AC 2011-1905: DESIGNING AND TESTING WATER FILTRATION DEVICES USING THE ENGINEERING DESIGN PROCESS: A DESCRIPTION OF AN EIGHTH GRADE CURRICULAR UNIT ON BIOREMEDIATION

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Johnny Thieken, MEd., is currently a high school mathematics teacher at the Paradise Valley School District and a doctoral student in the PhD in mathematics education at Arizona State University. He has as Bachelor of Science in Mechanical Engineering from Northern Arizona University and a Masters in Secondary Education from Old Dominion University. His experiences with the district include curriculum design (to include online coursework) and assessment design (district assessment exams and Arizona Instrument of Measurement Standards practice). Johnny is currently involved in doctoral research (Learning through Engineering Design and Practice, NSF ITEST Award# 0737616, 2007-11) under the guidance of PI Ganesh and Dr. James A Middleton and Dr. Finbarr Sloane, where he engages in measurement and analysis methodology design, data analysis (quantitative and qualitative), curriculum design, curriculum implementation, and sustainability.
Designing and Testing Water Filtration Devices using the Engineering Design Process: A Description of an Eighth Grade Curricular Unit on Bioremediation

Introduction

This paper describes the implementation and results from the study of a novel teaching and learning experience in K-12 Engineering Education. The specific novel teaching and learning experience focused on a Bioremediation/Wastewater treatment curricular unit. The thematic unit was part of Learning through Engineering Design and Practice, a three-year National Science Foundation sponsored Innovative Technology Experiences for Students and Teachers (ITEST, 2007) program. The project served over 100 students via a highly engaging after-school engineering education program in four middle schools from traditionally under-represented populations. Embedded within the project were opportunities to provide discovery-based learning experiences during summer industry internships around “renewable energy and resources” hosted at a local water and energy company. The specific bioremediation unit was delivered during a summer internship, which served 22 eighth-grade students.

The role of creative and critical thinkers is more important than ever. As our population and consumption rapidly grow it is vital that we find innovative and creative new solutions to problems of energy, food, housing, health care, communication, and manufacturing. Educational experiences within the K-12 school settings, colleges, and universities need to engage youth in not only the content knowledge, but also technological skills and values that can be thought of as ways of thinking: e.g., creativity, systems thinking, modeling, optimism. Unfortunately the current curricular approaches appear to be outdated and de-contextualized. In order to foster interest in the science, technology, engineering, and mathematics (STEM) fields students need exposure to inquiry-oriented learning environments. Therefore, it is our contention that current programs need to enhance early (6th, 7th, and 8th grade) STEM interest by providing inquiry-based realistic experiences both in school and out-of-school. By encouraging early STEM education we hope to influence high-school coursework, as well as career and educational pathways. The real world applications of engineering and the inquiry-based, hands-on nature of the engineering design process can serve as a means to integrate mathematics and science in ways that connect youth to the joy of learning, and to applying knowledge and skills to socially relevant challenges.

Recent science education reform focuses on the concerns that students are not gaining the skill sets necessary to maintain America’s economy. There has been a general call to change school experiences to prepare students’ for life and work in today’s global economy. Meadows stated that learning science by inquiry is central to these reforms as students will need skills for: (a) finding, organizing, and managing information; and (b) team working, oral communication, and

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1 This material is based upon work supported by the Learning through Engineering Design and Practice, National Science Foundation Award #0737616, Division of Research on Learning in Formal and Informal Settings, under Information Technology Experiences for Students and Teachers (ITEST) Youth-based Project. Opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation (NSF).
print communication. To facilitate such changes educators and researchers must change the ways
in which they are thinking about teaching and learning.7

The NRC8 advocated the use of engineering-design challenges as a means to bring a real-world
quality to the learning of science content knowledge. They also suggested that engineering
design as a problem solving strategy may be useful in enhancing learning of science and
mathematics content. This paper describes how the engineering design process was used to teach
bio-remediation through the design of water filtration devices, thereby making relevant the idea
that access to clean water can be had through treatment of wastewater. This highlights one of the
National Academy of Engineering’s grand challenges of our time, which is to provide access to
clean water.

Research efforts reported here focus on studying the implementation and impact of a
bioremediation curricular unit. Students were charged with designing a water filtration device
using the engineering design process to remove specific contaminants such as oil, fertilizer, and
particulates. In this paper we describe the curricular unit, the use of the engineering design
process in the unit, and how we accessed students’ understanding of ideas related to
bioremediation and the direct relationship of these ideas with their notions of what was necessary
to build a water filtration device. The curricular unit was designed and delivered by the project
team members (authors of this paper). The project team members were: a secondary education
certified science educator, a secondary education certified mathematics educator, and the
project’s principal investigator, an engineering education faculty who had a special focus on k-12
engineering education. This team was integral to developing the project curricula, design
principles, and instructional strategies for the ITEST project. The project team members’
intention was to design novel teaching and learning experiences that utilize the engineering
design process, field test them with middle school students, and make improvements to the
curricular unit which was one of the important deliverables of the ITEST project.

The Bio Remediation Unit – Bioengineering our Water

The Bio Remediation unit was conducted over two days of a three-day SRP Renewable Energy
Internship June 2-4, 2010. The internship was held at the premises of SRP, the Salt River Project,
a local water and energy service provider in Phoenix, Arizona. The theme for this internship was
water and how engineering can be used to solve problems related to this renewable resource. The
students first explored water as fuel. They were introduced to hydrogen fuel cell cars and given a
challenge to extract hydrogen from water using the process of electrolysis, which produced the
fuel (hydrogen) to make the cars run. Next, students experienced hydroelectric power by
designing, building, and testing their own water turbine. They explored water as a source of
energy. Their challenge was to build a water turbine capable of turning on three light emitting
diodes (LEDs). During the second day, students explored water quality and the process of
bioremediation. They visited an SRP Water Quality Environmental Laboratory and were given a
tour of the facility by two SRP scientists. Students were given background information on
bioremediation and then challenged to design, build and test a water filtration device that would
remove certain contaminants. On the third day of the internship, students had the opportunity of
sharing their lunchtime with SRP engineers. The engineers spoke with the students about what
their job at SRP entailed, their educational background, and what they enjoyed about their jobs.
The students were able to ask questions and discuss SRP’s role in managing the need for energy in the areas the SRP serves in Arizona. The internship experience ended on the third-day when the students shared what they learned by creating tri-fold poster presentations. Students displayed the hydrogen fuel cell cars, water turbines, and water filtration devices to their families.

If implemented during a school year, the bioremediation unit would span eight meetings (90 minutes each). Common threads throughout the unit included whole class discussions, student exploration/research, and group activities involving experimentation and the engineering design process. Class discussions were used to engage students in the overall engineering design challenge, while group activities held students accountable for their learning.

This unit was arranged in a series of activities that built upon the preceding one. Each activity was designed and implemented using the 5E learning cycle: Engage, Explore, Explain, Expand, and Evaluate. This strategy encourages students to take responsibility for their own learning. The teacher’s role is to provide resources, guidance and mentoring throughout the learning process. In other words, the teacher acts as a facilitator in a learner-centered instructional unit.

The overall engineering design challenge to students was to design, build and test a wastewater filtration device using the engineering design process so that the filtered water has a pH of 7 and is free of oil and particulates. To accomplish this challenge, students 1) explored the basic characteristics of microbes and how they are used in bioremediation; 2) described what wastewater may contain, and the step-by-step process of treating wastewater; 3) identified common contaminants and how they can be detected, 4) tested given substances for their effectiveness in removing water contaminants, and 5) designed, built, tested, and revised their water filtration device using the engineering design process. A description of this curricular unit is offered to provide readers with a view of the instructional design.

We initiated the overall unit by engaging students in brainstorming activities to elicit their prior knowledge about microbes and bioremediation. Facilitators validated student prior-knowledge by summarizing the large group’s collective input on the class white board. Brainstorming sessions were followed by student exploration of related topics on their own. Students were placed in teams and encouraged to explore areas of their choosing through a multiplicity of materials and resources. Provided with prompts to guide their exploration of resources, students successfully documented the new knowledge in their engineering notebooks. In a round-robin group share activity, each group was given an opportunity to explain what they had learned using poster presentations. During the group share activity, project facilitators elaborated on topics where appropriate, to include informal questioning concerning issues that were deemed important, but not reported in the group share activity. The activity culminated with students reflecting on their learning experience with descriptive notes and drawings in their engineering notebooks.

1. Many, Many Microbes. This activity began with facilitators distributing two photographs of microbes to each team of four students and rotating the sets of pictures to another group until all teams have seen all sets of photos. Through a whole group discussion, students brainstormed topics such as living vs. non-living, characteristics of microbes, where they live, what they eat, etc. For the exploration phase, students participated in a power-point visual activity involving
exploration of microbes using the Internet as a resource. Each team explored how the bacteria located on their two photographs were used in bioremediation. Using the round-robin method, each team then described to the rest of the students the information they found from their research. To expand this activity, students then were asked to discuss what events around the world in recent years could have possibly used bioremediation.

2. Where Does Wastewater Go? This activity began through facilitators initiating a whole group discussion. A photograph of a golf course, park, farmland, and a street median were shown to the students. Students were asked to consider where the water supply comes from that provides water to these areas. The students were directed to the idea that treated wastewater is the source for water supply to golf courses, etc. The students then explored the wastewater treatment process by attempting to place a set of “Wastewater Treatment cards” in the correct order. A discussion followed that allowed for each team to share their order of events and why they chose that order. Students were then instructed to refer to “Key Terms and Wastewater Description” content knowledge in their student engineering notebook, which showed the correct sequence for treating wastewater. Teams were allowed to make any corrections to their order, if needed. Expansion for this activity included students reading “Get Real; Flushing Nemo” (see http://express.howstuffworks.com/gr-nemo.htm) and then a whole group discussion that addressed the following scenario: “In Disney/Pixar’s Finding Nemo, a fish says that all drains lead to the ocean, and Nemo escapes a dentist’s office by jumping down the drain. Could a fish really get to the ocean this way?”

3. What’s In the Water? This activity began with engaging the students in a whole group discussion by eliciting their prior knowledge of possible contaminants found in water, and possible sources of these contaminants. During the explore phase, each team was provided the opportunity to figure out how to detect the contaminants found in the polluted water samples that were provided (oil, fertilizer, particulates) for their engineering-design project challenge. Here students were provided with opportunities to “test” for presence of specific contaminants. For instance students learned that when they dropped a drop of water contaminated with oil onto a piece of brown paper that the oil residue was retained on the brown paper whereas the distilled water did not leave any residue on the brown paper. Materials and instructions were provided to help students learn how to detect each contaminant. Teams conducted experiments and collected data to figure out what materials could be used to detect specific contaminants. In order to help expand their knowledge acquired from the explore phase, a map of Arizona was distributed to each team. Students were encouraged to identify possible sites in the state where pollutants previously detected could be entering into the water supply and were asked to describe why they believe this. A round-robin method was used for each team to share their ideas.

4. Purging the Pollutants!
To begin the engage phase of this activity, a whole group discussion was facilitated to elicit students’ prior knowledge gained in the activity about physical filtration, chemical treatment, and biological treatment. Students were then informed that they would be conducting a series of experiments to determine the following question: “Which substances are most effective in removing a particular contaminant?” During the explore phase, each team was assigned one of three different wastewater samples. Each sample contained a different contaminant (oil,
fertilizer, particulates). They were instructed to develop a hypothesis concerning which materials would most effectively remove the contaminant in their water sample.

Table 1. Materials Provided to Students for Investigations in the Bioremediation Unit

<table>
<thead>
<tr>
<th>Water Samples with contaminant (250 mL per group)</th>
<th>Materials for Contaminant Removal</th>
<th>Test Materials (found in student test kit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Oil</td>
<td>Activated carbon, Alum, cheese cloth, coffee filters, Kitty litter</td>
<td>1 disposable pipette; 2 pieces of brown grocery bag paper (5 cm x 5 cm)</td>
</tr>
<tr>
<td>2 Fertilizer</td>
<td>AmmoLock (which contains bacteria that convert ammonia to a less toxic substance), Epsom Salt, Activated Carbon, Buffer 7.0 and cheese cloth</td>
<td>pH paper</td>
</tr>
<tr>
<td>3 Particulates (clay, sand, soil)</td>
<td>Alum, Coffee Filters, Cheesecloth, Pine-Sol, and Activated Carbon</td>
<td>1 Secchi disk, Turbidity Assessment Guide</td>
</tr>
</tbody>
</table>

Students were provided with materials listed in Table 1 to help them conduct investigations. Each team then tested the provided materials with their water sample. Data were collected and recorded in their student engineering notebooks. During the explain phase, each team created a poster board presentation reflecting their hypothesis, observations, and data collected. A round-robin method was facilitated for each team to share their experimental design and results. Students were asked to describe what materials were effective in removing a specific contaminant and their reasons for such identification, which they had to support with data from their experiments. Students were aware that the results of their experiments would be used to inform their water filtration device design.

5. Bring On the Challenge… This activity spanned three ninety-minute sessions. Students first engaged in a whole group discussion to elicit their prior knowledge of the Engineering Design Process. As participants had been engaged in at least a year of after-school programming that used the engineering design process to complete challenges, students were familiar with the engineering design process. For the explore phase of this activity, students were given the challenge to design, build and test a wastewater filtration device so that the filtered water has a pH of 7, and is free of oil and particulates. At this point, new teams were formed, each member coming with knowledge from the previous activity on how to extract one of the three particular contaminants. This ensured that each team would have the necessary knowledge on how to extract the three different types of contaminants. The new teams were instructed to work through the following steps of the engineering design process to meet the challenge: identify the problem, gather information, imagine, plan, build, and test. Teams then presented their completed water filtration device, described their design, and reported their test results.

Materials. The following materials were provided to each team of three students: aluminum foil, plastic wrap, paper towels, scissors, rubber bands, metric rulers, three or four 12 or 16 oz clean plastic drinking bottles (e.g., water, Coke, Pepsi etc), duct tape. Materials to remove
contaminants and test the treated water included: one calibrated small medicine cup, plastic spoons, a grease pencil, straws, pH paper, activated carbon, Alum (Aluminum Potassium Sulfate), Ammo Lock (which contains bacteria that convert ammonia to a less toxic substance), Phosphate Buffer 7.0, Cheesecloth, Cotton balls, Epsom Salts, Coffee filters, kitty litter (unscented), Pine-Sol, sand, 4 small clear plastic cups, 4 stirring sticks (coffee stirrers), 2 disposable pipettes, 2 pieces of 1 inch by 1 inch brown grocery bag paper, 1 Secchi disk, 1 Turbidity Assessment Guide. Water sample that was contaminated with fertilizer, oil, and particulates; and distilled water were also provided.

Facilitators and students were asked to use the engineering design process as follows. Facilitators were asked to encourage students to carefully document each design iteration, as they iterated through their design, build and test phases. As teams tested their designs, they were also asked to defend their design decisions. Student teams discovered through the use of the Engineering Design Process that the design decisions they make had significant impact on the successful outcome of their effort. Most teams had to engage in at least two or three design iterations before they arrived at a final water filtration device. Students were reminded that there is no one correct method for accomplishing this task. They were encouraged to explore, create and discover!

The engineering design process with the following student prompts was included in the student engineering notebook. Students had already been introduced to the engineering design process in their ITEST program learning experiences.

**Identify the Problem.** Before you begin to gather solution ideas, it is important that you understand the problem. Identify what needs the specific problem addresses. Think about how you might remove oil, fertilizer, and particulates from your water sample. Refer to your experiments and match the contaminant to the contaminant removal technique(s) that was most effective as per your scientific exploration.

**Imagine.** Imagining a solution begins with brainstorming as many new ideas or improvements on old ideas as you can. Always remember that brainstorming is a technique used to generate all types of ideas, judgment and criticism is not allowed. Brainstorm within your group and decide, in what order, you need to remove the contaminants from your water. Develop a flowchart or sketch out the ways in which you would design your wastewater filtration device.

**Plan.** Select one or more of the most appropriate new ideas (or improved old ideas) created during the *imagine* stage and create a plan of action for each idea. Each plan should include drawings and descriptions for the overall look, size, parts, material, functions, etc. Each plan should be specific enough for you to use them in the next stage. Sketch the design of your wastewater filtration device as you now know what materials you are going to use, and in what order. Label each part of your treatment system. For example, label where the contaminated water comes in, what removal techniques you are using first, second, and so on (based on your
flowchart), the material, chemical or processes that you choose to use as your contaminant removal technique, what contaminants remain in the water after each removal technique is used, and where the “clean” or “treated” water comes out. (Refer to figures 1 and 2 in Student Work for examples of the ‘Plan’ phase of the engineering design process.)

**Build.** Follow your plan(s) to build your design. (Refer to figures 3 and 4 in Student Work for examples of the ‘Build’ phase of the engineering design process.)

**Test.** At this stage you want to evaluate how your built design(s) solve the needs of the problem. Consider the following questions:
- Does your design meet the needs of the problem?
- Can your design be improved and still meet the needs of the problem?

Process the contaminated water through your water filtration device. Using the testing methods you used earlier, test the treated water for each contaminant that was present in the contaminated water before treatment. In the results table, record the presence or absence of each contaminant. (Refer to figures 3 and 4 in Student Work for examples of the ‘Test’ phase of the engineering design process.)

**Repeat** the Engineering Design Process as needed. Assess the quality of your water filtration device in removing the contaminants and meeting the posed design challenge. Decide what you would do next time to improve your system. Conduct a careful analysis of what worked and what did not from your current design. Document the changes needed to improve your current design of the water filtration device. Justify these changes with data from your test phase. Make changes to your water filtration device by repeating the necessary steps in the engineering design process and test your water filter until you have achieved the design challenge of having treated water with a pH of 7 and is free of oil and particulates. This is called iteration and means the act of repeating a process with the aim of approaching a desired result.

Ultimately, whole group discussions were used to engage students in a reflection of their learning experience. The following questions were posed:
- What would you do differently if you could build another wastewater filtration device?
- What would you keep the same?
- What other possible pollutants could be found in Arizona water?
- Based on your experience building your own water filtration device, how would you propose to remove these pollutants?

**Participants**

The overall engineering-education project spanned three years and included four junior high schools from a large school district in Arizona. During the first year, two seventh grade cohorts in two junior high schools were selected utilizing a purposeful selection strategy. During the second year, two additional seventh grade cohorts from two different junior high schools in the same district were selected. Each ITEST participant was expected to stay with the program for two years, throughout his or her seventh and eighth grade experience. ITEST Participant demographics are provided in Tables 2 and 3.
The bioremediation unit was presented through a summer internship in June 2010 to eighth grade participants that joined the ITEST program during their seventh grade year. This was the first time the bioremediation unit had been offered to participants. Students had the option of attending the summer program and therefore, a smaller subset of the larger group took part in this program. Some students were involved with summer school, family vacations and sporting events which prevented them from attending. In all, twenty-two students participated in the bioremediation unit. Tables 4 and 5 provide participant demographics for the bioremediation unit.

Table 2. ITEST Project Participants by Sex

<table>
<thead>
<tr>
<th>Sex</th>
<th>Number</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female</td>
<td>32</td>
<td>35</td>
</tr>
<tr>
<td>Male</td>
<td>16</td>
<td>33</td>
</tr>
<tr>
<td>Total</td>
<td>48</td>
<td>68</td>
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</tbody>
</table>

Table 3. ITEST Project Participants by Ethnicity

<table>
<thead>
<tr>
<th>Ethnicity</th>
<th>Number</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
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<tr>
<td>Asian</td>
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<td>0</td>
</tr>
<tr>
<td>White</td>
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<td>21</td>
</tr>
<tr>
<td>Hispanic</td>
<td>25</td>
<td>46</td>
</tr>
<tr>
<td>Indian American</td>
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<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>48</td>
<td>68</td>
</tr>
</tbody>
</table>

Table 4. Bioremediation Unit Participants by Sex

<table>
<thead>
<tr>
<th>Sex</th>
<th>Number</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female</td>
<td>15</td>
<td>68%</td>
</tr>
<tr>
<td>Male</td>
<td>7</td>
<td>32%</td>
</tr>
<tr>
<td>Total</td>
<td>22</td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Bioremediation Unit Participants by Ethnicity

<table>
<thead>
<tr>
<th>Ethnicity</th>
<th>Number</th>
<th>Percent</th>
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<tr>
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<td>5%</td>
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<tr>
<td>White</td>
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<tr>
<td>Hispanic</td>
<td>11</td>
<td>50%</td>
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<tr>
<td>Total</td>
<td>22</td>
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</table>

Student Work

Before building the water filtration device, students worked through the “design” phase of the engineering design process by producing a sketch of their intended device.
As we can see from Figures 1 and 2, the sketches of the filtration device designs included layers of filtration materials, both physical (cotton balls, coffee filters) and bio-chemical (Ammo Lock, Alum) materials. The tiered design was common among all of the student sketches. However, the order of and kind of materials varied considerably from team to team based on their data from activity number four “Purging the Pollutants.” In figure 1 the order of materials included cheese cloth, cotton balls, and Ammo Lock, while the student design in Figure 2 selected Alum, kitty litter and coffee filters.

Figures 3 and 4 represent student work through the “build” and “test” phases of the engineering design process. Even though student work varied in appearance and performance, there were many similarities in the designs. The above figures show two water filtration devices representing the basic similarities throughout the student work. There are layers of filtration in both, but we can see that the number of layers vary. It is important to note that the discrepancy in
the number of layers is not a reflection of the materials used, as each group used three levels of filtration, but rather a factor of the discharge of treatment water. Some designs included a chamber that required students to manually empty the collection chamber, while alternate designs included a pre-chamber that allowed the treated water to flow into a larger container such as a bucket. Challenge performance was judged by the quality of the treated water. The goal was that the treated water had to have the pH of 7. The variation in the quality of the treated water was a direct result of the choice of materials used and the order in which the materials were placed. As stated earlier, part of the unit required students to investigate methods and techniques to identify contaminants within a sample of water. Therefore, students were able to determine the quality of their filtration design by using the skills they had gained throughout the unit.

**Data Analysis**

Student learning was assessed using formal and informal methods. A formal assessment consisted of a pre- and post-assessment. Informal assessments consisted of open-ended questioning, demonstrations, teacher observations, student reflections, scientific experimentaion plus analysis, and the student construction of a water filtration device. Students were asked to describe the order of materials within a flow chart. Examples of student descriptions and the resultant flow chart for the water filtration device appear in Figures 5 and 6.

<table>
<thead>
<tr>
<th>Team 1</th>
<th>Team 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use cotton balls and alum to clean water of particulates. Use cottonballs and ammolock to clean water of fertilizer and ammonia. Use cheesecloth and coffee filters to refine water of oil.</td>
<td>The contaminated water will first go through cheesecloth to remove the oil. Then through alum on top of cheesecloth to remove the particulates Then a coffee filter to remove excess oil, then through cotton balls and ammol lock to remove fertilizer.</td>
</tr>
</tbody>
</table>

![Figure 5. Team 1 Flow Chart](image)

![Figure 6. Team 2 Flow Chart](image)

Pre- and post-assessments in the form of open-ended and fill-in-the-blank questions relating to major unit content were administered. These assessments consisted of four questions (Appendix A). A rubric was created and refined throughout the scoring process. The final rubric that was
used to score the entire set of pre- and post-assessments is shown in Appendix B. A paired-sample dependent t-test was used to investigate statistical significance of score differences. T-test analysis started by calculating the differences between each student’s pre- and post-score. The mean and standard deviation were then calculated from these differences. To test the hypothesis that the average difference was significantly different from zero, the mean difference was divided by the ratio of the standard deviation and the square root of the sample size. Effect sizes were determined by dividing the mean difference by the standard deviation calculated from the score differences. Students with either missing pre- or post-assessments were eliminated from the analysis. The resulting statistics are shown below in Table 6.

<table>
<thead>
<tr>
<th></th>
<th>n=18</th>
<th>Mean</th>
<th>SD</th>
<th>Mean Difference</th>
<th>t</th>
<th>P</th>
<th>Effect Size</th>
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</thead>
<tbody>
<tr>
<td>Pre-Assessment</td>
<td>10.32</td>
<td>8.21</td>
<td></td>
<td></td>
<td>70.24</td>
<td>16.99</td>
<td>&lt; .001</td>
</tr>
<tr>
<td>Post-Assessment</td>
<td>80.56</td>
<td>18.47</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>16.78</td>
</tr>
</tbody>
</table>

Statistical analysis shows a statistically significant difference between the means for the pre- and post-assessments; \( t(17) = 16.99, p < .001 \). Students had not previously engaged in the topics associated with this unit and as a result they experienced high levels of performance. The results indicate that the technologically centered, hands-on learning experiences had a statistically significant impact on average student performance, as measured by the pre- and post-assessments. The effect size is very large at 16.78, suggesting an average increase of almost seventeen standard deviations from the pre-assessment mean. The effect size is unusually large due to the fact that students were allowed to refer back to their notes and drawings during the post-assessment. As such an accommodation makes it difficult to separate average learning gains from note references, results should be interpreted as an indication of student performance. Where performance represents the quality of engagement, note taking, organization, and ability to retrieve data in a logical manner. The intent of these results is not to generalize beyond the reported sample, as no effort was made to obtain a random sample or implement a research design consistent with the lack of a control group. The conditions of the ITEST project required voluntary participation in an informal after-school program over two-years that did not lend itself to random selection and assignment of participants to experimental and control groups.

Observations conducted by program facilitators showed that students were actively engaged in designing their water filtration devices through investigation and discussion. In addition to discovering which layers to use in their water filtration device, they also discussed ideas related to the actual design and construction of the water filtration device using the engineering design process. Examples of such engagement are illustrated by the following questions initiated through student discourse:

- How do we attach various filtration chambers one on top of each other?
- Will the filtration device stand on its own? How will we strengthen the physical structure of the water filtration device?
- If we need to replace the water filtration materials in the specific chambers of the device, after initial use, how can we design the device so removal and replacement of filtration materials can be done easily?
- How do we prevent the materials that are meant to serve as decontaminants themselves from
becoming a part of the treated water?

Student teams discussed and shared their designs to the whole group. During this phase students described how they overcame specific barriers with their design challenge. In many cases, students described that they iterated through the engineering design process and had to redesign and rebuild their water filtration device to ensure the physical stability of the constructed device (i.e., it could stand upright on its own without the student having to hold the device), the ability to re-use the filtration device by replacing materials used in the filtration process, and also to make modifications to their design as they realized that their initial design did not achieve the provided goal of having water that has a pH of 7 and is free of oil and particulates. This summary description of the reasons why students revised their water filtration devices shows that the use of the engineering design process helped students attend to ideas related to water filtration device design that not only focused on their project’s need to filter contaminated water, but also produce a device that was functional to some extent within the scope of such a project: could stand on its own and could be reused.

The project team members who designed and implemented this curricular unit learned that the deliberate use of the engineering design process facilitated important student learning goals. Our objective for designing and implementing novel teaching learning experiences was to ensure that middle school participants had multiple opportunities to investigate and explore phenomena in science and apply their knowledge of science in service of an engineering-design challenge. The NRC\textsuperscript{10} said that students need opportunities to engage in scientific reasoning, design their own investigations, use measurement devices, record and analyze data collected from investigations, discuss the results, and apply the results of such investigations to real world problems. We set the context for the engineering design challenge of designing and implementing a water filtration device within the National Academy of Engineering’s grand challenge, “Provide access to clean water.” Students were expected to record data, analyze the data collected from their investigations of using bioremediation methods to filter contaminated water, and explain their understanding of how and why the water filtration system worked. This was achieved by expecting students to select the filtration materials based on their experiments of which materials provided them with the best results in eliminating specific contaminants from the contaminated water sample.

The specific use of the engineering design process provided students with the opportunity to engage in the design-build-test iteration process to meet the project challenge of designing and implementing a water filter so the filtered water has a pH of 7 and is free of oil and particulates. From our prior work in engaging ITEST project participants in hands-on engineering design challenges we had learned that we needed to make the iteration aspect of the engineering design process explicit. Students were therefore expected to make changes to their tested designs and redesign their water filtration device by using evidence from their prior design implementation. Students had to describe their design changes and provide their reasoning with evidence to the project facilitators before they could proceed with redesigning their water filtration devices. This deliberate process was integrated into the curricular experience. This process provided students with opportunities to demonstrate that they could develop explanations using evidence and think critically to make relationships between the evidence they had collected and the explanations they offered. We used questioning strategies that gave students the opportunity to explore and
discover on their own (without the teacher telling them) how they could apply what they know from their scientific experiments to meet the engineering design challenge. We learned that the careful and deliberate structuring of the learning experience so students had to use the results and apply evidence of their scientific investigations to meet the overall engineering design challenge was instrumental in the successful implementation of the curricular unit.

**Educational Importance of the Study**

By utilizing a hands-on, project-based approach that used the engineering design process we were able to introduce and help cultivate in students problem solving skills while learning science content. The use of the engineering design process as an instructional strategy helped facilitators provide students with a more learner centered learning experience that was highly motivating. Students could assess for themselves if they had met the project challenge thereby removing the mystery from assessment. Students could apply their knowledge of science in service of filtering water, a real world challenge. Students could demonstrate their learning to peers and adults by making a poster presentation and also show how their water filtration device worked to meet the posed challenge. By structuring the curricular unit with an engineering design project challenge, students were given opportunities to:

- Assess their own learning and monitor their success. This is a key characteristic of metacognition\(^\text{11}\) and helps students transfer knowledge to different contexts.
- Broaden the content knowledge and its relevance to real life, as students constructed their knowledge through the diversity and exploratory freedom allowed by the challenges.
- Construct an end product that served as physical evidence of their learning.
- Explain their water filtration device design and its function to peers, family members, facilitators, and other community members through end of project presentations at a celebratory closing event.

Students who find traditional in-school science and math curricula uninteresting and disconnected from their learning experiences need to be engaged in learning by doing. The critical issue for our nation is to enthuse all youth, particularly, traditionally under-represented students: **females and ethnic minorities**, in STEM subjects. Results from this study will be useful for others who are interested in designing curricular experiences that use the engineering design process, developing informal learning strategies, and studying the impact of such efforts.

**References**


Appendix A
Pre/Post Assessment

1. Circle the words below that describe a microbe.
   - Virus
   - single-cell
   - multi-cell
   - bacteria
   - Fish
   - Protist
   - Can see without microscope

2. What are three toxins in our wastewater that microbes could digest?
   - Acids
   - Bacteria
   - Fertilizers
   - Oil
   - Metal
   - Solid Waste
   - Toxic Waste

3. You just came home from the summer internship where you learned about bioremediation. Your parents want to know all about it. Describe the bioremediation process to them.

4. If you were to design a water filtration device, what are the two main steps of waste removal? What does each step remove?

Appendix B
Rubric to Score Pre/Post Assessments

**Question 1 – Circle the words that describe a microbe.**

<table>
<thead>
<tr>
<th>Bacteria</th>
<th>Protist</th>
<th>Single-Cell*</th>
<th>Virus**</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Score 1</strong>: 1 point for each correct.</td>
<td><strong>Score 2</strong>: 1 point for each incorrect.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Some microcellular organisms are microscopic.**

**Viruses are considered non-living.

**Question 2 – What are three toxins in our wastewater that microbes could digest?**

<table>
<thead>
<tr>
<th>Acids</th>
<th>Bacteria</th>
<th>Fertilizers</th>
<th>Oil</th>
<th>Metal</th>
<th>Solid Waste</th>
<th>Toxic Waste</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Score</strong>: 1 point for each correct, up to 3 points.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Question 3 – Describe the bioremediation process.**

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Answer/Incorrect Answer</td>
<td>Clean the environment</td>
<td>Using microbes/organisms.</td>
<td>Using microbes/organisms to clean the environment</td>
</tr>
</tbody>
</table>

**Question 4 – What are two main steps of waste removal? What does each step remove?**

| Primary Treatment – removes solids. | **Score 1**: 1 point for each correct. |
| Secondary Treatment – removes dissolved solids | **Score 2**: 1 point for each correct. |