices. Proposals are requested even if a complete design solution has not been reached.

APPENDIX 1

SYSTEM DESIGN DATA: Assumptions, Definitions, Properties, and Cost

Assumptions:

- This is a fixed not hinged condition between the foundation and the vessel.
- Pre-consolidation has taken place in the surrounding soil.
- There are no surrounding buildings thus no vortex factors need be considered.
- The minimum thickness of any concrete cross section must be 3ft to allow for adequate steel reinforcement.
- Top two foot of vessel dome is to be excluded in overall analysis.

Abbreviations and Definitions

ft = foot
in = inch
gal = gallon
lb = pound
s = second
mph = miles per hour

Properties

Water density	ρ_w = 62.4 lb/ft3
Acceleration due to gravity	g = 32.2 ft/s2
Specific Gravity of Crude	S.G. = 0.94
Weight of concrete	w_c = 150 lb/ft3
Soil Bearing Strength	b = 3000 lb/ft2
Soil Density	ρ_s = 100 lb/ft3

Vessel Characteristics:

Empty weight: 260,000
Weight with internal components and insulation: 388,750
Operating weight: 647,000
Average Operating Temperature: 670 deg F

Soil Characteristics:

Frost depth is 4.5 feet.
Soil type is silty sand.

General Cost Estimation Data:

Excavation Costs = 16 labor-hours per 10yd3
Labor Costs = $65 / hour
Concrete Pouring and Forming = $900 / 1yd3
Soil Transport = $100 / yd3

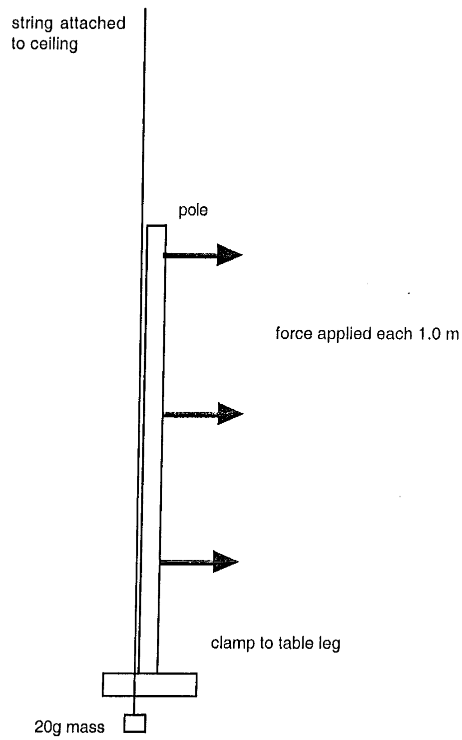
HP12

Deflection

As force is placed on a rod or pole that is firmly planted on one end, it will deflect. This experiment will investigate this deflection. The goal will to be developing a working formula that will predict this deflection for any size pole or tower.

When finding a new formula you should test all factors that will affect the concept. Then graph the results, determine the relationships and write a formula. Since this will be a working formula it will be important to find the constant for the formula.

When a factor is tested all other factors must be controlled. You may want to review the Centripetal Force lab to see how this is accomplished.



The drawing above shows the equipment set up for this experiment. The string is tacked to the ceiling and a 20g mass is hung from the bottom. The force being tested is applied each meter. This is called a distributed force (ex 4.0N/m). The deflection will be measured at the top of the pole.

Procedure

Part I: Force

The goal here is to test the affect of force on deflection. Select a 1/2 in PVC pipe that is about 1.5m long. Use a vernier caliper to determine the inside and outside diameter of the pipe. Set up the equipment as shown on the front page. Measure the height of the pipe from the U-clamps to the top of the pole. Tie a string with a loop on it about 10cm from the top of the pole and then another 1.0m below that string. Use 10N scales to pull apply a distributed force to the strings. Begin with 1.0N, increasing it by 1.0N at a time until 10N is reached. Record the deflection for each force. The deflection is the distance from the top of the pole to the string. Record all data (see chart below).

Part II: Diameter

The goal here is to test the affect of outside diameter on deflection. Use the pipe from part one and repeat a trial using a 6.0N distributed force. Replace the pipe with one of a different diameter. Measure the inside and outside diameter. Adjust the new pipes height to match the first pipe. Repeat the trial again using a 6.0N distributed force. Repeat with 3 other pipes with different diameters. Record all data.

Part III: Length

The goal here is to test the affect of length on deflection. Select a 10ft pipe. Measure it's inside and outside diameters. Clamp it into your apparatus. Tie string loops at 10cm from top, 1.0m below and 2.0m below the top string. Three force scales are needed for this test. Pull each string simultaneously with a 4.0N force. Now measure the deflection at each of these positions from the bottom U-clamps: .5m, 1.0m, 1.5m, 2.0m and 2.5m. Record all data.

Length (m)	Outer Diameter (m)	Inner Diameter (m)	Distributed Force (N)	Deflection (m)

A spreadsheet expert should develop a spreadsheet that will record all this data.

Part IV: Graphing

1)Use the JMP program to make the following graphs.

distributed force and deflection
outside diameter and deflection
length and deflection

2) A correct relationship needs to be determined and proven for each graph. To do this the graph needs to made straight. If you think it is a squared relationship then square the appropriate factor and regraph. If this doesn't make it straight then cube it and graph, and so on until it is straight. For inverse graphs ask the instructor what to do. All square, cubed and etc need to added to the chart. All graphs are to done on JMP.

The spreadsheet expert should expand the spreadsheet to include any squared, cubed, etc columns that were used in the relationships.

Part V: Equation
Use the relationships determined in Part IV to write and equation for the deflection of the pipe. **Next the have the spreadsheet expert add a column to calculate the constant.** Examine the list of constants throw out any outliers and find the average. Determine the unit for this constant.

Part VI: Material
Obtain an iron pipe. Run two trials using different forces with this pipe. Use your new equation to find the k for this iron pipe.

Have these trials added to your spreadsheet.

Questions:

1) Why was the pole pulled with more than one scale? How would it have changed the results if only one scale was used?

2) What does the constant represent in this experiment?

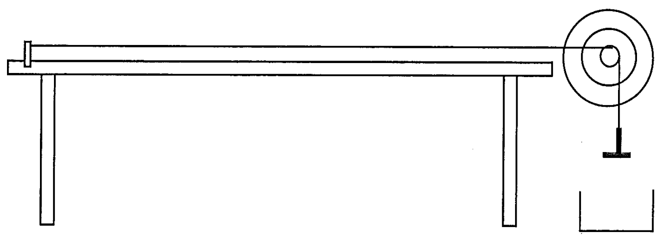
3) What could change the constant?

4) What type of energy is involved in the deflection of the pipe?

5) If the inside diameter was put into this formula, do you think it would affect the deflection? If so, how?

Elasticity: Stress and Strain

When a force is applied to an object it often changes shape. If the force is a pull the object gets longer. This experiment will examine this elongation.



Procedure: Cut a piece of wire about .5 m longer than the length of the table. Tie the aluminum wire to a small C-clamp on one end of the table. Tie an S hook to the other end of the wire. Wrap the wire one time around the small wheel of the wheel and axle. Adjust the protractor reading to zero at some point. Hang a 50g T-mass mass on the wire so that it straightens the wire. Record the length of the wire from the clamp to the wheel. Place a bucket of sand under the T-mass. Place a 100g mass on the T-mass, measure the degrees the wheel rotates. Remove the 100g mass and **GENTLY** replace it with 200g, repeat the measurements. Continue adding mass (100g at a time) until the wire breaks.

Convert the masses to weight (force). Measure the diameter of the small wheel with a vernier caliper. Convert the degree readings to length stretched (Δl) using the diameter of the small wheel. Recorded all values in a chart.

Mass	Degrees	Force	length stretched

A spreadsheet expert should now develop a spreadsheet that will record all the data.

Make a graph of the force vs the elongation with the elongation on the abscissa. On this graph identify the elastic region, proportional limit, elastic limit, the plastic region and the breaking point. Refer to section 9-5 of your text.

Questions:

1) Find the proportional constant (k) for your wire.

2) Does your graph match the example in the text. If not what is the difference?

3) Define these terms: proportional limit, elastic limit, ultimate strength, elastic modulus, stress, strain and breaking point.

4) Determine the radius of the wire using a micrometer. Find the cross sectional area of the wire.

-over-

5) Calculate each of the following values for each trial. Record them in the chart below. Show example calculations. Determine the unit on each value and include them on your chart.

a) Find the stress.
b) Find the strain.
c) Find the Elastic Modulus.

Stress	Strain	Elastic Modulus

The spreadsheet expert should expand the spreadsheet to include a calculations section.

6) Throw out any outliers from your Elastic Modulus list and find the average of the remaining.

7) Compare your elastic modulus to the accepted value for aluminum. (see your text)

8) Calculate the Tensile Strength for the aluminum wire fro each trial of the experiment. Extend your calculations table and add these values. Include a unit on the column.

The spreadsheet expert should also do this on the spreadsheet.

9) Throw out any outliers from your Tensile Strength list and find the average of the remaining.

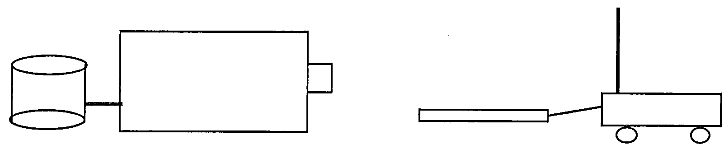
10) Compare your elastic modulus to the accepted value for aluminum. (see your text)

11) How would your data have changed if the wire had been steel rather than copper? (use text)

HP12

Force of Wind

When wind blows on a surface it produces a force on that surface. This experiment will investigate that force and develop a formula for the force. Since the force is applied over an area the result is called pressure with a unit of N/m^2. Refer to your notes to better understand this concept.



The above equipment consists of a vacuum connected to a powerstat. The exhaust end of the vacuum is used to produce the wind. The velocity of the wind can be adjusted by varying the power with the powerstat. The velocity of the wind can be measured with a anemometer. When checking the force on the cart make sure the entire sail is being covered by the wind. Also, make sure the spring scale is horizontal and zeroed.

Procedure:

Part I: Area

You are to first test the sail area's affect on the force.

1) Attach a support brace to the cart for the sail.
2) Cut out a 12x12cm piece of tag board and tape it to the support on the cart.
3) Adjust the vacuum so that it will produce a wind of about 8 mph. Make sure you position the vacuum so that the wind will blow parallel to the counter and will cover the area of the sail.
4) Attach a scale to the cart. Turn the vacuum on and measure the force.
5) Remove the cart and measure the exact wind speed.
6) Now remove the sail and support. Return it to the same position in #4 and measure the force on the cart without the sail. (the lower should remain in the exact same position)
7) Now repeat the above steps using 4 other areas, some less and some more. Make sure the wind will be able to cover the area being used. You must control the wind for these trials.
8) Record all data.

Data Table

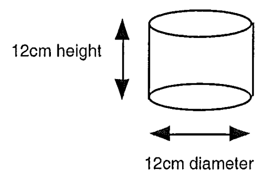
Length (m)	Width (m)	Force Sail & Cart (N)	Force Cart (N)	Wind Velocity (mph)

Part II: Wind Velocity
You are now going to test the effect of velocity of the wind on a force.

1) Attach the 12x12cm sail to the cart.
2) Run trials using different wind velocities from 2 mph to max. Six trials should be run. You are controlling the area.
3) Record all data in your data table.

Part III: Shape
You will now test the effect of shape on force.

1) Make a cylinder with a cross sectional area equal to that of the sail in part II.



2) Repeat all trials run in part II using this sail. All velocities and positions should be the same.
3) Record all data in your data table.

A spreadsheet expert should now develop a spreadsheet that will record all the data for Parts I - III.

Part IV: Calculations
Complete the following calculations recording them in a calculations table. Show example calculations below the table.

1) Find the area in square meters for each trial.
2) Find the force on the sail alone for each trial.
3) Convert the wind velocity to m/s.

Trial	Area (m^2)	Sail Force (N)	Wind Velocity (m/s)

The spreadsheet expert should expand the spreadsheet to include a calculations section.

Part V: Graphing & Equation

Now you will make graphs for Parts I & II. Part III will be dealt with separately.

1) Make the following graphs with the JMP program.

   Area and Force
   Wind Velocity and Force

2) A correct relationship needs to be determined and proven for each graph. To do this the graph needs to made straight. If you think it is a squared relationship then square the appropriate factor and regraph. If this doesn't make it straight then cube it and graph, and so on until it is straight. For inverse graphs ask the instructor what to do. All square, cubed and etc need to added to the chart. All graphs are to done on JMP.

3) Use the graphs to write an equation for the force on a sail.
4) Find the value for the constant for each trial. Extend your calculations chart and include these values.
   The spreadsheet expert should also do this on the spreadsheet.
5) Write a final equation with this constant including units.

Part VI: Shape Factor

Now the effect of shape needs to be addressed.

1) Find the ratio of the force on the cylinder to the force on the same size straight sail.
2) Analyze these ratios, throw out any outliers, and average the rest.
3) Add a symbol into your equation that would represent the sail shape.

Questions:

1) Why did you need to find the force on the cart alone?
2) How did the force on the cylinder compare to the straight sail? Why?
3) How was this experiment controlled?
4) Identify some sources of error for the experiment.

Bolt Information

for axially loaded columns per the AISC column formula should not exceed

$$P/2a \leq 17000 - 0.485\,(L/r)^2 \text{ psi},$$

where

$a = t_V(n - 0.25)$, the cross-sectional area of one stiffener, in.
L = length of the stiffener, in.
$r = (I/a)^{1/2} = 0.289t_V$, the radius of gyration of the stiffener, in.
P = the maximum bolt load, lb.
$(n - 0.25)$ = effective width of the stiffener, in.

The thickness t_V is usually between $\frac{1}{2}$ and $1\frac{1}{4}$ in., depending on bolt size. Where no uplift or only a very small uplift results from external loads the top ring section can be omitted between bolts and the design reduces to a bolting chair. The minimum size for bolts ($\frac{3}{4}$ to 1 in.) is selected and the anchor bolts serve merely to locate the vessel in place.

Skirt Material

The most frequently used materials for support skirts are carbon steels, A283 gr. C for thicknesses up to $\frac{5}{8}$ in. and A285 gr. C for thicknesses $\frac{5}{8}$ in. and above. Since this is a very important structural part the allowable stresses used are the same as for the pressure parts.

The heavy base rings are also fabricated from A285 gr. C with yield strength S_y = 30000 psi. Since the allowable bending stress for structural steels with S_y = 36000 psi in the AISC base plate formula is 20000 psi, the allowable bending stress for A285C to be used in the AISC formula can be determined as follows:

$S = 20000 \times 30/36 = 16700$ psi	weight only
$S = 1.33 \times 16700 = 22200$ psi	weight plus wind
$S = 1.2 \times 16700 = 20000$ psi	test weight

Higher allowable stresses are acceptable for the base ring than for the skirt shell because minor deformations of the base ring from overstressing would not cause any damage.

4.4. ANCHOR BOLTS

Self-supporting columns must be safely fixed to the supporting concrete foundations with adequately sized anchor bolts embedded in the concrete to prevent overturning or excessive swaying from lateral wind or earthquake loads. To compute the tension stress in the bolts and their required size and number one of three methods can be applied: (1) a simplified method, using generalized design conditions and ignoring dynamic effects and necessary preloading of bolts; (2) a more complete method, considering initial preload on bolts; and (3) disregarding initial preload on bolts.

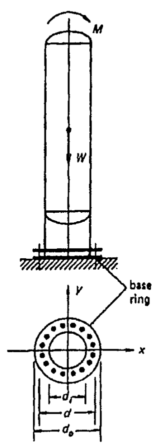
Simplified Method

The forces and the moments acting on a tall slender vessel are shown in Fig. 4.4 as assumed for the anchor bolt analysis.

Assuming that the column will rotate about the axis y in Fig. 4.4, the maximum uplift force F per bolt due to the outside moment M is determined as follows. The maximum tension on the bolt circumference in lb. per lin. in. is given by

$$T = (M/Z_L) - (W/C) = (4M/\pi d^2) - (W/\pi d) \text{ lb/in.}$$

If $4M/\pi d^2$ is larger than $W/\pi d$ there is a positive uplift force inducing tension stress, with magnitude depending on the distance x spanned by half the anchor



A_b = bolt tensile stress area, in.^{2}
M = overturning moment at base due to wind or earthquake, lb-in.
W = weight of the vessel, operating (W_o) or erection (W_e), lb
d = bolt circle diameter, in.
d_o = outside diameter of the base ring, in.
d_i = inside diameter of the base ring, in.
N = total number of anchor bolts in multiples of 4
Z_L = $\pi d^2/4$, linear section modulus of the bolt circle, in.^{2}
C = πd, circumference of the bolt circle, in.
x = distance of an anchor bolt from the neutral axis y, in.
S_a = allowable design stress for the anchor bolts, psi

Fig. 4.4.

bolts. The maximum force F on the bolt at distance $x = d/2$ from the axis y is

$$F = T\pi d/N = (4M/dN) - (W/N) \text{ lb/bolt}$$

and the required bolt area is

$$A_b = [(4M/d) - W]/NS_a.$$

The anchor bolts are not designed for the horizontal shear force since it is clearly counteracted by the friction between the base ring and the foundation.

Obviously, this approach is simplified, since it does not try to establish more accurately the actual design conditions, the initial bolt preload, and the dynamic effect of the external overturning moment. However, it is generally accepted for sizing the anchor bolts and, if a relatively conservative allowable stress S_a is used in the design, it gives acceptable results and is very simple to apply.

Initial Preload in Bolts Considered

Since wind and earthquake loads are essentially dynamic, initial tightening of the bolt nuts is required to reduce the variable stress range or any other impact effect on the nut under operating conditions.

The maximum force per bolt resulting from the combined action of the overturning moment M and the initial preload could be found by an approximate analysis with the following design conditions assumed, as follows.

1. The initial bolt preload together with the weight of the vessel is large enough to maintain a compressive pressure between the vessel base plate and the concrete pedestal under design loads.
2. As long as this compression exists at the contact area the skirt base and the pedestal behave as a continuous structure and the support base will rotate about the neutral axis of the contact area (axis y in Fig. 4.4).

Under moment M the maximum and the minimum pressure on the contact area becomes

$$S_c = (NF_i/A_c) + (W/A_c) \pm (Md_o/2I_c),$$

where

$$A_c = \pi(d_o^2 - d_i^2)/4$$

$$I_c = \pi(d_o^4 - d_i^4)/64$$

Substituting the above result into the previous expression for T, the thickness of the steel shell can be computed:

$$t_s = \frac{1}{S_s d}\left[\frac{M - W(zd)}{(jd)}\right]\left[\frac{1+\cos\alpha}{(\pi-\alpha)\cos\alpha + \sin\alpha}\right]$$

and *the required bolt area* is

$$A_b = t_s \pi d / N \text{ in.}^2 .$$

From the summation of the vertical forces acting on the vessel, $T + W - C = 0$, the minimum base ring width t_c can be determined:

$$t_c = [(T + W)/S_c d]\,[(1 - \cos\alpha)/(\sin\alpha - \alpha\cos\alpha)] .$$

To accommodate the anchor bolts t_c is usually made larger than required by the above equation for the computed location of the neutral axis. To maintain the position of the neutral axis and the validity of computations the area A_s is increased in direct proportion to A_c. However, the stresses in bolts will decrease in inverse proportion to A_c. If t_c and A_c only are increased the neutral axis shifts toward the compression side and A_s becomes oversized and can be decreased. In order to find the minimum A_s a redesign would be required.

Only an outline of this method has been presented here. The interested reader will find any additional information in refs. 42–45. The main shortcoming of the method is the omission of the initial preload in the bolts and the treatment of the loads as static. If high allowable stresses are used, the design can lead to unconservative results, and this is probably why this approach has not been generally used.

In practice, a considerable preload always has to be applied, and the bolts used should be of sufficient size to permit retightening in excess of minimum design requirements in order to prevent large stress fluctuations. On a few occasions in the writer's experience, excessive swaying of process towers developed simply because the anchor bolts were not pulled up tight enough by the erection crews.

Allowable Stresses for Carbon Steel Anchor Bolts

The standard material used for anchor bolts is carbon steel type A307 gr. A or B, with a minimum tensile strength of 60,000 psi. Bolt threads, standard coarse thread series or eight-thread series, should preferably be rolled, with forged nuts of heavy series. Sometimes a corrosion allowance of $\frac{1}{16}-\frac{1}{8}$ in. is specified and two nuts (one as a lock nut) per bolt are used where frequent heavy winds can be expected.

The allowable stress in tension for the threaded part of the anchor bolt is a matter of safe design, subject to engineering judgment. The allowable stress for A307 bolts in the AISC Manual is 20,000 psi. This high allowable stress would require an accurate stress analysis with well-defined static loads. Noting that

wind and earthquake loads are dynamic loads,
there is always a possibility of overload,
a failure of a process column would cause a large loss of property,
bolt material is comparatively cheap,
inspection of the anchor bolts is often inadequate, and
any repair in the field is very costly,

it is reasonable to accept lower allowable stresses.

It is a common engineering practice to select the allowable stresses for carbon steel anchor bolts as follows:

S_a = 15,000 psi under operating conditions

S_a = 15,000 X 1.2
= 18,000 psi under empty (erection) condition.

Types of Anchor Bolt

Some typical details of installed anchor bolts are shown in Figs. 4.8 and 4.9. The required length L of the bolt embedded in the concrete foundation is designed by the civil engineer. It has a holding power equal to the full tensile strength of the bolt. Minimum bolt spacing is usually set at 10 times nominal bolt diameter. The dimension h is usually specified as 12 in.; the longer the free length of the bolt, the higher its resilience, i.e., its ability to absorb an impact load without permanent deformation.

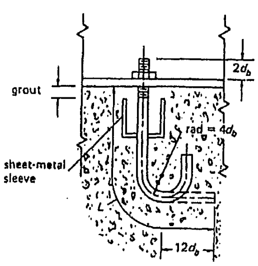


Fig. 4.8. Anchor bolt for small vessel.

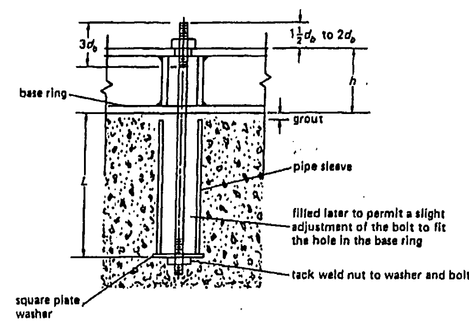


Fig. 4.9.

4.5. WIND-INDUCED DEFLECTIONS OF TALL COLUMNS

A sustained wind pressure will cause a tall column to deflect with the wind. The magnitude of the deflection may seriously influence the performance of a process column and has to be limited to a certain value. If too small a deflection at the top of the column is specified by the client's specifications, the shell thickness must be increased and the price of the tower will increase. Most engineering specifications ask for a maximum deflection of 6 in. per 100 ft of column height.

The deflection at the top of tall slender columns ($H/D \geq 15$) is routinely checked. Deflection computations are often computerized; however, a need may arise for such calculations to be made by hand.

No matter what short-cut analytical method is used, the computations are comparatively lengthy and subject to error. The method should be flexible enough to permit easy inclusion of such variables as shell thickness, modulus of elasticity due to changes in operating temperature, and wind pressure above the ground. The method should also be as simple as possible and permit the use of the results from previous computations of the wind moments and the wind loads for the determination of the shell thicknesses.

There are a number of methods which can be used.

The method of superposition can be applied here to advantage. The vessel is assumed to be a cantilever beam firmly fixed to the concrete pedestal. The effect of foundation movement is considered negligible. The six basic formulas used in this method are shown in Table. 4.2.

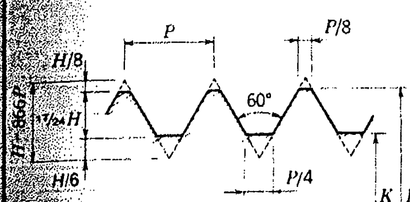
Consider the cantilever beam of Fig. 4.10. Using the formulas in Table 4.2 the individual deflections in Fig. 4.10 can be easily evaluated:

THREADED FASTENERS

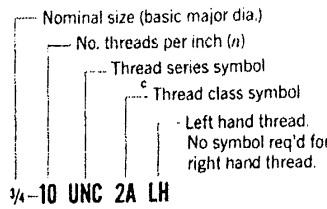
SCREW THREADS

Unified Standard Series—UNC/UNRC and 4UN/4UNR

ANSI B1.1–1982



Thread Dimensions



Standard Designations

Dia.		Area				Dia.		Area			
Basic Major D	Min. Root K	Gross A_D	Min. Root A_K	Tensile[a] Stress	Th'ds[b] per In. n	Basic Major D	Min. Root K	Gross A_D	Min. Root A_K	Tensile[a] Stress	Th'ds[b] per In. n
In.	In.	In.²	In.²	In.²		In.	In.	In.²	In.²	In.²	
¼	.189	.049	.028	.032	20	2¾	2.443	5.940	4.69	4.93	4
⅜	.298	.110	.070	.078	16	3	2.693	7.069	5.70	5.97	4
½	.406	.196	.129	.142	13	3¼	2.943	8.296	6.80	7.10	4
⅝	.514	.307	.207	.226	11	3½	3.193	9.621	8.01	8.33	4
¾	.627	.442	.309	.334	10	3¾	3.443	11.045	9.31	9.66	4
⅞	.739	.601	.429	.462	9	4	3.693	12.566	10.71	11.1	4
1	.847	.785	.563	.606	8	4¼	3.943	14.186	12.2	12.6	4
1⅛	.950	.994	.709	.763	7	4½	4.193	15.904	13.8	14.2	4
1¼	1.075	1.227	.908	.969	7	4¾	4.443	17.721	15.5	15.9	4
1⅜	1.171	1.485	1.08	1.16	6	5	4.693	19.635	17.3	17.8	4
1½	1.296	1.767	1.32	1.41	6	5¼	4.943	21.648	19.2	19.7	4
1¾	1.505	2.405	1.78	1.90	5	5½	5.193	23.758	21.2	21.7	4
2	1.727	3.142	2.34	2.50	4½	5¾	5.443	25.967	23.3	23.8	4
2¼	1.977	3.976	3.07	3.25	4½	6	5.693	28.274	25.5	26.0	4
2½	2.193	4.909	3.78	4.00	4						

[a]Tensile stress area = $0.7854\left(D - \frac{.9743}{n}\right)^2$

[b]For basic major diameters of ¼ to 4 in. incl., thread series is UNC (coarse); for 4¼ in. dia. and larger, thread series is 4UN.

[c]2A denotes Class 2A fit applicable to external threads, 2B denotes corresponding Class 2B fit for internal threads.

MINIMUM LENGTH OF THREAD ON BOLTS

ANSI B18.2.1–1972

Length of Bolt	Diameter of Bolt D, In.															
	¼	⅜	½	⅝	¾	⅞	1	1⅛	1¼	1⅜	1½	1¾	2	2¼	2½	2¾	3
To 6 in. Incl.	¾	1	1¼	1½	1¾	2	2¼	2½	2¾	3	3¼	3¾	4¼	4¾	5¼	5¾	6¼
Over 6 in.	1	1¼	1½	1¾	2	2¼	2½	2¾	3	3¼	3½	4	4½	5	5½	6	6½

Thread length for bolts up to 6 in. long is $2D$ + ¼. For bolts over 6-in. long, thread length is $2D$ + ½. These proportions may be used to compute thread length for diameters not shown in the table. Bolts which are too short for listed or computed thread lengths are threaded as close to the head as possible.

For thread lengths for high-strength bolts, refer to *Allowable Stress Design Specification for Structural Joints Using ASTM A325 or A490 Bolts.*

Foundation Design

Notation:

a = name for width dimension
A = name for area
b = width of retaining wall stem at base
= width resisting shear stress
b_o = perimeter length for two-way shear in concrete footing design
B = spread footing or retaining wall base dimension in concrete design
cc = shorthand for clear cover
d = effective depth from the top of a reinforced concrete member to the centroid of the tensile steel
= name for diameter
e = eccentric distance of application of a force (P) from the centroid of a cross section
f = symbol for stress
f'_c = concrete design compressive stress
$F_{horizontal\text{-}resisting}$ = total force resisting horizontal sliding
$F_{sliding}$ = total sliding force
F_x = force in the x direction
$F.S.$ = shorthand for factor of safety
h_f = height of a concrete spread footing
H = height of retaining wall
H_A = horizontal force due to active soil pressure
l_d = development length for reinforcing steel
L = name for length or span length
M = moment due to a force
M_n = nominal flexure strength with the steel reinforcement at the yield stress and concrete at the concrete design strength for reinforced concrete beam design
$M_{overturning}$ = total overturning moment
$M_{resisting}$ = total moment resisting overturning about a point
M_u = maximum moment from factored loads for LRFD beam design
n = name for number
N = name for normal force to a surface
o = point of overturning of a retaining wall, commonly at the "toe"
p = pressure
p_A = active soil pressure
P = name for axial force vector
= force due to a pressure
P_D = dead load axial force
P_L = live load axial force
P_u = factored axial force
q = soil bearing pressure
q_a = allowable soil bearing stress in allowable stress design, as is $q_{allowable}$
q_g = gross soil bearing pressure
q_{net} = net allowed soil bearing pressure, as is q_n
q_u = ultimate soil bearing strength in allowable stress design
= factored soil bearing capacity in concrete footing design from load factors, as is q_{nu}
R = name for reaction force vector
SF = shorthand for factor of safety
t = thickness of retaining wall stem at top
T = name of a tension force
V = name for volume
V_c = shear force capacity in concrete
V_u = factored shear for reinforced concrete design
w = name for width
w_u = load per unit length on a beam from load factors
W = name for force due to weight
x = horizontal distance
$\bar{y}$ = the distance in the y direction from a reference axis to the centroid of a shape
ϕ = resistance factor
γ_c = density or unit weight of concrete
γ_s = density or unit weight of soil
π = pi (3.1415 radians or 180°)
ρ = reinforcement ratio in concrete beam design = A_s/bd
μ = coefficient of static friction

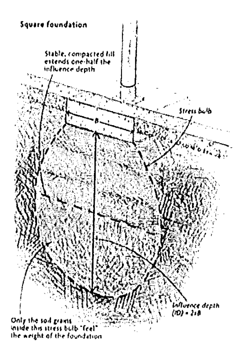
Foundations

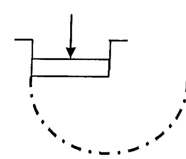
A foundation is defined as the engineered interface between the earth and the structure it supports that transmits the loads to the soil or rock. The design differs from structural design in that the choices in material and framing system are not available, and quality of materials cannot be assured. Foundation design is dependent on geology and climate of the site.

Soil Mechanics

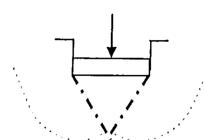
Soil is another building material and the properties, just like the ones necessary for steel and concrete and wood, must be known before designing. In addition, soil has other properties due to massing of the material, how soil particles pack or slide against each other, and how water affects the behavior. The important properties are

- specific weight (density)
- allowable soil pressure
- factored net soil pressure – allowable soil pressure less surcharge with a factor of safety
- shear resistance
- backfill pressure
- cohesion & friction of soil
- effect of water
- settlement
- rock fracture behavior





slip zone



punched wedge

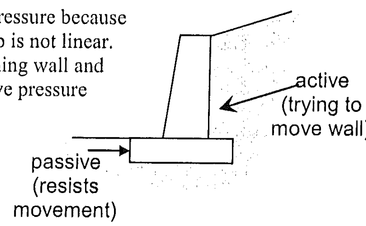
Structural Strength and Serviceability

There are significant serviceability considerations with soil. Soils can settle considerably under foundation loads, which can lead to redistribution of moments in continuous slabs or beams, increases in stresses and cracking. Excessive loads can cause the soil to fail in bearing and in shear. The presence of water can cause soils to swell or shrink and freeze and thaw, which causes heaving. Fissures or fault lines can cause seismic instabilities.

A geotechnical engineer or engineering service can use tests on soil bearings from the site to determine the ultimate bearing capacity, q_u. Allowable stress design is utilized for soils because of the variability do determine the allowable bearing capacity, $q_a = q_u/(\text{safety factor})$.

Values of q_a range from 3000 – 4000 psi for most soils, while clay type soils have lower capacities and sandy soils to rock have much higher capacities.

Soil acts somewhat like water, in that it exerts a lateral pressure because of the weight of the material above it, but the relationship is not linear. Soil can have an active pressure from soil behind a retaining wall and a passive pressure from soil in front of the footing. Active pressure is typically greater than passive pressure.



Foundation Materials

Typical foundation materials include:

- plain concrete
- reinforced concrete
- steel
- wood
- composites, ie. steel tubing filled with concrete

Table 7-1 Average Bearing Capacities of Various Foundation Beds

Soil	Bearing Capacity, q_a (ksf)
Alluvial soil	≤ 1
Soft clay	2
Firm clay	4
Wet sand	4
Sand and clay mixed	4
Fine dry sand (compact)	6
Hard clay	8
Coarse dry sand (compact)	8
Sand and gravel mixed (compact)	10
Gravel (compact)	12
Soft rock	16
Hard pan or hard shale	20
Medium rock	30
Hard rock	80

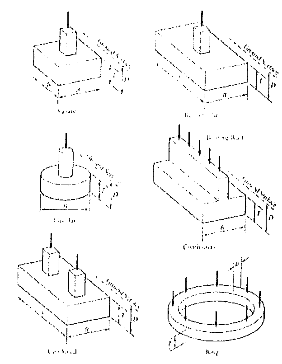
Foundation Design

Generalized Design Steps

Design of foundations with variable conditions and variable types of foundation structures will be different, but there are steps that are typical to every design, including:

1. Calculate loads from structure, surcharge, active & passive pressures, etc.
2. Characterize soil – hire a firm to conduct soil tests and produce a report that includes soil material properties
3. Determine footing location and depth – shallow footings are less expensive, but the variability of the soil from the geotechnical report will drive choices
4. Evaluate soil bearing capacity – the factor of safety is considered here
5. Determine footing size – these calculations are based on working loads and the allowable soil pressure
6. Calculate contact pressure and check stability
7. Estimate settlements
8. Design the footing structure – design for the material based on applicable structural design codes which may use allowable stress design, LRFD or limit state design (concrete).

Shallow Foundation Types



Considered simple and cost effective because little soil is removed or disturbed.

Spread footing – A single column bears on a square or rectangular pad to distribute the load over a bigger area.

Wall footing – A continuous wall bears on a wide pad to distribute the load.

Eccentric footing – A spread or wall footing that also must resist a moment in addition to the axial column load.

Combined footing – Multiple columns (typically two) bear on a rectangular or trapezoidal shaped footing.

Unsymmetrical footing – A footing with a shape that does not evenly distribute bearing pressure from column loads and moments. It typically involves a hole or a non-rectangular shape influenced by a boundary or property line.

Strap footing – A combined footing consisting of two spread footings with a beam or strap connecting the slabs. The purpose of this is to limit differential settlements.

Mat foundation – A slab that supports multiple columns. The mat can be stiffened with a grid or grade beams. It is typically used when the soil capacity is very low.

Deep Foundation Types

Considerable material and excavation is required, increasing cost and effort.

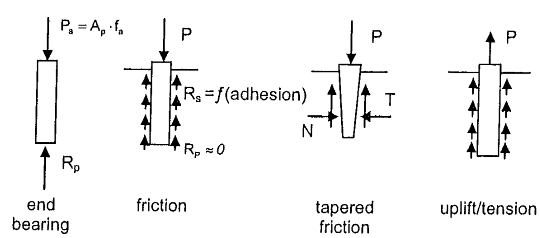
Retaining Walls – A wall that retains soil or other materials, and must resist sliding and overturning. Can have counterforts, buttresses or keys.

Basement Walls – A wall that encloses a basement space, typically next to a floor slab, and that may be restrained at the top by a floor slab.

Piles – Next choice when spread footings or mats won't work, piles are used to distribute loads by end bearing to strong soil or friction to low strength soils. Can be used to resist uplift, a moment causing overturning, or to compact soils. Also useful when used in combination to control settlements of mats or slabs.

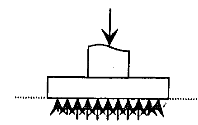
Drilled Piers – Soil is removed to the shape of the pier and concrete is added.

Caissons –Water and possibly wet soil is held back or excavated while the footing is constructed or dropped into place.



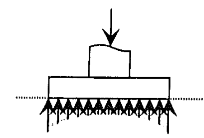
Pile Types

Loads and Stresses



RIGID footing on sand

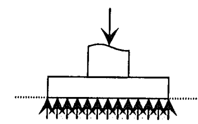
Bearing loads must be distributed to the soil materials, but because of their variability and the stiffness of the footing pad, the resulting stress, or soil pressure, is not necessarily uniform. But we assume it is for design because dealing with the complexity isn't worth the time or effort.



RIGID footing on clay

The increase in weight when replacing soil with concrete is called the overburden. Overburden may also be the result of adding additional soil to the top of the excavation for a retaining wall. It is extra *uniformly distributed load* that is considered by reducing the allowable soil pressure (instead of increasing the loads), resulting in a net allowable soil pressure, q_{net}:

$$q_{net} = q_{allowable} - h_f(\gamma_c - \gamma_s)$$



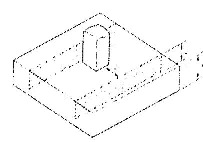
IDEAL stress

In order to design the footing size, the actual stress P/A must be less than or equal to the allowable pressure:

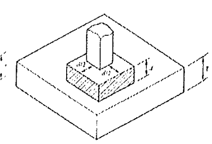
$$\frac{P}{A} \le q_{net}$$

Design Stresses

The result of a uniform pressure on the underside of a footing is identical to a distributed load on a slab over a column when looked at *upside down.* The footing slab must resist bending, one-way shear and two-way shear (punching).



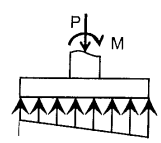
one-way shear

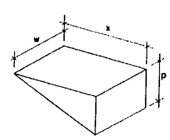


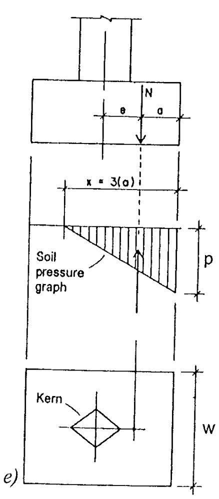
two-way shear

Stresses with Eccentric Loading

Combined axial and bending stresses increase the pressure on one edge or corner of a footing. We assume again a linear distribution based on a constant relationship to settling. If the pressure combination is in tension, this effectively means the contact is gone between soil and footing and the pressure is really zero. To avoid zero pressure, the eccentricity must stay within the kern. The maximum pressure must not exceed the net allowable soil pressure.







If the contact is gone, the maximum pressure can be determined knowing that the volume of the *pressure wedge* has to equal the column load, and the centroid of the *pressure wedge* coincides with the effective eccentricity.

Wedge volume is $V = \frac{wpx}{2}$ where w is the width, p is the soil pressure, and x is the wedge length ($3a$), so $p = \frac{2P}{wx} or \frac{2N}{wx}$ (and $e = \frac{M}{P} or \frac{M}{N}$ and $a = ½\ width - e$)

Overturning is considered in design such that the resisting moment from the soil pressure (equivalent force at load centroid) is greater than the overturning moment, M, by a factor of safety of at least 1.5

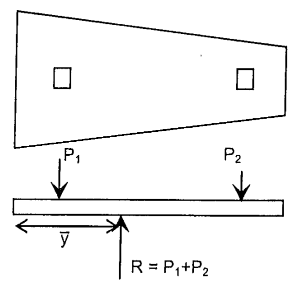
$$SF = \frac{M_{resist}}{M_{overturning}} \geq 1.5$$

where

M_{resist} = average resultant soil pressure x width x location of load centroid with respect to column centroid

$M_{overturning}$ = P x e

Combined Footings

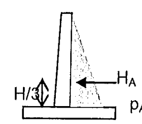


The design of combined footing requires that the centroid of the area be as close as possible to the resultant of the two column loads for uniform pressure and settling.

Retaining Walls

The design of retaining walls must consider overturning, settlement, sliding and bearing pressure. The water in the retained soil can significantly affect the loading and the active pressure of the soil. The lateral force acting at a height of H/3 is determined from the active pressure, p_A, (in force/cubic area) as:

$$H_A = \frac{p_A H^2}{2}$$



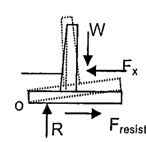
Overturning is considered the same as for eccentric footings:

$$SF = \frac{M_{resist}}{M_{overturning}} \geq 1.5 - 2$$

where

M_{resist} = summation of moments about "o" to resist rotation, typically including the moment due to the weight of the stem and base and the moment due to the passive pressure.

$M_{overturning}$ = moment due to the active pressure about "o".



Sliding must also be avoided:

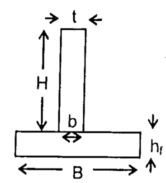
$$SF = \frac{F_{horizontal\text{-}resist}}{F_{sliding}} \geq 1.25 - 2$$

where:

$F_{horizontal\text{-}resist}$ = summation of forces to resist sliding, typically including the force from the passive pressure and friction ($F = \mu \cdot N$ where μ is a constant for the materials in contact and N is the normal force to the ground acting down and shown as R).

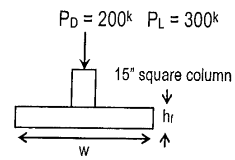
$F_{sliding}$ = sliding force as a result of active pressure.

For sizing, some rules of thumbs are:



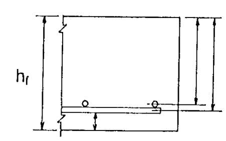
- footing size, B
- reinforced concrete, B ≈ 2/5 - 2/3 wall height (H)
- footing thickness, h_f ≈ 1/12 - 1/8 footing size (B)
- base of stem, b ≈ 1/10 - 1/12 wall height ($H+h_f$)
- top of stem, t ≥ 12 inches

<u>Example 1 (page 533)</u>



Example 2. Design a square column footing for the following data:

Column load = 200 kips [890 kN] dead load and 300 kips [1334 kN] live load
Column size = 15 in. [380 mm] square
Maximum allowable soil pressure = 4000 psf [200 kPa]
Concrete design strength = 3000 psi [21 MPa]
Yield stress of steel reinforcement = 40 ksi [280 MPa]
*Assume the soil has a density of 90 lb/ft^3



Problem Planning

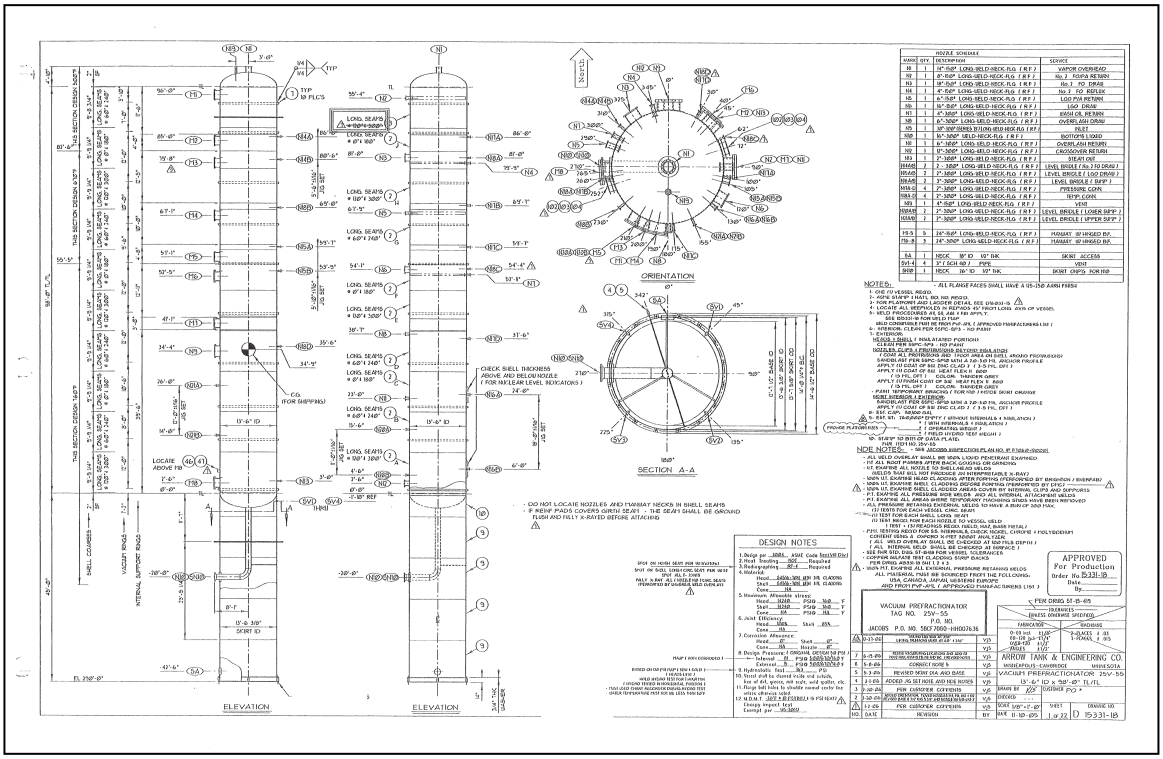
After you complete this sheet turn place it in your packet. Next ask for the solution suggestions.

Read through the RFP. Define the problem and describe what you think your end product will look like.

Make a list of all the things you think you will need to determine to solve this problem. After each item explain how you expect to find that answer.

-over-

List all the equations you think you will need to find the solution to the task.


ELEVATION
ELEVATION
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APPROVED
For Production
ARROW TANK & ENGINEERING CO.

Deflection Formula

You found the formula and constant for the deflection of a plastic tube. The engineer would already have studied a general formula for this deflection. The general formula for deflection of an object at its end by a distributed force is as follows.

$$\Delta x = qL^4/8EI$$

where

Δx is the amount of deflection at the end of the object
q is the distributed force per unit length in lbs/in
L is the length in ft
I is the Area of Moment Inertia in ft^4
(see attached section for this separate formula)
E is the elasticity of the material in lbs/in^2
the group that did the Elasticity lab understands this number
(see chart of properties)

Check the equation with the results from your lab. See if you can get the same deflection with the formula as you saw in lab for a given 2 trials with different diameters of **PVC** and 1 trial with **steel**. You will need to convert your experimental values to units that match the units in the above formula. And convert E units to lbs/in^2 if necessary before you use the equation.

Correct format and unit analysis must be used in these solutions.

Compare your lab result and calculated value.

Turn your work in with the names of the group members who did the Elasticity lab on the report.

Solving the 2012 Problem

The following order is suggested for the solving of the problem. A spreadsheet should be developed to find the following tasks. This will allow you to change values and determine the resulting outcome. Then you can determine your recommended solution.

1) Find the forces of the wind at different levels for the vessel (see Height Factor below).

2) Convert forces to distributed forces.

3) Calculate the deflection using the maximum distributed force (see Deflection Formula Help attached).

4) Size the foundation (see Foundation Help attached).

5) Check foundation for Overturning Moment.

6) Determine the number of bolts needed on the attachment ring (see Bolt Information).

7) Find the cost of the recommended foundation and your second option.

*Optional- determine the thermal growth of the vessel. (see teacher for help)

Height Factor

The ground will have an effect on the velocity of the wind. The higher you go the less this effect. The following chart was found in an engineering text. The four columns A,B,C, and D are exposure categories for different regions of the country. Minnesota falls in category B region. Choose the height you are working with and place this k value into your equation directly to the force. Now break the vessel up into sections that match the chart and calculate the force on each section using the formula that you found in lab. Use a maximum wind gust shown in the attached map at the back of this packet.

Velocity Pressure Exposure Coefficients, K_h and K_z

Height above ground level, z ft	(m)	A	B	C	D
0-15	(0-4.6)	0.32	0.57	0.85	1.03
20	(6.1)	0.36	0.62	0.90	1.08
25	(7.6)	0.39	0.66	0.94	1.12
30	(9.1)	0.42	0.70	0.98	1.16
40	(12.2)	0.47	0.76	1.04	1.22
50	(15.2)	0.52	0.81	1.09	1.27
60	(18)	0.55	0.85	1.13	1.31
70	(21.3)	0.59	0.89	1.17	1.34
80	(24.4)	0.62	0.93	1.21	1.38
90	(27.4)	0.65	0.96	1.24	1.40
100	(30.5)	0.68	0.99	1.26	1.43
120	(36.6)	0.73	1.04	1.31	1.48
140	(42.7)	0.78	1.09	1.36	1.52
160	(48.8)	0.82	1.13	1.39	1.55
180	(54.9)	0.86	1.17	1.43	1.58
200	(61.0)	0.90	1.20	1.46	1.61
250	(76.2)	0.98	1.28	1.53	1.68
300	(91.4)	1.05	1.35	1.59	1.73
350	(106.7)	1.12	1.41	1.64	1.78
400	(121.9)	1.18	1.47	1.69	1.82
450	(137.2)	1.24	1.52	1.73	1.86
500	(152.4)	1.29	1.56	1.77	1.89

Deflection Formula Help

You found the formula and constant for the deflection of a plastic tube. The engineer would already have studied a general formula for this deflection. The general formula for deflection of an object at its end by a distributed force is as follows.

$$\Delta x = \frac{qL^4}{8EI}$$

where

- Δx is the amount of deflection at the end of the object
- q is the distributed force per unit length in lbs/in
- L is the length in ft
- I is the Area of Moment Inertia in ft^4
  (see attached section for this separate formula)
- E is the elasticity of the material in lbs/in^2
  (see chart of properties)

Determine each of the values for the vessel in the Flint Hills problem using the RFP and calculate the deflection for a high wind event.

Foundation Help

The foundation needs to be sized for the vessel. To begin this part of the problem list all the factors that will put pressure on the ground. **Include a list of these in your packet.** There are many of these so be careful.

Determine a design for the foundation. (design expert)

You may want to begin thinking about the size of the foundation with no wind consideration. To do this find all the weights that will put pressure on the soil for this vessel and its foundation. Size the foundation so as to not exceed the soils Bearing Strength.

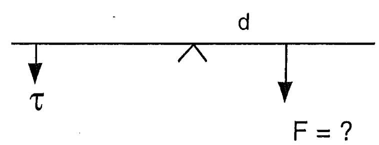
Now add wind factors to your solution (see information on Torque and Areas on the next page). Be careful to consider the overall effects of the wind on the foundation. All resulting pressures need to be dealt with.

Torque and Areas

In our last chapter you studied torque. Force was always calculated at a point using the formula τ = F d. You also looked at how torque effects a rotating object. Here it was learned that the rotational inertia effects how fast an object will rotate. You saw that different types of objects needed different formulas, to make predictions, because the mass in each of these objects was distributed differently. These two basic concepts must be used to understand the torque on an area.

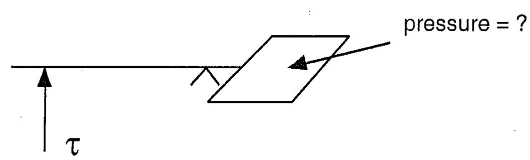
In the FH problem you are not dealing with force at a point but rather pressure on an area. It is still the same basic idea but the shape of the area must be taken into account. Like the shape of the rolling object was taken into account in the rotational inertia lab.

from chap 8



solution $F = \tau / d$

effect of Area

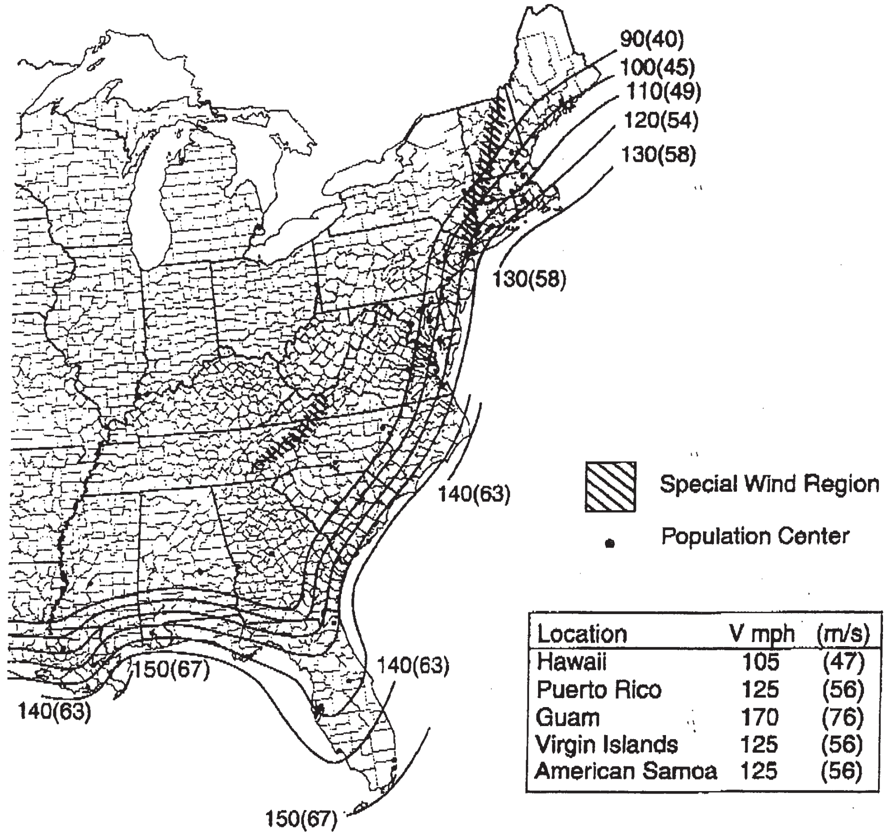


solution $P = \tau$ / Area Inertia

You can imagine that if the above problem had a circle rather than a rectangle, where the pressure is produced, that the answer would be different. This is the reason for having different formulas for different shaped areas. When you look at the formulas on the following page you will notice a strong similarity to the rotational formulas we used in chapter 8.

To find an **Area Inertia** take the formula for the moment of inertia (I) and divide by the shortest distance to the center (C).

Appendix



Location	V mph	(m/s)
Hawaii	105	(47)
Puerto Rico	125	(56)
Guam	170	(76)
Virgin Islands	125	(56)
American Samoa	125	(56)

Notes:
1. Values are 3-second gust speeds in miles per hour (m/s) at 33 ft (10m) above ground for Exposure C category and are associated with an annual probability of 0.02.
2. Linear interpolation between wind speed contours is permitted.
3. Islands and coastal areas shall use wind speed contour of coastal area.
4. Mountainous terrain, gorges, ocean promontories, and special wind regions shall be examined for unusual wind conditions.

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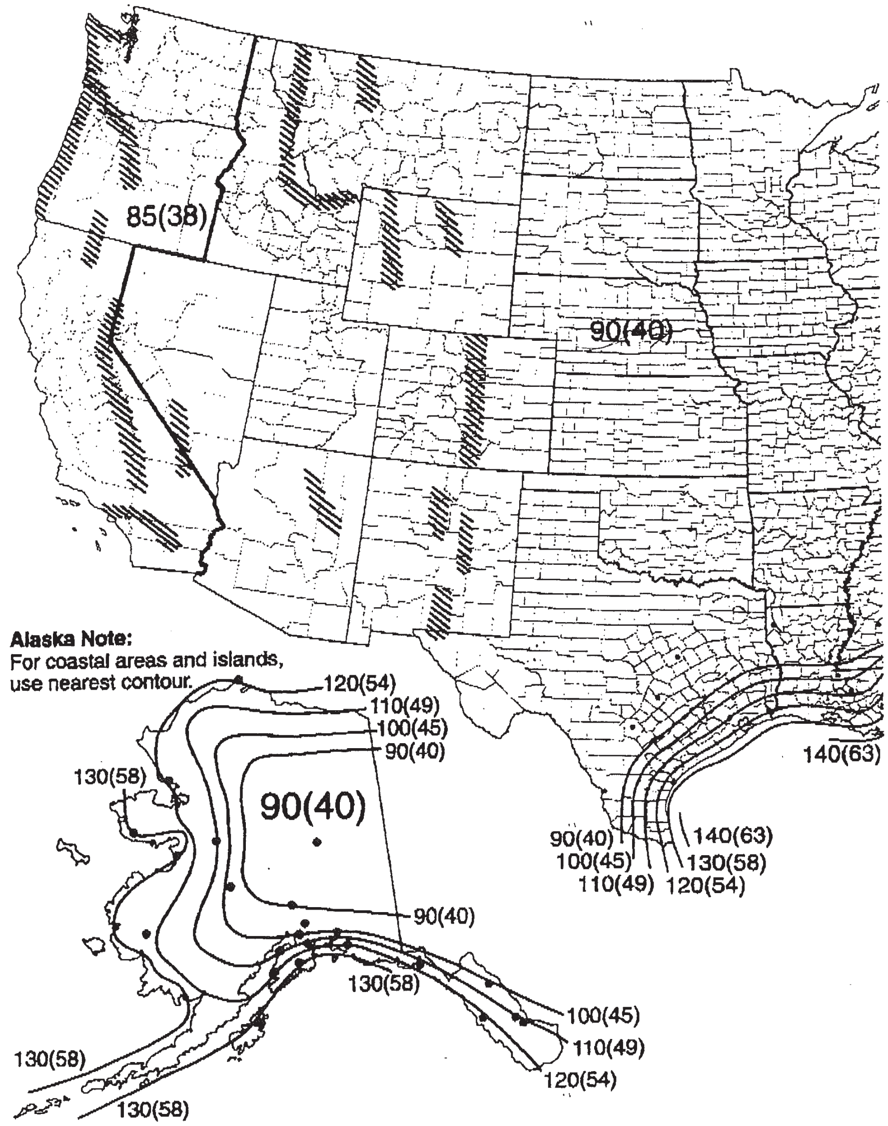

FIG. 6-1. Basic Wind Speed

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Table H-2 Moduli of elasticity and Poisson's ratios

Material	Modulus of elasticity E		Shear modulus of elasticity G		Poisson's ratio ν
	ksi	GPa	ksi	GPa	
Aluminum alloys	10,000–11,400	70–79	3,800–4,300	26–30	0.33
2014-T6	10,600	73	4,000	28	0.33
6061-T6	10,000	70	3,800	26	0.33
7075-T6	10,400	72	3,900	27	0.33
Brass	14,000–16,000	96–110	5,200–6,000	36–41	0.34
Bronze	14,000–17,000	96–120	5,200–6,300	36–44	0.34
Cast iron	12,000–25,000	83–170	4,600–10,000	32–69	0.2–0.3
Concrete (compression)	2,500–4,500	17–31			0.1–0.2
Copper and copper alloys	16,000–18,000	110–120	5,800–6,800	40–47	0.33–0.36
Glass	7,000–12,000	48–83	2,700–5,100	19–35	0.17–0.27
Magnesium alloys	6,000–6,500	41–45	2,200–2,400	15–17	0.35
Monel (67% Ni, 30% Cu)	25,000	170	9,500	66	0.32
Nickel	30,000	210	11,400	80	0.31
Plastics					
Nylon	300–500	2.1–3.4			0.4
Polyethylene	100–200	0.7–1.4			0.4
Rock (compression)					
Granite, marble, quartz	6,000–14,000	40–100			0.2–0.3
Limestone, sandstone	3,000–10,000	20–70			0.2–0.3
Rubber	0.1–0.6	0.0007–0.004	0.03–0.2	0.0002–0.001	0.45–0.50
Steel	28,000–30,000	190–210	10,800–11,800	75–80	0.27–0.30
Titanium alloys	15,000–17,000	100–120	5,600–6,400	39–44	0.33
Tungsten	50,000–55,000	340–380	21,000–23,000	140–160	0.2
Wood (bending)					
Douglas fir	1,600–1,900	11–13			
Oak	1,600–1,800	11–12			
Southern pine	1,600–2,000	11–14			

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Plastics Properties Table

Directions

EMAIL PAGE

TYPICAL PHYSICAL MECHANICAL THERMAL ELECTRICAL ALL PROPERTIES

RESET PROPERTIES TABLE

MATERIALS	TENSILE STRENGTH 73° F	FLEX MOD OF ELASTICITY psi 73° F	IZOD IMPACT (notched) 73° F	HEAT DEFLECT TEMP 66psi	HEAT DEFLECT TEMP 264psi	WATER ABSORPTION Immersion 24 Hours
ABS	4,100	304,000	7.7	200	177	0.30
ACRYLIC (Continuously Processed)	10,000	480,000	0.4	-	195	0.20
KYDEX® 100	6,100	335,000	18.0	-	173	0.05 - 0.08
NORYL® (Modified PPO)	9,600	370,000	3.5	279	254	0.07
PETG	7,700	310,000	1.7	164	157	0.20
POLYCARBONATE	9,500	345,000	12.0 - 16.0	280	270	0.15
POLYCARBONATE (20% Glass Filled)	16,000	800,000	2.0	300	295	0.16
POLYSTYRENE (High Impact)	3,500	310,000	2.0	-	185	-
POLYSULFONE	10,200	390,000	1.3	358	345	0.30
PVC (Rigid)	7,500	481,000	1.0	-	158	0.06
RADEL R®	10,100	350,000	13	-	405	0.37
ULTEM®	15,200	480,000	1.0	410	392	0.25
ULTEM® (30% Glass Filled)	24,500	1,300,000	1.6	414	410	0.16
ACETAL (Copolymer)	9,800	370,000	1.0	316	230	0.20
ACETAL (Homopolymer)	10,000	420,000	1.5	336	257	0.25
HDPE	4,000	200,000	-	172	-	0.10
LDPE	1,400	30,000	no break	122	-	0.10
NYLON (6 Cast)	10,000 - 13,500	420,000 - 500,000	0.7 - 0.9	400-430	200-400	0.60 - 1.20
NYLON (6/6 Extruded)	12,400	410,000	1.2	-	194	1.20
PBT	8,690	330,000	1.5	310	130	0.08
PEEK	14,000	590,000	1.6	-	306	0.50
PET (Semicrystalline)	11,500	400,000	0.7	240	175	0.10
PP (Homopolymer)	5,400	225,000	1.2	210	-	slight
PP (Copolymer)	3,800	215,000	12.5	190	-	slight
PPS	12,500	600,000	0.5	400	220	0.02
PTFE	1,500 - 3,000	72,000	3.5	250	-	<0.01
PVDF (Homopolymer)	7,800	310,000	3.0	300	235	0.02
UHMW-PE	3,100	110,000	18.0[1]	-	-	slight
POLYAMIDE-IMIDE TECATOR™ 2154	21,000	711,000	2.3	-	532	0.30
POLYIMIDE VESPEL® SP-1	12,500[2]	450,000	0.8	-	~680	0.24
POLYIMIDE VESPEL® SP-21	9,500[2]	550,000	0.8	-	~680	0.19
POLYIMIDE VESPEL® SP-22	7,500[2]	700,000	-	-	-	0.14

POLYIMIDE VESPEL® SP-211	6,500[2]	450,000	-	- -	0.21
POLYIMIDE VESPEL® SP-3	8,200[2]	475,000	0.4	- -	0.23
POLYIMIDE VESPEL® SCP-5000	23,600[2]	836,000	-	-	0.08
POLYIMIDE VESPEL® SCP-50094	18,000[2]	923,000	-	-	0.06
POLYIMIDE VESPEL® SCP-5050	10,500[2]	1,130,000	-	-	0.04
XX (Paper Phenolic)	11,500	-	0.4	-	-
CE (Canvas Phenolic)	9,000	1,500,000	1.5	-	-
LE (Linen Phenolic)	9,000	1,200,000	1.1	-	-
FR-4 (Glass Epoxy)	38,000	2,400,000	-	-	-
G7 (Glass Silicone)	34,600	-	-	-	-

[1]Double-15° notch, [2]Tensile Specimens per D1708, [3]D-3702, Steady State in Air, vs Steel, PV 25kpsi-fpm

RESET PROPERTIES TABLE

NEED MORE INFORMATION?
Contact Curbell Plastics at 1-888-287-2355 for more specific information about belting materials or complete our request for quote online form.

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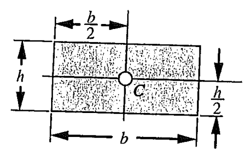
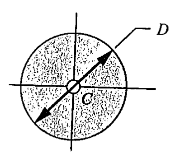


$A = bh$ $\qquad J_z = I_x + I_y$

$I_x = \dfrac{bh^3}{12}$ $\qquad I_y = \dfrac{b^3 h}{12}$

$k_x = \sqrt{\dfrac{I_x}{A}}$ $\qquad k_y = \sqrt{\dfrac{I_y}{A}}$

(a) Rectangle

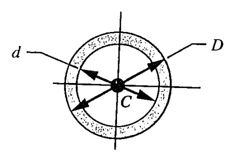


$A = \dfrac{\pi D^2}{4}$ $\qquad J_z = \dfrac{\pi D^4}{32}$

$I_x = \dfrac{\pi D^4}{64}$ $\qquad I_y = \dfrac{\pi D^4}{64}$

$k_x = \sqrt{\dfrac{I_x}{A}}$ $\qquad k_y = \sqrt{\dfrac{I_y}{A}}$

(b) Circle

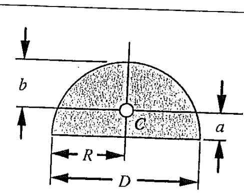


$A = \dfrac{\pi}{4}\left(D^2 - d^2\right)$ $\qquad J_z = \dfrac{\pi}{32}\left(D^4 - d^4\right)$

$I_x = \dfrac{\pi}{64}\left(D^4 - d^4\right)$ $\qquad I_y = \dfrac{\pi}{64}\left(D^4 - d^4\right)$

$k_x = \sqrt{\dfrac{I_x}{A}}$ $\qquad k_y = \sqrt{\dfrac{I_y}{A}}$

(c) Hollow circle



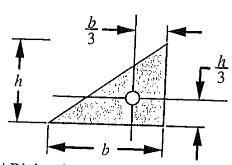
$A = \dfrac{\pi D^2}{8}$ $\qquad J_z = I_x + I_y$

$I_x = 0.109\,8 R^4$ $\qquad I_y = \dfrac{\pi}{8} R^4$

$a = 0.424\,4 R$ $\qquad b = 0.575\,6 R$

$k_x = \sqrt{\dfrac{I_x}{A}}$ $\qquad k_y = \sqrt{\dfrac{I_y}{A}}$

(d) Solid semicircle



$A = \dfrac{bh}{2}$ $\qquad J_z = I_x + I_y$

$I_x = \dfrac{bh^3}{36}$ $\qquad I_y = \dfrac{b^3 h}{36}$

$k_x = \sqrt{\dfrac{I_x}{A}}$ $\qquad k_y = \sqrt{\dfrac{I_y}{A}}$

(e) Right triangle

Proposal

2 pages:

- Problem Statement
- Short description of solutions
  (minimum 2 solutions)
- Preferred Solution in detail
  (describe foundation shape size and depth,
  deflection, bolts # and size,
  reason for choices, costs)
- Companies background

Illustrations

Spreadsheet
(wind forces, distributed
forces, bolt torques, foundation torque, bolts,
soil pressure, cost)

Figures (calculations:
forces, distributed F,
deflection, foundation sizing
bolts, costs)

Presentation

Introduction
(team members,
define problems as
understood)

Possible Solutions
(minimum 2 brief
possible solutions)

Description of
recommended solution
(detailed: deflection, foundation, & bolts)

Costs

Problem 2012

Hour 6 | Group # 1 | Group Name Intelligent Design, Inc.

F factor 1 | **Proposal** 1

A factor 1

V factor 2

constant .00123 | Ks 0.82

Torque area 135

length foundation 50 | Concrete Support Width 15

width foundation 50 | Concrete Support Diameter

diameter foundation

thickness foundation sq 3 | Foundation Depth sq 5

Thickness found Circle | Foundation Depth Circle

Bolt Number 32 | Cost for 1 bolt 23.76

Total torque bolts	2304735	Bolt Area	3.32	Bolt Diameter (in)	2.06
Torque on Foundation	2445814	Deflection (in)	1.12	Bolt Diameter actual	1.03

Rectangular base

Total Weight 2322500

press by moment rec	117	Bolt Diameter	2.06
Total press rectangle	1350	Overturning Safety Ratio square	14.80

Bolt Cost	760.32
Excavation	$48148
Transportation	$30278
Concrete	$257500
Total cost	$336686

Circular base

Total Weight 1130000

press by moment circ	?	Bolt Diameter	2.06
Total press circ	?	Overturning Safety Ratio circle	0.00

Bolt Cost	760.32
Excavation	
Transportation	
Concrete	
Total cost	$760

Problem 2012

Hour	6	Group #	3	Group Name	Kings and Queens Engineering Inc

F factor	1	Proposal	1
A factor	1		
V factor	2		
constant	.000429	Ks	0.82
Torque area	135		
length foundation	41	Concrete Support Width	15.5
width foundation	41	Concrete Support Diameter	
diameter foundation			
thickness foundation sq	3	Foundation Depth sq	6
Thickness found Circle		Foundation Depth Circle	
Bolt Number	20	Cost for 1 bolt	29.04

Total torque bolts	801886	Bolt Area	-0.41	Bolt Diameter (in)	?
Torque on Foundation	860789	Deflection (in)	0.39	Bolt Diameter actual	?

Rectangular base

Total Weight 1994563

press by moment rec	75	Bolt Diameter	?
Total press rectangle	1594	Overturning Safety Ratio square	26.66

Bolt Cost	580.80
Excavation	$38850
Transportation	$21347
Concrete	$176108
Total cost	$236886

Circular base

Total Weight 1130000

press by moment circ	?	Bolt Diameter	?
Total press circ	?	Overturning Safety Ratio circle	0.00

Bolt Cost	580.80
Excavation	
Transportation	
Concrete	
Total cost	$581

Problem 2012

Hour 6 Group # 5 Group Name Vessel Design Inc

F factor 1 Proposal 1

A factor 1

V factor 2

constant .00143 Ks 0.82

Torque area 135

length foundation Concrete Support Width

width foundation Concrete Support Diameter 25

diameter foundation 35

thickness foundation sq Foundation Depth sq

Thickness found Circle 5 Foundation Depth Circle 9.5

Bolt Number 20 Cost for 1 bolt 33.60

Total torque bolts	2679489	Bolt Area	6.74	Bolt Diameter (in)	2.93
Torque on Foundation	2679489	Deflection (in)	1.30	Bolt Diameter actual	1.47

Rectangular base Total Weight

press by moment rec			
?	Bolt Diameter	2.93	
Total press rectangle	Overturning Safety Ratio square	0.00	
?			

Bolt Cost	672.00
Excavation	
Transportation	
Concrete	
Total cost	$672

Circular base Total Weight 1130000

press by moment circ		
637	Bolt Diameter	2.93
Total press circ	Overturning Safety Ratio circle	1.67
3776		

Bolt Cost	672.00
Excavation	$35188
Transportation	$26894
Concrete	$233865
Total cost	$296618

Problem 2012

Hour 6 Group # 6 Group Name AVES

F factor 1 Proposal 1

A factor 1

V factor 2

constant .0015 Ks 0.84

Torque area 135

length foundation 53 Concrete Support Width 18

width foundation 53 Concrete Support Diameter

diameter foundation

thickness foundation sq 3 Foundation Depth sq 4.5

Thickness found Circle Foundation Depth Circle

Bolt Number 20 Cost for 1 bolt 33.00

Total torque bolts 2865872	Bolt Area 7.45	Bolt Diameter (in) 3.08
Torque on Foundation 3023756	Deflection (in) 1.36	Bolt Diameter actual 1.54

Rectangular base Total Weight 2466950

press by moment rec 122	Bolt Diameter 3.08	Bolt Cost	660.00
		Excavation	$48689
		Transportation	$34811
Total press rectangle 1263	Overturning Safety Ratio square 13.95	Concrete	$291700
		Total cost	$375860

Circular base Total Weight 1130000

press by moment circ ?	Bolt Diameter 3.08	Bolt Cost	660.00
		Excavation	
		Transportation	
Total press circ ?	Overturning Safety Ratio circle 0.00	Concrete	
		Total cost	$660