I. INTRODUCTION

A majority of engineering classes involve the “teaching by telling” approach (i.e., lecture-based approach), which is still the most dominant teaching method for engineering classes (Elshorbagy and Schönwetter, 2002). However, this traditional lecture method leaves engineering graduates ill-prepared for the engineering profession (Lattuca, et al., 2006). The traditional lecture approach falls short because it is not an effective motivator for students as they are passive recipients of information rather than being actively involved in the learning process (Prince and Felder, 2006). Furthermore, the types of problems students often solve in classrooms using this traditional approach do not necessarily prepare them for the real-world problems they will encounter as engineers.

Real-world problems are complex, ill-structured, without a clear solution, have conflicting goals, and can be presented in a number of ways (Jonnasen, Strobel, and Lee, 2006). Use of the traditional lecture method also has led to low levels of student attendance and retention in the engineering disciplines (Seymour and Hewitt, 1997). Seymour and Hewitt found that students reported poor teaching method as one of the main reasons for leaving or switching out of science, mathematics, and engineering majors. There is a 40 percent attrition rate in the engineering disciplines between freshmen and senior years (Seymour and Hewitt, 1997). The student loss is proportionally even greater among women and minorities, leading to increased under-representation of these populations in engineering disciplines (Seymour and Hewitt, 1997).

The issues of student retention, preparing students for the nature of engineering, and lack of student motivation raises many questions for engineering educators. How do engineering educators allow students to “comprehend the nature of workplace problem solving” to prepare them for the real world of practice (Jonnasen, Strobel, and Lee, 2006)? How do engineering educators engage undergraduate engineering students? Hence, engineering educators face the challenges of not only preparing students for the workplace, but also engaging students in order to decrease attrition rates, especially among women and minorities. The use of case studies is one pedagogical technique that may offer a solution through its focus on student-centered learning and engagement in authentic problem solving.

II. CASE TEACHING METHOD

A. Case-based Instruction

Case-based instruction has been used within other professional fields, such as in medicine and business, to educate students to work in complex and ill-structured domains and prepare students for the real world of practice (Davis, 1999; Williams, 1992). Case-based instruction is designed to help students acquire knowledge “deeply...
rooted” in the discipline and allow them to take part in self-directed learning. Cases could be problem-based, historical in nature, present exemplary scenario, dilemma-based, and/or illustrate critical issues in the field (Yadav and Barry, 2009). Cases allow students to apply their theoretical knowledge to practical situations in a supportive environment without concerns regarding the impact of their actions. Christopher Columbus Langdell, who has been credited with the creation of the “case method” approach, advocated the use of case studies to help students develop diagnostic skills in a field that is continuously changing, complex, and ill-structured (Garvin, 2003; Williams, 1992). Langdell believed that the best way to study law is by examining appellate court decisions as cases and advocated that such use of cases would prepare students for the real world of practice (Garvin, 2003). Similarly, engineering problems do not have a clear-cut solution and require engineers to make complex decisions. Thus, cases have the potential to be an effective medium for illuminating the complex nature of engineering because they provide students with realistic contextual information to solve workplace problems.

Previous research on case-based instruction has suggested that case studies make the content easier to remember, make the class more enjoyable for students, and increase student attendance (Hoag, Lillie, and Hoppe, 2005; Lundeborg, 1999). In one study, Hoag investigated the effect of cases in a Clinical Immunology and Serology course on students’ critical thinking, class attendance, and course satisfaction (Hoag, Lillie, and Hoppe, 2005). Two semesters of the same course were examined; one semester taught without cases (N = 56) and the next semester taught with case-based instruction (N = 67). The case-based instruction included nine cases interspersed throughout the semester with each case taking one 50-minute class period in which students worked in groups of five or six. The authors collected items of student performance on five critical thinking multiple-choice exam questions and student attendance on case study days and traditional lecture days. The authors found that the student performance on critical thinking was similar in the two semesters; however, student attendance was significantly higher on the days cases were used (95.6 percent) as compared to when lecture was used (80.3 percent). However, 13 percent of the course grade was from case studies and attendance was mandatory to earn those points, which confounded the statistical difference in attendance for case days. The end of the course evaluations suggested that students reported higher instructor involvement, student-instructor interaction, and course organization when cases were used.

Cases have also been found to increase students’ critical thinking and problem-solving skills (Dochy et al., 2003; Yadav and Beckerman, 2009), higher-order thinking skills (Bergland et al., 2006; Dori, Tal, and Tsauhu, 2003), conceptual change (Gallucci, 2007), and their motivation to learn (Yadav et al., 2007). For example, 200 non-science major students participated in a study to investigate the effects of using cases to teach biotechnology concepts (Dori, Tal, and Tsauhu, 2003). Using a pre–post test experimental design, the researchers measured students’ knowledge, understanding of concepts, application of knowledge to new contexts, and higher-order thinking skills (i.e., question posing, argumentation skills, and system thinking). The authors found a significant improvement in students’ knowledge and higher-order thinking skills for students at all academic levels and the gap between students at the low and high academic level narrowed. In addition, female undergraduates respond particularly well to case-based instruction and positive effects of small-group learning associated with case study teaching are significantly greater for under-represented populations such as African Americans and Latinos (Springer, Stanne, and Donovan, 1999).

B. Case-based Instruction in Engineering

Case studies in engineering education began in the 1960’s to 1970’s with several projects created to help develop cases for engineering faculty (Raju and Sankar, 1999; Richards et al., 1995). Cases in engineering present students with real or hypothetical situations that are “an account of an engineering activity, event or problem containing some of the background and complexities encountered by an engineer” (Fuchs, 1970). Fuchs made an argument for using cases in engineering because they bring “outside reality inside the classroom,” which is an important aspect of engineering education (Fuchs, 1970). He stated that bringing outside reality into the classroom sensitizes students to kinds of experiences they find after leaving school, which in turn motivates them to learn the concepts they need to master in their engineering disciplines. In addition to introducing the real world, cases illustrate what engineers do, help teach basic concepts and problem-solving skills, and provide engineering experience to students (Henderson, Bellman, and Furman, 1983). Richards and colleagues also proposed the use of cases in engineering education because cases can make the curriculum relevant for students, motivate them, make learning active, push students to integrate the concepts they have learned from other courses, and build upon students’ prior experiences (Richards et al., 1995).

Previous research has suggested that case studies make learning more interesting and motivating for students while allowing them to relate to real world situations. Vesper and Adams evaluated the case method in two engineering courses, one a senior machine design course at the University of Santa Clara and another a freshmen engineering drawing course at Stanford University (Vesper and Adams, 1969). They asked the students to complete a questionnaire at the end of each course, which asked them to rate the educational value of the various teaching methods used in each course: case method, traditional lecture, and laboratory sessions. The questionnaire also included open-ended items for students to express their opinions about each teaching method. Results suggested that the case method received the highest rating and students reported that case studies presented a realistic view of engineering. In addition, the authors developed a teaching objectives checklist in an attempt to capture the most likely objectives of the case method and three groups of participants completed the checklist: 30 professors, who participated in a case method summer institute; four professors, who taught first-year graduate course Case Studies in Mechanical Engineering at University of California, Berkeley; and 18 students, who took the Berkeley course. The authors found that both students and professors agreed that cases “convey knowledge of what engineers do and how they work,” “develop skills in spotting key facts amid less relevant data,” and “identify and define practical problems.”

Raju and Sankar also evaluated the effectiveness of a case study in a senior level mechanical engineering project design course (Raju and Sankar, 1999). The authors found that students rated the cases used as effective on the four dimensions (i.e., usefulness, attractiveness, challenging, and clear) being measured. Specifically, students
found case studies to be very useful and challenging as they brought real world problems to the classroom (Raju and Sankar, 1999). In another study, Garg and Varma examined students’ perceptions of learning from case studies in a software engineering course when compared to traditional lecture approach (Garg and Varma, 2007). The authors found the case study approach was rated higher than the traditional lecture approach. Students reported that case studies were better at helping them to improve their communication skills, ability to think critically, and apply the concepts and skills learned in the course.

Despite the popularity of case study approach within engineering, the practice of using cases has not become widespread and most educators have limited knowledge of how to implement cases into their classrooms (Raju and Sankar, 1999). Further, the empirical research on the effectiveness of case studies is limited and the research that does exist has primarily focused on student perceptions of their learning rather than actual learning outcomes (Prince and Felder, 2006). The increased interest in student-centered and problem-based teaching creates a need for the field to better understand case-based instruction and its benefits for engineering students (Das, 2006). Specifically, the field needs to examine whether the use of case studies results in increased student learning and engagement.

In this study, the researchers examined the influence of case studies on students’ conceptual understanding and their attitudes towards the use of case studies. Specifically, the research sought to answer the following research questions: (1) what is the influence of case-based instruction on students’ conceptual understanding compared to traditional lecture teaching method?, and (2) what are the attitudes of students towards the use of case studies?

III. METHODOLOGY

A. Participants

Seventy-three participants from two sections of the same systems modeling mechanical engineering course participated in this study. The course provides an introduction to modeling electrical, mechanical, fluid, and thermal systems containing elements, including sensors and actuators used in feedback control systems. Participants included eight females and sixty-five males. Thirty-one participants were from Instructor A’s section and 42 participants were from Instructor B’s section. All participants were enrolled in the Mechanical Engineering program at a large mid-western university and were required to take the course.

B. Materials

1) Case Studies: The authors developed two case studies based on actual events that related to two course topics (i.e., hydraulics and thermal systems). The case studies were written by the last two authors and examined to make sure they met the basic rules for what makes a good case (Herreid, 1997). According to Herreid, a good case: has pedagogical value, tells a short story, contains relevant details about the events, and is applicable to the students’ field of study to arouse their interest. The students were given a handout of the case study prior to its introduction in class along with the case discussion questions. In the following class, the instructor reviewed the case study, describing the problems presented and discussing the case study questions. Specifically, the instructors led a class discussion after the in-class individual case study work to brainstorm hypotheses about what might have caused the problems described in the case studies. The case study discussion also allowed students to consider any alternative explanations for the failures, solutions to prevent it from happening again, and consider key elements of the mathematical models. The case studies were implemented across two class periods of 50 minutes each, worked on individually by students, and were not graded. These case studies presented real-life problems to allow students to develop analytical and critical thinking skills. Specifically, these were “issue cases,” where the main focus of the case was on “what is going on here?” allowing students to develop hypothesis and consider alternative explanations (Herreid, 1994).

These case studies were used to challenge students thinking and allow them to understand and apply course concepts to real-life scenarios. Both case studies involved developing hypotheses and mitigation strategies for component failure in complex systems that led to catastrophic failure. The case studies were designed to scaffold students’ understanding of complex dynamic models; hence, allowing them to generalize their learning to other situations. During the case study work, students hypothesized about what caused the failure in the dam or the reactor core and develop a dynamic model to explain the failure and strategies to prevent it from happening again. The development of the model itself was an iterative process as the students went through multiple models taking into account various elements presented in the case studies. Due to the time constraint of covering a topic in two 50-minute lectures, the cases only focused on the topic at hand and were kept short. We provide an overview of the case studies and have included them in Appendix A.

Hydraulics Case Study. The hydraulics modeling was presented via a case study of human fatalities resulting from two catastrophic failures of hydro-electric dam penstocks due to a dynamic phenomenon call “water hammer.” Penstocks are large pipes that carry water from a large reservoir to a turbine, which spins in response to the water flow. The turbine rotates an electric generator, thereby turning the water energy into electrical energy. When the flow through the turbines is abruptly slowed via a restriction (i.e., penstock valve/gate closing), a dynamic phenomenon called “water hammer” occurs in response to the moving water inertia. While the water flow near the restriction is slowed, the water mass upstream continues to move under the influence of its inertia. This causes increases in water pressure inside the penstock and may lead to penstock failure. The case study discussed how mathematical models can predict this phenomenon and provided insight as to how it can be avoided.

Thermal Systems Case Study. The case study covering thermal systems focused on the Three Mile Island nuclear power plant disaster. After a brief overview of the plant and its history, a timeline of the events on the day of the partial reactor meltdown was covered. The case study was accompanied by technical details to allow students to conduct thermal calculations to help explain the events of Three Mile Island. Specifically, students were asked to do an energy balance to assess how much reactor energy had to be dissipated once the steam turbines were shut down. After
that, focus shifted to a closer look at the individual reactor fuel rods, and once again, students were asked to use course principles to determine surface and core temperatures in the fuel rods during the meltdown. Students also conducted a transient analysis to estimate the rise in fuel rod temperature as a function of time, to gain a sense of how quickly the reactor core heated and melted.

2) Knowledge test: A pre-post test format was used to assess students’ conceptual understanding of the two topics used in this study: thermal systems and fluid systems. We wanted to assess students’ conceptual understanding by measuring their ability to apply their learning to solve a complex problem. Instead of using objective tests, which assess students’ ability to remember facts and figures, open-ended problems were developed to illuminate the impact of cases on students’ conceptual understanding. The tests were designed to check for conceptual understanding as they consisted of problems that required a comprehensive understanding of the underlying concepts to set up the necessary equations and to properly combine them for the final answer. The pre-tests consisted of one problem statement to assess students’ prior knowledge of the corresponding topic (thermal systems or fluid systems). This test allowed the researchers to consider students’ prior knowledge when assessing the impact of the teaching method (case-based instruction vs. traditional lecture) and allowed them to make better predictions about the impact of the teaching method. The post-test consisted of a similar but more complex problem as compared to the pre-test question. The rationale for increasing the difficulty of the post-test was to allow enhanced assessment of student learning in thermal and fluid systems modeling. The students could not simply plug in numbers into an equation to produce the solution. An additional question was posed in the post-test, requiring the students to interpret their previous answer and make an assessment of the broader implications of their analysis. Reliability of the tests was determined by using the split-half reliability method to reflect that the tests were measuring the constructs. The correlation coefficient was 0.88, which indicates good reliability for the tests. Specifically, the tests took the following form:

a. Thermal system test:
   i. Pre-test problem: mathematical modeling of a heat-generating computer chip
   ii. Post-test problem: mathematical modeling of a heat-generating computer chip with heat sink

b. Fluid system test:
   i. Pre-test problem: mathematical modeling of a reservoir-driven flow through a valve restriction (fluid inertia effect neglected)
   ii. Post-test problem: mathematical modeling of reservoir-driven flow through a valve restriction and pump (fluid inertia effect included)

The tests are provided in Appendix B. Independent sample t-tests conducted on the pre-test scores between the two classes exhibited that there were no statistical differences on knowledge about hydraulics topic (p = 0.31) and thermal topic (p = 0.42).

3) Survey: Participants also completed a 22 Likert-item survey that was adapted from a national survey on faculty perceptions of benefits and challenges of case-based instruction (Yadav et al., 2007). The survey items were changed to reflect students’ (rather than faculty) perspective on the influence of case studies on their learning, engagement, and motivation. The survey had previously been implemented with education undergraduate students to assess their perceptions of cases (Yadav, 2006). The survey was used to assess student attitudes towards the use of case studies in the mechanical engineering classes. Participants were asked about their perceptions of the influence of case studies on their learning (e.g., “The case study was helpful in helping me synthesize ideas and information presented in the course”), critical thinking (e.g., “The case study allowed me to view an issue from multiple perspectives”), and engagement (e.g., “I was more engaged in class when using the case study”). See Table 4 for all survey items (Note: the items were randomized in the actual survey given to the students). Internal reliability of the survey and each subscale was determined by using Cronbach’s Alpha: overall (α = 0.91), learning (α = 0.83), critical thinking (α = 0.65), and engagement (α = 0.78); see DeVillis (2003) for a detailed discussion on internal consistency reliability.

C. Procedure

The present study was counter-balanced for the content (i.e., thermal systems vs. fluid systems) and instructional method (traditional vs. case method) to account for any bias towards a particular content. The basic design of this study is depicted in Table 1. Instructor A used the case method for the thermal systems topic and the traditional method for the fluid systems topic. In contrast, Instructor B switched the teaching method for the two topics, with the traditional method being used for the thermal topic and the case method being used for fluid systems topic. The instructors taught each concept at the same time in their respective classes. The instructors were familiarized with the case method by regular meetings with the first author to discuss implementation of case studies and also evaluated the case studies together. The two instructors were also provided resources from the National Center for Case Study Teaching in Science on how to write cases, teach with cases, and assess the case method. The two instructors also met weekly to discuss teaching strategies to ensure that the same topics were covered similarly and used the same assignments and quizzes. Data were collected using the pre-/post-tests and the surveys. Participants completed each of the two knowledge pre-tests before the topic was introduced in the class and then completed the post-test after the topic was covered in class (either via traditional lecture or via the case method). Finally, at the end of the study, participants completed the attitude survey.

D. Data Analysis

The second and third authors coded the knowledge pre-tests and post-tests on a scale of 0–3 to assess students’ conceptual understanding of thermal and fluid mechanics. The scale is based on

<table>
<thead>
<tr>
<th>Class A</th>
<th>Thermal</th>
<th>Fluid Mechanics</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N = 31)</td>
<td>Case</td>
<td>No Case</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Class B</th>
<th>Thermal</th>
<th>Fluid Mechanics</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N = 42)</td>
<td>No Case</td>
<td>Case</td>
</tr>
</tbody>
</table>

Table 1. Research design.
the work of Emert and Parish who used it to obtain measures of conceptual attainment in undergraduate core mathematics courses (Emert and Parish, 1996). Specifically, a score of zero was given if the student was unable to solve the problem and exhibited no understanding of the problem; one was assigned if the student showed some grasp of the topic, but was unable to solve the problem (i.e., average understanding); two was assigned if the student exhibited good grasp of the topic, but was unable to solve the problem in a clear and succinct manner (i.e., good understanding); and a score of three was assigned if the student accurately solved the problem in a clear and succinct manner with no false starts (i.e., excellent understanding). A rubric was used to facilitate this coding, which included representative responses from participants on each of the four points of the scale.

In order to establish inter-rater reliability, the two raters were first trained together on the rubric by scoring a sample of the knowledge tests from each topic. When the researchers were satisfied that both raters agreed on the rubric and how to score the tests, they each independently coded the same 10 percent of the knowledge tests from each topic, which were selected randomly. This led to an inter-rater reliability of 90 percent, which was deemed sufficient for the raters to code the remaining tests independently. One rater coded the remaining thermal knowledge tests, while the second rater coded the fluid mechanics tests.

The conceptual scores from the knowledge post-test were analyzed using a univariate analysis of covariance (ANCOVA) blocking design with four factors: Condition (Traditional Lecture vs. Case Studies) × Topic (Thermal Systems vs. Fluid Systems) × Classroom (Class A vs. Class B) × Participants (the blocks in the design). Participants’ pre-test scores were used as a covariate in the analysis. Finally, the survey was analyzed using frequency distribution and Chi Square Tests of Association to analyze whether more students agreed that case studies helped to increase their learning, critical thinking, and engagement.

IV. RESULTS

A. Knowledge

The ANCOVA results revealed that condition did not have a significant influence on the conceptual understanding of participants, \( F(1, 70) = 0.01, p = 0.92, \eta^2_p = 0.00, r = 0.02, 1-\beta = 0.05. \) The post-hoc power analysis to calculate power (1-\( \beta \)) was conducted using G*Power 3; see (Faul et al., 2007; Grissom and Kim, 2005) for a detailed discussion on effect size (\( r \)) and power (1-\( \beta \)). The descriptive statistics suggested that participant scores when traditional lecture was used (marginal mean = 2.12) were identical to when case studies were used as the method of instruction (marginal mean = 2.11). There was also no significant difference between the two topics, \( F(1, 70) = 0.771, p = 0.38, \eta^2_p = 0.01, r = 0.11, 1-\beta = 0.15. \) Participants scored an average of 2.17 for the thermal topic, while scoring an average of 2.06 on hydraulics test. However, the results did reveal a statistically significant difference between the two classes, \( F(1, 70) = 37.26, p = 0.00, \eta^2_p = 0.35, r = 0.18, 1-\beta = 0.32. \) Participants in Class B (marginal mean = 2.41) outperformed participants in Class A (marginal mean = 1.71) (See Table 2 for a detailed descriptive statistics and Table 3 for ANCOVA statistics).

B. Survey

Results from the survey indicated that overall students had positive attitudes towards the use of case studies in the mechanical engineering course (see Table 4).

A vast majority of the students felt that the use of case-based instruction added realism to the class (79.1 percent), was thought provoking (68.6 percent), and relevant to learning about the course concepts (64.0 percent). A majority of the students reported that the case studies allowed for more discussion of the course ideas (60.4 percent), enabled them to view an issue from multiple perspectives (59.3 percent), and was applicable to their field of study (53.4 percent). Students also felt that the use of case based instruction was beneficial for them in learning the course material. Specifically, students reported that case studies allowed them to analyze the basic elements of the course concepts (55.8 percent), form a deeper understanding (52.3 percent), synthesize ideas and information presented in the course (52.3 percent), and retain more from the class (47.7 percent). In addition, students reported that cases

<table>
<thead>
<tr>
<th>Topic</th>
<th>Lecture</th>
<th>Case Studies</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td>2.18 (SE = 0.10)</td>
<td>2.17 (SE = 0.11)</td>
<td>2.17 (SE = 0.09)</td>
</tr>
<tr>
<td>Hydraulics</td>
<td>2.07 (SE = 0.11)</td>
<td>2.06 (SE = 0.10)</td>
<td>2.06 (SE = 0.09)</td>
</tr>
<tr>
<td>Class</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class A</td>
<td>1.72 (SE = 0.11)</td>
<td>1.70 (SE = 0.11)</td>
<td>1.71 (SE = 0.88)</td>
</tr>
<tr>
<td>Class B</td>
<td>2.42 (SE = 0.10)</td>
<td>2.41 (SE = 0.10)</td>
<td>2.42 (SE = 0.80)</td>
</tr>
<tr>
<td>Total</td>
<td>2.12 (SE = 0.08)</td>
<td>2.11 (SE = 0.08)</td>
<td></td>
</tr>
</tbody>
</table>

*Note: Means are adjusted for the covariate.*

Table 2. Comparing students across conditions.

<table>
<thead>
<tr>
<th>Factor</th>
<th>df</th>
<th>Mean Square</th>
<th>F-statistics</th>
<th>p-value</th>
<th>Partial Eta-squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition</td>
<td>1, 70</td>
<td>0.01</td>
<td>0.01</td>
<td>0.92</td>
<td>0.00</td>
</tr>
<tr>
<td>Class</td>
<td>1, 70</td>
<td>17.80</td>
<td>37.26</td>
<td>0.00</td>
<td>0.35</td>
</tr>
<tr>
<td>Topic</td>
<td>1, 70</td>
<td>0.37</td>
<td>0.77</td>
<td>0.38</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 3. Results of ANCOVA.
<table>
<thead>
<tr>
<th>Learning</th>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neutral</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
<th>Mean (S.E.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I felt the use of case study was relevant in learning about the course concepts.</td>
<td>4.7</td>
<td>59.3</td>
<td>23.3</td>
<td>10.5</td>
<td>2.2</td>
<td>2.47</td>
</tr>
<tr>
<td>The case study helped me analyze the basic elements of the course concepts.</td>
<td>2.3</td>
<td>53.5</td>
<td>27.9</td>
<td>14.0</td>
<td>2.3</td>
<td>2.60</td>
</tr>
<tr>
<td>I felt that what we were learning in using the case study was applicable to my field of study.</td>
<td>8.1</td>
<td>45.3</td>
<td>31.4</td>
<td>14.0</td>
<td>1.2</td>
<td>2.55</td>
</tr>
<tr>
<td>The case study was helpful in helping me synthesize ideas and information presented in the course.</td>
<td>3.5</td>
<td>48.8</td>
<td>32.6</td>
<td>15.1</td>
<td>0.0</td>
<td>2.59</td>
</tr>
<tr>
<td>The case study allowed me to retain more from the class.</td>
<td>3.5</td>
<td>44.2</td>
<td>24.4</td>
<td>24.4</td>
<td>3.5</td>
<td>2.80</td>
</tr>
<tr>
<td>I felt that we covered more content by using the case study in the class.</td>
<td>5.8</td>
<td>16.3</td>
<td>27.9</td>
<td>41.9</td>
<td>8.1</td>
<td>3.30</td>
</tr>
<tr>
<td>Critical Thinking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I thought the use of case study in the class was thought provoking.</td>
<td>11.6</td>
<td>57.0</td>
<td>22.1</td>
<td>9.3</td>
<td>0.0</td>
<td>2.29</td>
</tr>
<tr>
<td>The use of case study allowed for more discussion of course ideas in the class.</td>
<td>8.1</td>
<td>52.3</td>
<td>24.4</td>
<td>12.8</td>
<td>2.4</td>
<td>2.49</td>
</tr>
<tr>
<td>The case study allowed me to view an issue from multiple perspectives.</td>
<td>7.0</td>
<td>52.3</td>
<td>30.2</td>
<td>9.3</td>
<td>1.2</td>
<td>2.45</td>
</tr>
<tr>
<td>The case study allowed for a deeper understanding of course concepts.</td>
<td>3.5</td>
<td>48.8</td>
<td>25.6</td>
<td>19.8</td>
<td>2.3</td>
<td>2.69</td>
</tr>
<tr>
<td>The case study brought together material I had learned in several other mechanical engineering courses.</td>
<td>4.7</td>
<td>40.7</td>
<td>30.2</td>
<td>24.4</td>
<td>0.0</td>
<td>2.74</td>
</tr>
<tr>
<td>I was able to apply the course concepts and theories to new situations as a result of using the case study.</td>
<td>1.2</td>
<td>43.0</td>
<td>30.2</td>
<td>20.9</td>
<td>4.7</td>
<td>2.85</td>
</tr>
<tr>
<td>Engagement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The case study added a lot of realism to the class.</td>
<td>18.6</td>
<td>60.5</td>
<td>11.6</td>
<td>9.3</td>
<td>0.0</td>
<td>2.12</td>
</tr>
<tr>
<td>I was more engaged in class when using the case study.</td>
<td>9.3</td>
<td>41.9</td>
<td>30.2</td>
<td>17.4</td>
<td>1.2</td>
<td>2.59</td>
</tr>
<tr>
<td>The case study was more entertaining than it was educational.</td>
<td>9.3</td>
<td>27.9</td>
<td>30.2</td>
<td>30.2</td>
<td>2.3</td>
<td>2.88</td>
</tr>
<tr>
<td>I felt immersed in the activity that involved the use of case study.</td>
<td>1.2</td>
<td>31.4</td>
<td>40.7</td>
<td>24.4</td>
<td>2.3</td>
<td>2.95</td>
</tr>
<tr>
<td>I took a more active part in the learning process when we used the case study in the class.</td>
<td>5.8</td>
<td>24.4</td>
<td>41.9</td>
<td>25.6</td>
<td>2.3</td>
<td>2.94</td>
</tr>
<tr>
<td>I was frustrated by ambiguity that followed when using the case study.</td>
<td>2.3</td>
<td>24.4</td>
<td>19.8</td>
<td>47.7</td>
<td>5.8</td>
<td>3.30</td>
</tr>
<tr>
<td>I felt that the use of case study in the course was inefficient.</td>
<td>8.1</td>
<td>17.4</td>
<td>26.7</td>
<td>43.0</td>
<td>4.8</td>
<td>3.19</td>
</tr>
<tr>
<td>I found the use of case study format challenging in the class.</td>
<td>1.2</td>
<td>24.4</td>
<td>34.9</td>
<td>37.2</td>
<td>2.3</td>
<td>3.15</td>
</tr>
</tbody>
</table>

*Table 4. Student attitudes towards the use of case studies.*
brought together material learned in several other mechanical engineering courses (45.4 percent) and enabled them to apply the course concepts to new situations (44.2 percent). Students also felt that case studies made the class more engaging with about half of the students (51.2 percent) reporting that they were more engaged in class when cases were used, and only 18.6 percent disagreeing with that statement. The percentages reported here are aggregate of agree and strongly agree.

Survey results also indicated that students had mixed feelings towards how the case studies were implemented in the course. For example, 37.2 percent of the students reported that the use of case study was more entertaining than educational, and 32.5 percent disagreed with that. About one-third of the students reported that the case study took more time than it was worth (32.6 percent), while another one-third felt that case study was worth the time (34.7 percent). It is also interesting to note that 50.0 percent of the students believed that the use of cases allowed for less content to be covered in the class. Finally, frequency of the individual survey items was aggregated to give each of the three subscales (i.e., learning, critical thinking, and engagement) a total frequency count and chi-square analysis was conducted on the resulting contingency table. The Chi Square Test of Association suggested that significantly more students agreed that case studies increased their learning, critical thinking, and engagement, \( \chi^2 (2) = 10.124, p = 0.038 \).

### V. CONCLUSION

#### A. Implications

Results suggest that students had an overall positive attitude towards the use of case studies. For example, students felt that the case studies added significant realism to the class, were relevant to the course concepts, and they were more engaged when case studies were used. These findings from the survey provide support that case-based instruction can be beneficial for students in terms of actively engaging them and allowing them to see the application and/or relevance of engineering to the real world. Therefore, this method has the potential to “address many of the problems commonly associated with teaching undergraduate science and engineering” (Yadav et al., 2007) by making the problems more relevant to students and helping them to “vicariously experience situations in the classroom that they may face in the future and thus help bridge the gap between theory and practice” (Raju and Sankar, 1999).

However, the results from this study suggest that the use of case studies did not have any significant impact on students’ conceptual understanding of the course concepts being taught via the case method as compared to traditional lecture. However, the case studies also did not harm students’ understanding and made the content relevant to the students. Considering previous research has found that students report lack of relevance, implications, and applicability to the real world as one of the main reasons for switching out of engineering, this is an important finding for retention of undergraduate engineering students (Seymour and Hewitt, 1997).

A possible hypothesis for the lack of significant difference in achievement between case study and lecture approach could be a result of how case studies were implemented in the course; specifically, the way case studies were implemented emphasized “theoretical representation of the real-world problem” (Raju and Sankar, 1999). Previous research in psychology has suggested that higher interest levels do not necessarily lead to better student performance (McDaniel et al., 2000). Gallucci further argued that even though case studies provide a positive and engaging experience for students, if not implemented carefully, they might not promote conceptual understanding of the topic (Gallucci, 2006). She stated, “students may enjoy the case study, especially if it is a change from classroom routine, but we need to ask: what concept understanding have they gained or developed?” (Gallucci, 2006). This is highlighted by results from this study, which suggest that even though students had positive feelings towards the use of case teaching method, the implementation of case studies in this study did not lead to an increase in students’ conceptual understanding.

Previous research in motivation has suggested that “unless teachers act in ways that promote cognitive engagement, students’ motivation to learn will not necessarily translate into thoughtful-ness or greater understanding of the subject matter” (Blumenfeld, Mergendoller, and Puro, 1992). Blumenfeld, Puro, and Mergendoller (1992) argued that teachers need to both “bring the lesson to students” and “bring students to the lesson” in order to translate motivation into thoughtfulness. The implementation of cases in this study “brought the lesson to students” by enhancing their interest and increasing their perceived value of the content being covered. However, the implementation of cases failed to “bring students to the lesson,” which requires teaching practices that cognitively engage students on the main point of the lesson and allow them to apply the concepts to new situations. In our study, the cases illustrated abstract course ideas through interesting stories, but did not become the focal point around which the course concepts were structured. Additionally,
students did not have the opportunity to apply the concepts learned, via separate activities and assignments, between their learning from case studies and the post-test. Hence, the manner in which cases were implemented could be hypothesized for the result that students did not differ on their conceptual understanding between the lecture and the case method.

Another possible conjecture for the finding that case studies did not lead to a significant improvement in conceptual understanding could be because of initial student resistance with respect to the amount of material covered in the class. Since students were not familiar with case studies, this pedagogical technique might have faced some student resistance. Recall that only 22 percent of the students felt that more content was covered by using case studies, while half of the students felt that lecture covered more content. Consequently, students might have felt that the use of case studies took time away from their learning, and when completing the knowledge test they might have felt unprepared as "the material was not covered in the class." This is congruent with previous research, which has suggested that faculty report initial student resistance to case studies because this method does not present a clear solution, requires students to critically examine the situation, and asks them to make decisions in a complex environment (Yadav et al., 2007).

Results suggested that students from Class B scored significantly higher than students from Class A. Recall that this study utilized a quasi-experimental research design with two instructors teaching the two classes and students were not randomly assigned to the two classes. There could also have been differing teaching styles between the two instructors, which might also help explain the differences between the two classes.

These findings have important implications for how case studies should be implemented within engineering courses. First, the results from this study suggest it may be important for engineering educators to gradually introduce case studies in order to allow students time to adjust to this method of instruction as well as help students understand the purpose of this teaching approach. Students in these classes may have viewed case studies as real world stories that provided a "break from the routine" rather than viewing them as authentic problems that raise relevant issues the instructor wanted them to examine. Students, in general, view learning as only being achieved through "direct instruction" due to their prior experiences as K-12 students and active learning processes, such as the use of case studies, challenge students’ epistemological beliefs (Yadav and Koehler, 2007). Students in this study reported that cases allowed for less content to be covered in the class; hence, it seems important that instructors highlight the relevance of case studies to course goals and students’ learning. This would allow students to see case-based instruction being applicable to their learning in the course and alleviate any potential student resistance, while allowing them to develop problem-solving skills required in their future engineering careers.

Second, the type of case studies used and how they are implemented plays an important role in the success of this approach in increasing students’ conceptual understanding. In this study, case studies were used only once and tertiary to the course material rather than as an integral part of the course, which may not have been sufficient to truly highlight the benefits of case-based instruction. Hence, case studies need to be carefully selected and implemented in engineering courses so that their benefits are maximized. For example, whether case studies need to be long vs. short, real vs. hypothetical, success vs. failure, or present single vs. multiple issues should be guided by the pedagogical goals of the instructor and what he/she wants students to grasp from the activity.

Third, it is important to use measurement tools that assess student outcomes and provide an effective means to gauge true differences between control and experimental conditions. Yadav and Barry stated, “Measuring student learning to assess the impact of an intervention (e.g. case studies) is important because of the effect the type of assessment used can have on outcome measures” (Yadav and Barry, 2009). Hence, researchers need to carefully develop instruments that assess students’ critical thinking and conceptual understanding. Lundeberg and Yadav argued for using Mazur’s paired problem testing by giving students open-ended problems and having them explain their solutions qualitatively (Lundeberg and Yadav, 2006).

B. Limitations and Future Research

This study had a few limitations. The first limitation of this study was that it focused on the impact of case studies on only two topics in a within-subjects quasi-experimental design, and within each class students experienced the case method only once. Since this was likely the first time students encountered the case method, two topics might have not been sufficient to successfully implement case studies and see the benefits of this approach on students’ conceptual understanding. In addition, this research study used two pre-/post-tests that required students to have a comprehensive understanding of the underlying concepts to solve the problem; however, the measurement tools might not have fully captured students’ conceptual understanding. Future research needs to examine the impact of case studies by making it a dominant classroom experience for students using carefully constructed measures that assess a broader range of student outcomes. This would allow researchers to more rigorously examine what concepts students have gained from cases after the initial novelty or resistance from students has dissipated.

Another limitation of this study was that the two classes were not statistically equivalent as there was no random assignment and it involved two instructors, which could have resulted in the classroom differences observed on student outcomes. In order to remove such classroom effects, subsequent research needs to be conducted with one instructor teaching two classes where students are randomly assigned. If a comparable classroom is not available, an A-B-A-B research design could be used to assess the impact of cases in a single classroom (Yadav and Barry, 2009). Note, this study included two different instructors teaching the two sections of the same course, but we did not specifically explore any instructor differences. Further research could explore instructor differences by asking whether certain teaching styles are more likely to be successful at using case studies. Future research needs to also examine the actual implementation of cases by observing classes when cases are implemented as well as interviewing faculty who use cases for the first time and faculty who have used cases previously. This research did not examine how student perceptions of their learning and engagement matched with their actual learning outcomes. Future research should examine whether students’ perceptions of learning match with their actual learning outcomes. Additionally, researchers should investigate the long-term impact of learning from case studies.
studies, such as retention of concepts and ability to apply concepts in the workplace. Having students apply the concepts (learned via case studies and/or lecture) in a 6–10 week follow-up assessment would allow researchers to examine retention. However, the ability to apply concepts in the workplace would involve a complicated research design and include qualitative observation in the field, interviews with supervisors as well as quantitative performance data of students’ applying the concepts.

REFERENCES


January 2010
AUTHORS’ BIOGRAPHIES

Aman Yadav is an assistant professor of Educational Psychology at Purdue University. His research focuses on the use of case-based instruction and problem-based learning in STEM disciplines. In addition to his Ph.D. in Educational Psychology and Educational Technology, Dr. Yadav also has Bachelors in Electrical Engineering and Masters of Science in Electrical Engineering. Dr. Yadav has undertaken both quantitative and qualitative research projects and has a strong familiarity with both types of analyses.

Address: Department of Educational Studies, Purdue University, 100 N. University Street, West Lafayette, IN 47907; telephone: (+1) 765.496.2354; fax: (+1) 765.496.1228; e-mail: amanyadav@purdue.edu.

Greg Shaver is an assistant professor of Mechanical Engineering at Purdue University. He is also a graduate of Purdue University’s School of Mechanical Engineering, having obtained a Bachelor’s degree with highest distinction. He holds a Masters degree and a Ph.D. in Mechanical Engineering from Stanford University. His research interests and background include the modeling and control of advanced combustion processes. Greg is an active member of the American Society of Mechanical Engineering (ASME), participating in the ASME Dynamic Systems and Controls Division and the ASME Automotive and Transportation Systems Panel. He is the editor of the 2007 International Federation of Automatic Control (IFAC) Symposium on Advances in Automotive Control, and is a recent recipient of the Kalman award for the best paper published in the Journal of Dynamic Systems, Measurement, and Control.

Address: School of Mechanical Engineering, Purdue University, 585 Purdue Mall, West Lafayette, IN 47907-2088; telephone: (+1) 765.494.9342; fax: (+1) 765.494.0787; e-mail: gshaver@purdue.edu.

Peter Meckl obtained his Ph.D. in Mechanical Engineering from MIT in 1988. He joined the faculty in the School of Mechanical Engineering at Purdue University in 1988, where he is currently a professor. Dr. Meckl’s research interests are primarily in dynamics and control of machines, with emphasis on vibration reduction and motion control. His teaching responsibilities include undergraduate courses in systems modeling, measurement systems, and control, and graduate courses in advanced control design and microprocessor control. Dr. Meckl was selected as an NEC Faculty Fellow from 1990 to 1992. He received the Ruth and Joel Spira Award for outstanding teaching in 2000. He is a member of the American Society of Mechanical Engineers (ASME), the Institute for Electrical and Electronics Engineers (IEEE), and the American Society for Engineering Education (ASEE).

Address: School of Mechanical Engineering, Purdue University, 585 Purdue Mall, West Lafayette, IN 47907-2088; telephone: (+1) 765.494.5686; fax: (+1) 765.494.0539; e-mail: meckl@purdue.edu.
Thermal Case Study: Three Mile Island Nuclear Generating Station

This case study uses concepts from thermal systems to describe the Three Mile Island nuclear power plant disaster. The three-mile island nuclear generating station contained two pressurized water reactors, each of which generated 850MW. These reactors were built by Babcock and Wilcox in 1968–1969 and entered service between 1974–1978. The reactor consisted of 177 fuel assemblies, which contained $15 \times 15$ array of “fuel rods” 3.5 m long, and 1.1 cm in diameter. Only 208 of the 225 rods were fuel rods. Sixteen were guide tubes within which the control rods were moved in and out of the reactor. The fuel rod tubes were made of Zircaloy, a corrosion-resistant alloy consisting mainly of the metal zirconium. In these long, thin tubes the reactor's fuel, in the form of small cylinders of uranium dioxide, was stacked.

The Three Mile Island Reactor 2 (shown schematically in Figure 1) experienced a loss of coolant accident on March 28th, 1979. The timeline for the accident is as follows:

- **4:00:37 AM:** Due to maintenance for a recurring problem with the demineralizer, condensate pumps trip, main feedwater pumps trip, and turbine trips. Auxiliary feedwater pumps start up, but can’t deliver water since block valves have been mistakenly shut after routine maintenance two days earlier.
- **4:00:40 AM:** Pressure relief valve opens as reactor pressure rises.
- **4:00:45 AM:** Reactor trips and control rods drop into core to stop nuclear reaction.
- **4:00:50 AM:** Pressure relief valve is signaled to close, but doesn’t.
- **4:02 AM:** Loss of coolant water triggers emergency core-cooling system, which is erroneously shut down by operators soon after.
- **4:10 AM:** Reactor building sump overflows into containment building.
- **4:15 AM:** Saturation temp is reached, meaning boiling can occur; fuel rods become damaged.
- **6:18 AM:** Operators close block valve for pressurizer.
- **6:57 AM:** Radiation level shows marked increase.
- **7:30 AM:** General emergency is declared.
- **5:30 PM:** Relief valve is closed, reactor coolant system is repressurized.

A timeline of the reactor core pressure during the accident is shown in Figure 2. In the aftermath of the accident, 10 MCi of xenon 133 and 15 Ci of iodine 131 were released into the atmosphere, more than 90 percent of TMI-2’s uranium fuel core was damaged in the accident, between 30 to 50 percent of the core actually melted (1 Ci = $3.7 \times 10^{10}$ atomic disintegrations per second). Figure 3 shows the reactor after the accident.

If the turbine is 30 percent efficient, compute the total thermal power produced by the Three Mile Island Reactor 2. Where do you think this power goes?
If the coolant temperature was 300 °C and the heat transfer coefficient is $1.77 \times 10^4 \text{W/m}^2\text{°C}$, what would be the reactor fuel rod surface temperature?

Assume density of the uranium oxide pellet is $10.2 \times 10^3 \text{kg/m}^3$ and its heat capacity is 360 J/kg·°C. Also assume that the convective heat transfer coefficient initially drops to 1 percent when loss of coolant occurs. Compute the temperature rise with loss of coolant.

How is energy balance achieved in a nuclear reactor? How does the heat transfer occur between the interface of a solid material and a fluid? Furthermore, the center of the pellets is at a different temperature than the surface. What do you think is going on here?

How can a model be used to determine how long it takes for the reactor core to reach a critical value?

**Hydraulics Case Study: Hydro-electric dam failures**

At 11:40 am on Saturday, January 7, 1984, the damtender began reducing water releases from Reclamation's Bartlett Dam outside of Phoenix, Arizona. The outlet works was controlled by two 66-inch water-operated needle valves. Shortly after noon, the Maricopa County Sheriff's office received a call from a fisherman downstream from the dam, saying that he heard a loud “popping” sound from inside the outlet works gatehouse and then saw water flowing at high volume from the doorway and windows. John Steffen, Salt River Project (SRP) Manager, arrived via helicopter at 1:00 pm just as Glenn Harris arrived from the nearby Horseshoe Dam. Together they entered the gatehouse from the top of the dam. Mr. Steffen first closed the upper needle valve, then closed the upstream butterfly valve for the lower outlet pipe, completely shutting off water releases. Inspection revealed that the lower needle valve body located at the end of the penstock had ruptured violently. The top portion of the body, approximately 1 by 2 meters, had separated, and the valve operating pedestal on which the operator was probably standing was destroyed. The gatehouse windows and doors were blown out, and a walkway inside the door leading to the operating platform was found in the rubble. The damtender, an 18-year SRP employee was killed in the accident.
Shortly after midnight on Wednesday December 6, 1984, a seven-man maintenance crew was completing work to automating equipment at Utah Power & Light Company’s Oneida Station hydroelectric plant, about 32 kilometers northeast of Preston, Idaho. To put the units back on line, the 144-inch diameter water-operated needle valve was opened. As the valve opened, it started moving rapidly and then slammed shut. This event was followed by a 1 by 3 feet eruption of the steel penstock. The water blew out the wall of the powerplant and swept away the maintenance shop building, the parking area, four vehicles, and the seven workers. Three of the workers were able to swim ashore in the sub-zero temperature and darkness, but four were killed in the accident.

Both catastrophic events followed the rapid closure of needle valves regulating the flow of water from a penstock. A penstock is a pipeline used to convey water under pressure to the turbines of a hydroelectric plant.

Develop a dynamic system model incorporating a reservoir and valve resistance for a dam with a reservoir depth of 188 feet, mean flow rate of 75$m^3$/s, and penstock length and diameter of 60 m and 4 m, respectively. Do you anticipate that this model will capture any potentially destructive pressure increases (or decreases) during valve closure-induced flow resistance increases?

Now add the fluid inertia of the water in the penstock to the model. How does this effect the system dynamics during rapid valve closure? Does this model predict any potentially destructive pressure increases (or decreases) during valve closure-induced flow resistance increases?

Now add the fluid capacitance affect of the in-penstock water bulk modulus to the model. How does this effect the system dynamics during rapid valve closure? Does this model predict any potentially destructive pressure increases (or decreases) during valve closure-induced flow resistance increases?

What do you think caused the failures? How could it be related to valve closure events?

How would you keep it from happening again? How could you use a mathematical model to answer these questions? What would be the key elements of such a model?

Thermal

**Pre-test:** A computer chip is represented in the schematic diagram below:

![Schematic diagram of a computer chip](Diagram)

- $T_p$ is the temperature of the chip (in degrees C) and $\rho_p$ is its mass density (in kg/m$^3$), $d_p$ is the height of the chip (in m), and $A_p$ is its top surface area (in m$^2$). Assume that only convective heat transfer occurs through the top surface to the surroundings, which are at ambient temperature $T_a$. This heat transfer can be described as follows:

$$q_{\text{conv}} = \frac{1}{R} (T_p - T_a)$$

where $q_{\text{conv}}$ is the heat transfer rate (in W) and $R$ represents a thermal resistance (in units of degrees C/W). Ignore any heat transfer through any other surfaces.

Determine an expression for the steady-state chip temperature $T_p$ when the chip is turned on and begins generating heat at a rate given by $q_{\text{IN}}$. Heat energy can be stored as described by a material's heat capacity $c_p$, which is usually given in units of J/kg-degree C. Develop a differential equation that describes how the chip temperature $T_p$ responds when the chip is turned on and begins generating heat at a rate given by $q_{\text{IN}}$.

**Post-test:** Consider the two computer chips below

- **Computer chip 1 without a heat sink.**

  ![Computer chip 1 without a heat sink](Diagram)

- **Computer chip 2 with added heat sink.**

  ![Computer chip 2 with added heat sink](Diagram)

The mass density of the chip material is represented by $\rho_p$, $c_p$ represents the specific heat of the chip material, $T_p$ is the temperature of the chip, $d_p$ is the height of the chip, and $A_p$ is its top surface area. The heat sink has height $d_h$. Assume that only convective heat transfer (with convective coefficient $h_2$) occurs to the surroundings, which are at ambient temperature $T_a$. Conductive heat transfer (with conductive coefficient $k$) occurs between the chip and the heat sink. Ignore any heat transfer through the sides and bottom of the chip and the sides of the heat sink.

Derive a differential equation for the computer chip with the heat sink that describes the time response of the chip temperature $T_p$ when the chip is turned on and begins generating heat at a rate given by $g$. If the convective coefficients for chip 1 and chip 2 are such that $h_2 > h_1$, which arrangement (with or without a heat sink) does a better job of removing heat from the chip? Please explain your answer.

Hydraulics

**Pre-test:** Consider a hydraulic tank in series with a resistive valve

![Hydraulic tank diagram](Diagram)

Where:

- $\omega_i(t)$ – inlet flow to tank [m$^3$/s]
- $\omega_o(t)$ – outlet flow from system and tank [m$^3$/s]
- $P_a$ – atmospheric pressure [N/m$^2$]
- $P(t)$ – absolute pressure at bottom of tank [N/m$^2$]
- $P_{1,g}(t)$ – gage pressure at bottom of tank [N/m$^2$], such that $P_{1,g}(t) = P(t) - P_a$
- $R$ – “flow resistance” of valve

**Determine:** input-output differential equation for system where the input is $w_i(t)$, and the output is $P_{1,g}(t)$.

**Post-test:** Consider a hydraulic tank in series with a resistive valve

Where:

- $\omega_i(t)$ – inlet flow to tank [m$^3$/s]
- $\omega_o(t)$ – outlet flow from system and tank [m$^3$/s]
- $P_a$ – atmospheric pressure [N/m$^2$]
- $P_{1}(t)$ – absolute pressure at bottom of tank [N/m$^2$]
- $P_{1,g}(t)$ – gage pressure at bottom of tank [N/m$^2$], such that $P_{1,g}(t) = P(t) - P_a$
- $R$ – “flow resistance” of valve

**Determine:** input-output differential equation for system where the input is $w_i(t)$, and the output is $P_{1,g}(t)$.

Appendix B: Pre-tests/Post-tests

Computer chip 1 without a heat sink.

Computer chip 2 with added heat sink.
Determine: equations of motions for the system where the inputs are \( P_i \) and \( w_i(t) \), and the outputs are \( P_{1,i}(t) \) and \( w_o(t) \). Clearly indicate your process for synthesizing the model. Please explain your answer.