AC 2009-261: SYSTEMS ENGINEERING IN UNDERGRADUATE EDUCATION: AN ACTIVITIES-, PROJECT-, AND PROBLEM-BASED LEARNING APPROACH

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Systems Engineering in Undergraduate Education: An Activities, Project, Problem-Based Learning Approach

Abstract

Systems engineering is an interdisciplinary collaborative process by which a customer's needs are satisfied through the conceptualization, design, modeling, testing, implementation, verification, and operation of a working system. It provides a focus that enables practicing engineers to integrate their specialties in the development of complex products and processes. Systems engineering concepts are extremely important to industry. As companies or organizations bring new products to market, whether it is a small standalone widget or a large-scale "system of a system," a systems approach in design is omnipresent throughout a broad cross-section of industries today.

Formally teaching systems engineering to undergraduate students is somewhat controversial. Some educators with an industrial background have suggested that a true systems engineering approach can only come with years of industrial experience. A cursory look around the country indicates that a handful of institutions offer a BS program in systems engineering, many are computer oriented, management slanted or exclusively online programs.

Whether or not there should be an entire undergraduate program devoted to systems engineering can be debated. However, engineering students can be exposed to the concepts of systems engineering in mainstream engineering classes throughout their undergraduate education. This paper describes one approach to introduce the concepts of systems engineering to students in a junior-level fluid mechanics course through the student's participation in a team-oriented class project. The model used for student learning is an activities, project, and problem-based Learning approach. A survey of student perceptions concerning systems engineering before and after the course is presented.

Introduction

Systems Engineering Around the Country
According to the International Council on Systems Engineering[1] there are 69 programs in the United States that offer a mix of bachelors, masters, doctoral level and certificate programs in systems engineering and systems engineering management. A Wikipedia search[2] identified an additional 20 programs that had the term systems engineering in the title. A cursory look at these programs indicates that many are online, computer oriented, or with a management slant, i.e., more MBA oriented than technical engineering. It is interesting to note that the Accreditation Board for Engineering and Technology does not have a curricular discipline in systems engineering.

Using a systems engineering approach in the undergraduate capstone experience as well as in pre-college has been reported. Details of this approach are applied to a BSEE program[3] that used a tailored systems engineering process in a capstone course to increase the possibility that students developed desired ABET-related outcomes within their design experience. A systems engineering and management process[4] was successful in achieving program goals by aligning the capstone course assignments to a decision making process and incorporating a real-world client into the course. The introduction of systems engineering into pre-college education[5] was shown to give students a more broad perspective with which to interact with the world. Systems engineering was used with students as young as 5 years old to emphasize the kind of interactive and interdependent group learning that fosters growth in social skills, giving children the opportunity to think and act critically in society.

Although aspects of systems engineering are utilized in various stages throughout K-20 academia, the suggestions and results reported herein are novel in that they may be easily applied in any given classroom/laboratory setting and are tied to an innovative learning strategy called Activities, Project, and Problem-Based Learning (APP-B Learning).

An Industry Perspective

Commenting on the relationship systems engineering has in industry, Albert A. Winn, the Vice President of Government and Apache Rotorcraft Programs and former Vice President of Engineering - The Boeing Company, says[6] –

> *"It takes us about 3 to 5 years to train an engineer as they come out of college and work in industry jobs. The issue is in industry today that the jobs related to Systems Integration and Systems of Systems Development that an engineer must have a solid experience in design and development of the subsystems to base their foundational knowledge. They then grow into the ability to discuss the systems engineering aspects of the design with the customers. Aerospace government contracts require such detail and understanding of the "stated" and "not stated" requirements that without 4 to 8 years of experience in the systems themselves that it will be hard to establish the full requirements of the product. That is why Boeing and many other companies have been working with universities across the US to develop specific and specialized master's degree programs in Systems Engineering. In the discussion of developing an industry-based engineering graduate program one of the requirements is that the students would need to have no less than two or three years of industry experience before the companies will allow them to enter the degree programs and pay the fees from their education funds.*

The specialized graduate degree program that Mr. Winn is refereeing to is called The National Collaborative for the Reform of Graduate Engineering Education.[7,8,9] The idea from the National Collaborative movement is that one-size graduate education does not fit all. Excellence in basic research and in engineering practice for world-class technology development and innovation are two very different pursuits.

These comments might suggest that industry does not value a systems engineering degree, particularly one without appropriate industry experience. However, systems engineering concepts are important to industry as indicated in the survey given to our Industry Advisory Board (IAB). 100% indicated that systems engineering was important to their company and that even without a formal "systems engineering" title, most engineers operate as a "project as a system" engineers. The IAB reported that a senior engineer with between 6 – 10 years of experience would be termed a systems engineer within their companies. The question becomes how can undergraduate students exit academia without a formal systems engineering degree and still have an appreciation for systems engineering concepts that are integral to industry?

A Template for Teaching Systems Engineering using APP-B Learning

Oregon Institute of Technology has used a project-based education model for many years in their manufacturing and mechanical engineering technology programs. Projects are used to supplement the theory behind important engineering concepts used in industry. A liberal mix of projects utilized throughout the "applied engineering" curriculum always tended to hold the student's attention to a larger degree than "theory only" class time and was an important bridge to overall learning. Recently, a mechanical engineering program[10] has been introduced alongside the engineering technology programs and a focused goal for the faculty has been to preserve the use of projects. In fact, the use of projects are now more integral to some courses and are being more formalized in order to meet certain ABET requirements.

A modification of the typically discussed Project-Based Learning[11] (PBL) is presented herein. The modification is based along the lines of the learning method of the pre-engineering curricula developed through Project Lead The Way[12] (PLTW) and presented in context with high school/university STEM education.[13] Although PLTW is a pre-engineering curriculum, many of the methods can easily be applied to the university environment. The method is called APP-B Learning, that is, learning based on the use of activities, projects and problems.

The importance of APP-B Learning

Activities are a method of instruction that involve directed teaching of a particular process or procedure. Activities "*engage*" students in learning skills that are later applied in more complex situations. *Project-based learning* is a comprehensive approach to instruction that presents a project or relevant activity that enables students to synthesize the knowledge they have received and to resolve problems in a curricular context. *Problem-based learning* is an instructional strategy that presents a problem that is relevant and related to the context of what students are covering in the classroom; they synthesize and construct knowledge to help them actively struggle with the complexities of the problem. Students develop strategies to enable and direct their own learning. When students experience a problem in context, they are more likely to make connections and see the relevance in what they are learning in the classroom.

Several of the attributes of APP-B Learning are:

- When working toward a solution to a problem, students often find themselves acquiring higher levels of academic skills and knowledge than if they were taught them in isolation.
- This type of teaching promotes lifelong learning. Exposure to activities, projects and problems teaches students to take control of their learning, their first step as lifelong learners.
- Students generate strategies for solving problems by gathering, analyzing, and testing their data, sharing their findings with peers, and determining their solutions. Thus, students develop the abilities to work with peers, work in teams, and develop group skills.
- It meets the needs of students with varying learning styles. Students are expected to experience and to use multiple modalities in the process of researching and solving a problem and then communicate the solutions. This active learning takes advantage of student differences in interests and learning styles, giving each student a chance to excel in various learning activities.

Course Management

The specific course that this method is being piloted in (course has been taught in fall ’07 and ’08) is MECH 318 Fluid Mechanics. Mechanical engineering students in their junior year are required to take the 10-week, 4-credit course in the fall quarter with pre-requisites of engineering statics and integral calculus. The class utilizes a relatively common textbook[14] that is found in many other mechanical engineering programs around the nation. A typical syllabus from the course is given in Appendix I. Students were broken up into teams based on their lab section. Teams consisted of between 3 and 4 students each.

The time allotted to the elements of the course that have a systems engineering content are as follows.

<u>Activities</u> – Two 3-hour lab periods

The first activity consisted of the calibration of a pressure transducer. This was a team activity. The lab was structured such that the particular transducer was brought in to a testing lab and the students were the techs conducting the calibration. A report was written to the customer that provided the calibration curve and any other important information deemed necessary based on the testing. This report was not graded.

The second activity was to use the calibration curve of the pressure transducer to make velocity measurements of a flow in a wind tunnel using a pitot/static probe. Here the students made use of the Bernoulli Equation that had been developed in class to calculate velocity. The twist was that the report generated in Activity One was given to a different team to use, i.e., not the team that generated the report. The Activity Two students provided a peer review of the Activity One report regarding ease of use and technical correctness. The instructor then used this peer review to grade Activities One and Two.

The use of student generated reports, utilized by different students, is extremely valuable in emphasizing the importance of writing an industry report that might not be used for months or years in the future. Students typically do not realize that the report they write might someday actually be used by others.

These two activities provided a resource and experience for the students to use when they needed to measure the velocity exiting the nozzle used in their project.

Project/Problem – Three 3-hour lab periods and three 1-hour class periods

The project consisted of a water tower apparatus, shown in Fig. 1 and based on the Hydro Power Contest.[15] Criteria for the project is given in Appendix II. Student teams were to build a nozzle that directed the water from the device onto a turbine. The turbine rotated around a shaft that included a pulley that raised a weight. The power generated was then one of the requirements for success. Each of the four student teams were given a different aspect of the entire design as their responsibility. The specific responsibilities of each of these four teams were:

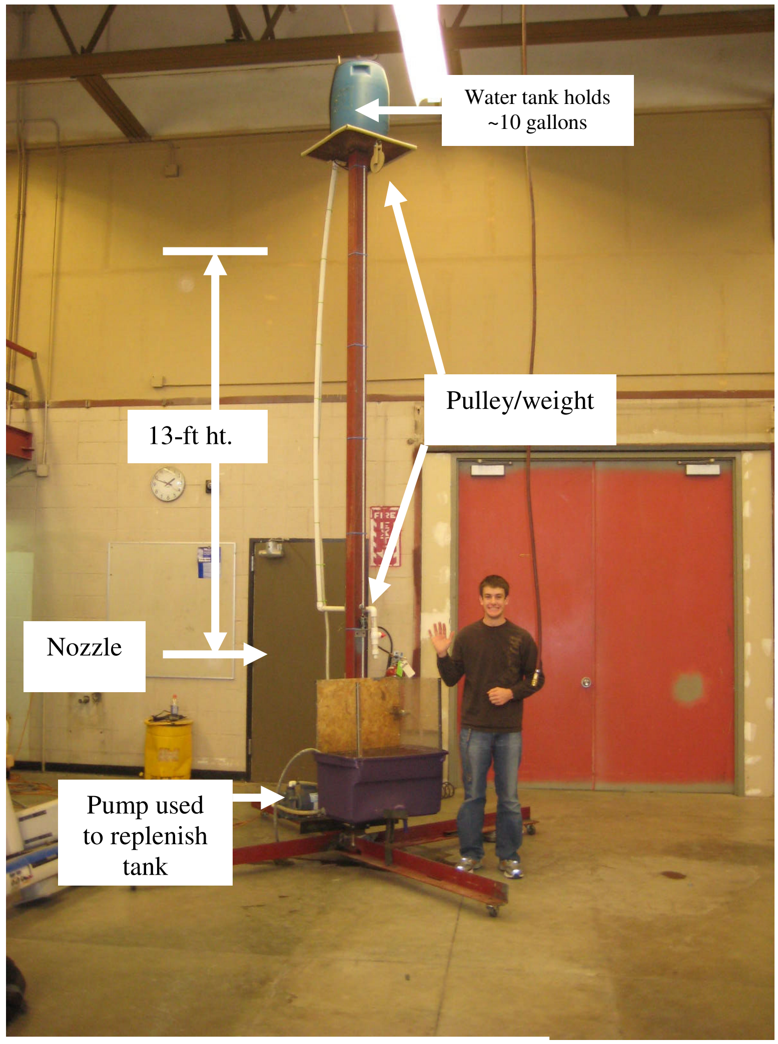


Fig. 1. Hydro Power Apparatus

1. Integrating Contractor
   a. Acts as the Project Manager for the project
   b. Defines how much energy is available and characterizes available flow
   c. Assembles all parts of the device during test
   d. Determines timeline and tracks progress
2. Nozzle & Housing Design
   a. Responsible for the transition of the water from the given PVC pipe (takes the energy from the water and converts it to some type of kinetic energy)
   b. Concerned about size & weight constraints
   c. Provides misc. structure

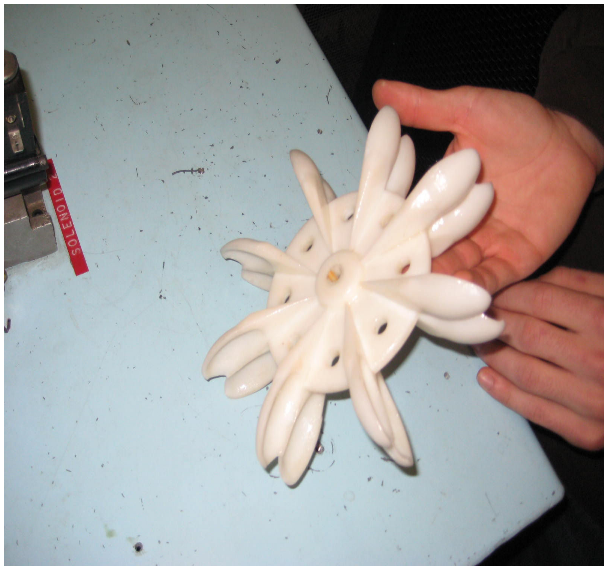


Fig 2. Turbine wheel.

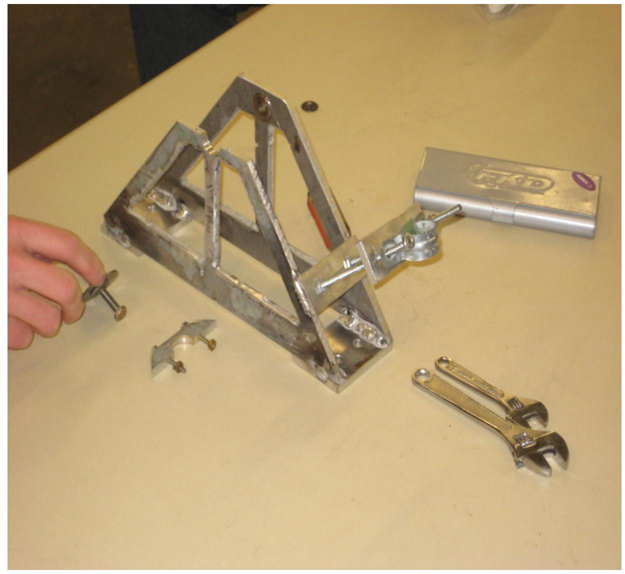


Fig 3. Structural housing.

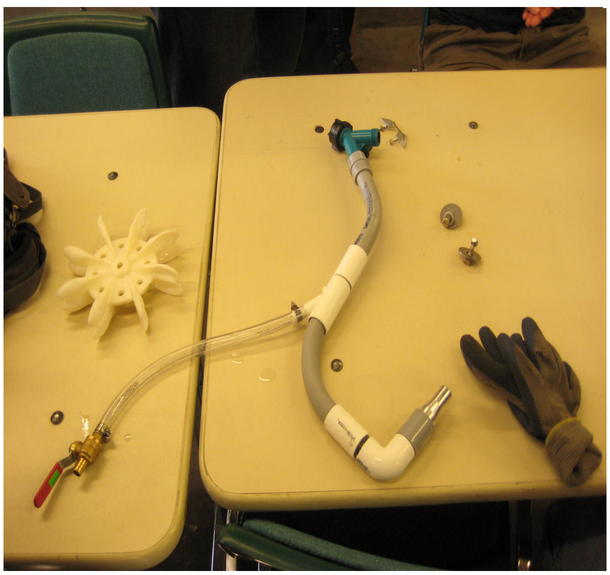


Fig. 4. Nozzle and water release.

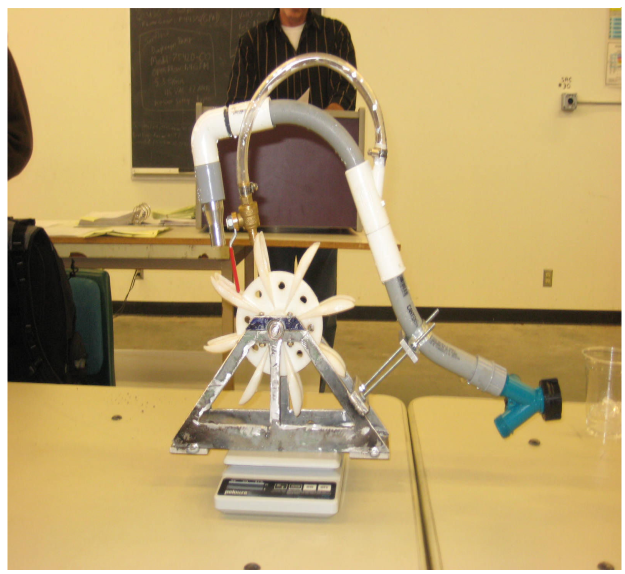


Fig. 5. Turbine, nozzle, housing.

3. Turbine Design
    a. Responsible for the design of the turbine wheel (or whatever is necessary to take the energy of the water and convert it to mechanical energy)
4. Shaft/Bearing/Pulley Design
    a. Responsible for the shaft that the turbine rides on and any bearings that are necessary

Although four teams were selected this past quarter, the preceding year six teams were used due to a larger number of students in the course. In order to distribute the team responsibilities adequately, the nozzle and housing as well as the shaft/bearing and the pulley were split into two teams with a six team class.

Results

Three Designs

Three of the four teams actually produced a design. The turbine shown in Fig. 2 was based on a Pelton Wheel concept and was made using a 3-D Printer. A significant amount of research work was conducted by the team to determine the optimum number of buckets, along with each bucket's height, width, and depth.

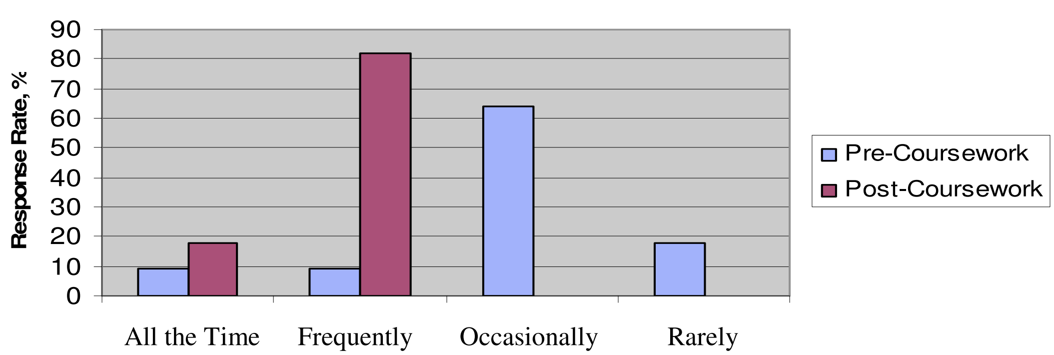
The housing that was necessary to orient the nozzle, bearings and shaft is shown in Fig. 3. All housing components were made from aluminum. Fig. 4 shows the nozzle. Notice that the nozzle is made with a throttling mechanism that was used to allow some of energy from the water to be "dumped" before impinging on the turbine. This was necessary because one of the project requirements was that the horse power of the device needed to be 0.003 $\pm$ 10%, i.e., there was a specific range in power necessary for success. The entire student designed apparatus is shown being weighed in Fig. 5.

The fourth team acted as the integration contractor. This team was responsible for all the coordination of the schedule for the three design teams. They were the program managers, responsible for the interface documentation that included timelines, interface specifications between the teams, i.e., nozzle to turbine, nozzle to housing, turbine to shaft, etc. This team assembled each of the components for the final demonstration.

Student perceptions

The results of a pre/post-course survey of student perceptions of what systems engineering is and its importance in industry is given in Figs. 6 and 7. A significant change occurred from the beginning of the course to the end of the course in the student's

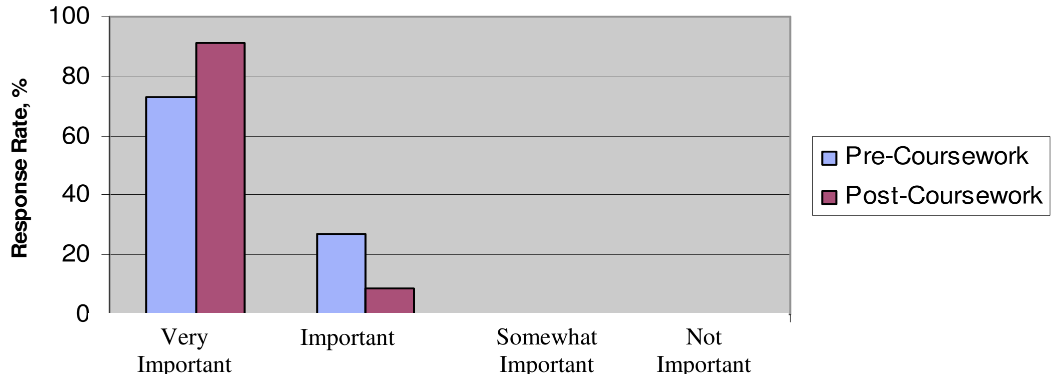
Fig. 6. Have you heard the term "systems engineering" before?



familiarity with the term "systems engineering." The students also increased their perception of how important systems engineering was to companies. With this exposure, students are better suited to go into their Capstone courses as well as entering industry.

Any time a team project is used in academia fairness in student grading becomes a question. The approach[16] used in this class was from both a team-to-team peer review (i.e., one team's perception of how the other teams contributed to the success of the project) as well as an individual peer review. The individual review was from a single member of a team's perception of their specific team mates contribution.

Fig. 7. How important is "systems engineering" to the typical company?



An important question that was not addressed through this investigation was how a systems engineering approach using APP-B Learning concepts was beneficial to student learning. Did the approach described herein have more impact on student learning than a traditional learning approach? These are important questions that need more study.

Conclusions

There is a distinction between a "Systems Engineer" and a systems engineering approach to design. Having been in industry, I tend to agree with Mr. Winn from Boeing that a Systems Engineer is "made" through years of experience working with different aspects of a product. An informal survey taken with our industry advisory board concluded that an engineer would have to work for a company for at least 6 years before they would be considered a Systems Engineer. Here I distinguish between the job title (in capitol letters, Systems Engineer) and the method or approach utilized in the design process (small letters, systems engineering).

However, all engineers graduating from an undergraduate program should be familiar with the systems engineering approach to the design of any product. It was shown that an Activities, Project, Problem-Based Learning approach to education is a good way to expose engineering students to the concepts of systems engineering. Through APP-B Learning various ABET outcomes may also be addressed.

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Appendix I

TENTATIVE SCHEDULE, Fall 2008

DATE	TOPIC	CHAPTER/SECTIONS	HOMEWORK ASSIGNMENTS
	WEEK 1		
Sep 29	Introduction	Intro PPT	First-Week Exam (take-home)
Oct 1	Dimensions, Units, Fluid behavior	1.1, 1.2	1.8, 1.21, 1.34, 1.44
Oct 3	Fluid Properties	1.7-1.9	1.60, 1.69, 1.79
Lab #1	**Pressure Calibration**		
	WEEK 2		
Oct 6	Pressure	2.1-2.4	**HW Chap #1 DUE**, 2.5, 2.8, 2.12,
Oct 8	Manometers	2.5-2.7	2.24, 2.26, 2.29,
Oct 10	Work on **Group Design Project**		
Lab #2	**Streamline Studies & Viscosity Measurements**		
	WEEK 3		
Oct 13	Hydrostatic Pressures/ Buoyancy	2.8-2.11	2.60, 2.63, 2.87, 2.89
Oct 15	Fluid Dynamics	3.1-3.4	**HW Chap #2 DUE,** 3.17, 3.18,
Oct 17	Static, Dynamic, Total Pressures	3.5-3.7	3.23, 3.30, 3.33,
Lab #3	**Pressure Measurements**		
	WEEK 4		
Oct 20	Bernoulli Eq. Restrictions	3.8	3.86, 3.95, **HW Chap #3 DUE**
Oct 22	**EXAMINATION # 1**	over material Chapters 1, 2 & 3	
Oct 24	Conservation Equations, mass	5.1	5.10, 5.12, 5.27, 5.29
Lab #4	**Pump Lab Demonstration**		
	WEEK 5		
Oct 27	Work on **Group Design Project**		
Oct 29	Conservation Equations, momentum	5.2	5.32, 5.53
Oct 31	Conservation Equations, energy	5.3	5.94, 5.108, 5.116, 5.123 **Interface Spec**
Lab	**No formal lab this week, Use Lab time to work on Project**		
	WEEK 6		
Nov 3	Laminar flow	8.1-8.2	**HW Chap #5 DUE,** 8.4, 8.14, 8.21
Nov 5	Turbulent flow	8.3	8.35, 8.38, 8.43, 8.47
Nov 7	Moody diagram, losses	8.4	8.80
Lab #5	**Hydraulics**		
	WEEK 7		
Nov 10	Pipe flow	8.5	8.104, **Paper Designs Due**
Nov 12	Pipe flow	8.6	8.104
Nov 14	**EXAMINATION # 2**	over material covered through Chapter 5	
Lab #6	**Pneumatics - Electrical Ladder Diagrams**		
	WEEK 8		
Nov 17	Boundary layer	9.1-9.2	9.3, 9.14, 9.17,
Nov 19	Drag	9.3	9.56, 9.61, **HW Chap #8 DUE**
Nov 21	Work on **Group Design Project**		
Lab #7	**Pump Characteristics & Parallel Flow Demonstration**		
	WEEK 9		
Nov 24	Drag & Lift	9.3, 9.4	9.56, 9.61, **HW Chap #8 DUE**
Nov 26	Work on **Group Design Project**		
Nov 28	Thanksgiving Holiday, ***No Class***		
Lab	**No formal lab this week, Use Lab time to work on Project**		
	WEEK 10		
Dec 1	Lift	9.4	**HW Chap #9 DUE**
Dec 3	**EXAMINATION #3** over material covered Chapters 8, and 9		
Dec 5	Review for Final		
Lab #8	**Group Project Presentations & Demonstration**		
Dec 9th	**Comprehensive FINAL EXAMINATION,** ***Tuesday, 10:00am - 12:00 pm***		

Appendix II
Group Project Laboratory
Hydro Power

PURPOSE:

- *to function effectively on teams,*
- *to communicate effectively via a specification interface document,*
- *to have a commitment to quality & timeliness,*
- *to integrate multiple components to make a device,*
- *to demonstrate ideas for turning water into power,*
- *to show sustainability in the overall design of the device,*
- *to use project management techniques.*

REQUIREMENTS:

Horse Power Generation: hp = 0.003 $\pm$ 10%
Height: weight(s) must travel 8 feet
Assembly time: < 30 minutes
Weight of entire device: < 5 lb_f
Size: See rules below
Parts of the device that must "stand alone" are the Nozzle, Turbine, Shaft/Pulley. These four parts must be attached to the device housing at the time of assembly.

TEAMS:

1. Integrating Contractor (company name is ____________)
    - Acts as the Project Manager for the project
    - Defines how much energy is available, characterizes available flow.
    - Assembles all parts of the device during test
    - Determines timeline and tracks progress
2. Nozzle & Housing Design (company name is ______________)
    - Responsible for the transition of the water from the given PVC pipe (takes the potential energy from the water and converts it to some type of kinetic energy)
    - Concerned about size & weight constraints
    - Provides misc. structure
3. Turbine Design (company name is ___________________)
    - Responsible for the design of the turbine wheel (or whatever is necessary to take the energy of the water and converting it to mechanical energy)
4. Shaft/Bearing/Pulley Design (company name is _________________)
    - Responsible for the shaft that the turbine rides on and any bearings that are necessary

Appendix II, cont'd

- Determines weights to be used & attachment method (takes the shaft rotating energy and converts it to the required horse power that will raise the weight to the required height)

REQUIRED INTERFACE DOCUMENTS:

These documents are the legal documents that describe the specifications and requirements that each of the individual components of the design must meet.

A. Nozzle/Turbine Interface Document
Sign-off by Integrating Team, Nozzle Team & Turbine Team

B. Turbine/Shaft & Pulley Interface Document
Sign-off by Integrating Team, Turbine Team & Shaft/Pulley Team

C. Housing/Shaft & Pulley Interface Document
Sign-off by Integrating Team, Housing Team, & Shaft/Pulley Team. Assures that all size and weight specifications are adhered to.

TIMELINE:

Turn in all Interface Specification Documents w/sign-offs of A, B, & C: Week 5
Turn in individual paper design for the Nozzle, Turbine, Shaft, Pulley, and Housing: Week 7
Testing (if necessary): Weeks 8-9
Final assembly and test validation: Week 10

RULES:

1. The measure of mechanical power produced will be the time, in seconds, required for the device to lift a weight to a 3-meter vertical height. Times will be recorded to the nearest tenth second.
2. No means of storing mechanical energy in the device or take-up line prior to its operation by water is allowed. Must use existing hardware (fishing line/ pulley).
3. The device may use shaft gears, pulleys, or other mechanisms attached to the mounting board to convert turbine power to mechanical movement. However, no liquid lubricants or greases may be used unless they are contained in a sealed enclosure.
4. No electrical items may be a part of a device.
5. Your device is attached to a mounting board that is 20 inches wide and 15 inches in height. The mounting board shall be at no more than 1/2 inch thick.
6. No part of the device may protrude from the back of the mounting board. You cannot hold board.
7. The turbine shaft can be in any orientation on the mounting board.
8. General questions concerning rule interpretations are to be submitted to the instructor.

Appendix II, cont'd

GRADING CRITERIA:

The contribution of this project to your overall grade is 20%. Of this 20%, the following will apply:

20% Anonymous peer review of your contribution to the team,

20% Effective communication via your specification interface document, that is:

- Nozzle/Turbine Interface Document
- Turbine/Shaft Interface Document
- Shaft/ Pulley Interface Document
- Housing/Shaft/Pulley Interface Document

20% Individual paper design of your component, that is:

- Integrating contractor – energy availability
- Nozzle/Housing design
- Turbine design
- Shaft/Bearing/Pulley design

30% Adhere to the device requirements, that is:

- Horse Power: hp = 0.003 $\pm$ 10%
- Height: weight(s) must travel 8 feet
- Assembly time: < 30 minutes
- Weight of entire device: < 5 lb_f

10% Show sustainability in the overall design of the device.