Comparing the Effectiveness of Ferromagnetism and a Hydrophobic Net for Oil Spill Remediation

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I. Abstract: The oceans are one of earth's most precious ecosystems, providing a home for thousands of diverse organisms. As oil spills threaten this ecosystem, removing oil from the environment is imperative. However, current methods of oil spill remediation, such as oil booms, are ineffective if the oil is widely dispersed, and chemical dispersants are toxic to marine life. Thus, new methods such as ferromagnetism and a hydrophobic net can be employed. In this experiment, the neodymium magnet and hydrophobic net methods were tested to determine which removes a greater volume of oil. A two-sample *t* test resulting in a p-value of 4.2×10^{-8} determined that there is evidence that the neodymium magnet method removes a greater volume of oil than the hydrophobic net method. The hypothesis, stating that if the neodymium magnet method is used then about 5 mL of oil (the greatest volume of oil) will be removed from the water, was accepted, because the neodymium magnet method removed an average of 7.8 mL of oil, compared to the hydrophobic net, which removed an average of 6.4 mL of oil.

II. Table of Contents:

III. Key Words: Ferromagnetism, Oil Boom, Dispersants, Hydrophobicity, Iron (II, III) Oxide, Van der Waals Force, Magnetic Field, Neodymium Magnet

IV. Acknowledgements: The researchers would like to thank Mr. Moore for assisting with the statistical analysis of the data, Mrs. Hilliard for helping with the experimental design, and Professor Carol Miller[11] from Wayne State University for helping with the scientific concepts related to this research and the experimental design.

V. Biography: Catherine August is a senior at the Macomb Mathematics Science Technology Center (MMSTC), a selective half-day STEM program, and Lake Shore High School. Each year at MMSTC, Catherine designed and conducted an experiment of her choosing. For her senior research, she knew she wanted to do something surrounding the environment and specifically oil spills, because growing up around lakes, she grew to love the environment. She plans to major in Earth and Environmental Sciences at the University of Michigan in the fall. She hopes to continue researching various environmental issues in the future in order to protect the environment for generations to come.

Olivia Hagan is a senior at the Macomb Mathematics Science Technology Center (MMSTC), a selective half-day STEM program, and Lake Shore High School. Each year at MMSTC Olivia designed and conducted an experiment of her choosing. For her senior research with her partner Catherine August, she wanted to pursue a topic that focused on aiding the environment, as that is her greatest passion. She plans to major in Environmental Engineering at Michigan State University in the fall. She hopes to continue researching and solving important environmental issues to protect and preserve the environment for all to enjoy.

1. Introduction: Despite today's seemingly eco-friendly society, little progress has been made to find environmentally conscious ways to clean up oil spills. Oil spills are a serious threat facing oceans; in 2018, there were approximately 116,000 tons of oil lost to the environment, which is the largest annual quantity recorded in 24 years.[13] Oil spills have been an ongoing issue for quite some time; between 1970 and 2016, almost six million tons of oil were lost to the environment as a result of tanker incidents.[15] These statistics are concerning, because oil spills can negatively impact lifeforms near and around oceans. Oil destroys the insulating ability of fur-bearing mammals and the water repellency of a bird's feathers, thus exposing these animals to the harsh elements when covered in oil. Without the ability to insulate and repel the cold ocean water, these animals die from hypothermia. Along with this, birds and mammals could ingest oil when trying to clean themselves, which poisons them.[7] Therefore, it is important for humanity to find quick, effective ways to clean oil spills and prevent animals from suffering.

Oil enters the world's oceans in a multitude of ways, most of which have to do with human activity. Oil spills can occur when people make mistakes or are careless, causing an oil tanker, or a ship that carries oil from one country to another, to leak into the ocean. Spills can also occur when equipment breaks down while extracting crude oil from the depths of the ocean. When countries are at war, people may even decide to dump gallons of oil into the other country's oceans. Similarly, people and companies may illegally dump crude oil into the ocean to avoid spending money on decomposing waste oil.[8] Finally, oil spills can also occur from natural oil seeps on the seafloor, such as the Coal Oil Point along the California coast where an estimated 7,570 to 11,400 liters of crude oil are released each day.[16]

After decades of oil spills damaging the environment, environmental scientists are hoping to develop new, quick, and effective methods of oil remediation. A new form of oil recapture involves magnetizing the oil by adding ferromagnetic material, iron (II,III) oxide (Fe_3O_4), to the oil spill. Oil on its own does not exhibit magnetic properties, but the addition of ferromagnetic particles causes it to behave magnetically. Ferromagnetism occurs when an external magnetic field is applied to a substance that, on its own, has magnetic domains that face different directions, thus exhibiting no overall magnetic force. However, the magnetic force allows the magnetic domains to align and magnetically attract.[2] When iron (II,III) oxide (Fe_3O_4), a ferromagnetic material, is added to oil, the oil exhibits magnetic properties. This interaction is due to Van der Waals' law that states there is a relatively weak electric force that attracts neutral molecules to each other. One side of a molecule is always somewhat positive and the other side negative, thus the positive and negative charges of two molecules will align, creating a net force.[2] Therefore, when a magnetic field is introduced into the oil combined with the iron (II,III) oxide, the magnet attracts the iron (II,III) oxide particles and the iron (II,II) oxide pulls the oil nanoparticles along with it, due to the weak force stated in Van der Waals law, as demonstrated in Figure 1.[12]

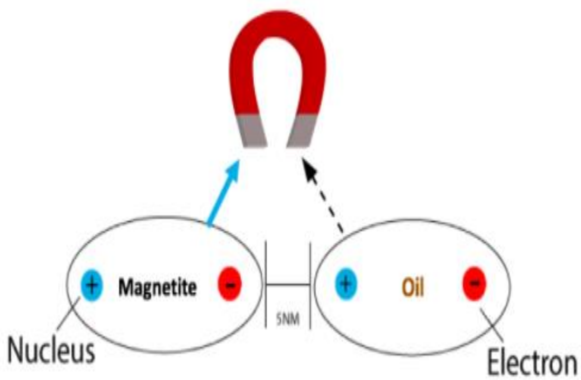


Figure 1. Van der Waals' Law[12]

Figure 1 illustrates how the Van der Waals force between the iron (II,III) and the oil, creates a weak bond. Once an external magnetic field is introduced the ferromagnetic iron (II,III) oxide is attracted to the magnet, pulling the oil along with it.

Another new method of oil remediation involves using porous hydrophobic and oleophilic materials (PHOMs), which repel water and attract oil.[3] PHOMs, in the form of functionalized membranes with bio-spired surfaces, including steel meshes and fabrics, are hydrophobic, or "water fearing". On a molecular level, being hydrophobic is having the ability to repel water. When exposed to water, hydrophobic, nonpolar (having no positive or negative poles) molecules disrupt hydrogen bonds between water molecules and form a clathrate structure on the surface. As these nonpolar molecules clump together, their exposure to water, as well as the entropy of the system, or degree of disorder, decreases.[6] In this experiment, NeverWet spray was used to create a hydrophobic base coat and hydrophobic topcoat on a woven wire mesh. NeverWet spray creates a clathrate structure, thus when it was sprayed on the mesh, it repelled water.

The purpose of this experiment is to determine which of these two methods of oil remediation removes the greatest volume of oil, in milliliters (mL), from a simulated oil spill. It is hypothesized that if the process of ferromagnetism is used, in which magnetite powder (Fe_3O_4) is injected into an oil spill, and collected in mL using a neodymium magnet, then 5 mL of oil (the greatest volume of oil) will be removed from the water, when compared with a hydrophobic net.

Previous research helped design the experiment and determine the hypothesis. One previous study conducted by Sachin Narayan[12], a high school student who conducted his experiment with the aid of Schmahl Science Workshops and chemistry professor Debani Roy, Ph. D, evaluated the use of oleophobicity, the ability to repel oil, and ferromagnetism in containing and recapturing underground oil spills. He utilized a fish tank cleaning net with an Ultra Ever-Dry oleophobic coating for one removal method, and injected iron (II,III) oxide (Fe_3O_4) into an oil spill and used a neodymium magnet to extract the oil for another.[12] He found that using the oleophobic net yielded 60.70% effectiveness and the neodymium magnet yielded 43.79% effectiveness. Although this research is similar to Narayan's[12], there are a few distinct differences. Unlike Narayan's[12] research, oil was removed from the surface of water rather than underground. This research also utilized a hydrophobic net method rather than a fish tank cleaning net with an Ultra Ever-Dry oleophobic coating, due to the availability of materials. Information from Narayan's[12] research was helpful for this experiment, as Narayan's[12] experiment provided the initial idea for this research, helped give a basis for the experimental design, and determined that it was possible to clean oil spills using ferromagnetism.

Another study done by Ibrahim Ali Amar[1], a professor in the department of chemistry at Sebha University in Sebha, Libya, applied cobalt ferrite ($CoFe_2O_4$) magnetic nanoparticles to oil to magnetize it, and found that it created a considerable magnetic force that is strong enough to remove oil spills from a water surface.[1] Again, this research is similar to Amar's[1], but instead of applying cobalt ferrite ($CoFe_2O_4$) magnetic nanoparticles to the oil spill, this research utilized magnetite powder (Fe_3O_4). This previous research was also useful for the experimental design, as it confirmed that magnetizing oil is a possibility for effective oil remediation, providing one removal method to test in this experiment.

This research can help the public understand that developing new methods of oil remediation is beneficial. If informed of the negative impacts that oil spills have on sea animals, citizens may take action to protect oceans from devastating oil spills. In turn, this will provide more protection for these animals. This research is also valuable to the scientific community and environmental scientists. Environmental scientists are working to develop new, innovative methods for oil remediation. Little research has been done testing the neodymium magnet and hydrophobic net methods of oil remediation, ergo this research could provide one source that determines which method of these two is more effective. Environmental scientists could then use the oil remediation method that was most effective to treat oil spills.

2. Materials and Methods:

Materials:

(3) Plastic Containers (Holds 735 mL)
(16 cm. x 16 cm. x 5 cm.)
Syringe (30 mL Barrel)
Filippo Berio Olive Oil (750 mL)
Scale 0.0001 g Precision
Weigh Boat
Scoopula
Beaker (20 mL)
Graduated Cylinder (1 L)
Graduated Cylinder (0.5 L, See Annex I)
FloTool Funnel (11.9 cm. Dia.)
(2) Measuring Cup (5 mL and 237 mL)
Plastic Test Tube (Holds 45 mL)
(117 mm. x 34 mm.)
Pure and Natural Morton Salt (875 g)
Never Wet Hydrophobic Base Coat
Fe_3O_4 (Magnetite Powder) (5.0 g)
(5) Magnet Source Neodymium Magnet
(19 mm. Dia. x 1.53 mm. Thk.)
Hydrophobic Net
Home Store Dish Soap (887 mL)
Scrub Buddies Sponge
(11.4 cm x 8.1 cm x 2.3 cm)
Masking Tape
Plastic Container (Holds 15 L)
(38 cm. x 30 cm. x 23 cm.)
Tidy Cats Cat Litter (5 Cups)
(50) White Cloth Strips
(2.54 cm x 12.70 cm)
Cleaning Rod
Top Fine Mesh Fit Net (7.62 cm)
Never Wet Hydrophobic Topcoat

Procedures:

1. Using the TI-Nspire calculator randomizing function, randomize the order in which the 40 trials will be completed. Generate numbers 1 through 40, with 1 through 20 representing the neodymium magnet method trials, and 21 through 40 representing the hydrophobic net method trials. Do this until each number appears, and conduct trials in the order the numbers were generated. Also, complete the 10 control trials throughout the duration of the experiment by doing a control after every two trials that were generated.
2. Place the three plastic containers on a table. Use scotch masking tape and a sharpie to label one container "Neodymium Magnet Method", another container "Hydrophobic Net Method", and the final container "Control".
3. Create a stock saltwater solution that resembles the salinity of oceans (3.5%). To do this, pour 25 L of water and 875 g of salt in a 60 cm. x 40 cm. x 35 cm. latch storage box. Allow 30 minutes for the salt to dissolve.
4. Use a 237 mL measuring cup to add 237 mL of the stock saltwater solution to the 1 L graduated cylinder. Then, use the 237 mL measuring cup to add 263 mL of the stock saltwater solution to the 1 L graduated cylinder to total 500 mL of saltwater in the 1 L graduated cylinder. Pour this into the specified container.

5. Pour 5 mL of olive oil into the 5 mL measuring cup. Pour the 5 mL of olive oil from the 5 mL measuring cup into the 20 mL beaker. Do this process twice to pour a total of 10 mL of olive oil into the 20 mL beaker. Olive oil is used as a substitute for crude oil, as crude oil is a dangerous substance. Olive oil has a viscosity of 10 centipoise, which is within the 1 to 10^5 centipoise range of the viscosity of crude oil.[5] Viscosity is the resistance of a fluid to change in shape, thus as olive oil and crude oil have similar viscosities they will behave and move similarly.[17]
6. Use the 30 mL barrel syringe to collect the oil from the 20 mL beaker and inject it in the center of the surface of the water in the plastic container. Let the oil spread over the surface for 15 seconds.
7. The following steps pertain to the neodymium magnet method of oil removal.
    a. Use a weigh boat and a scoopula to measure 0.25 g Fe_3O_4 (magnetite powder) on the scale. Record the actual mass of the magnetite powder in the observations table.
    b. Sprinkle the 0.25 g Fe_3O_4 (magnetite powder) from the weigh boat on top of the oil spill. Allow it to spread over the spill for 20 seconds.
    c. Using masking tape, adhere the neodymium magnet to the outer part of the 45 mL plastic test tube, about 35 mL up from the bottom of the tube. Submerge the 45 mL plastic test tube sideways, halfway underwater.
    d. Hold the 45 mL plastic test tube halfway underneath the water for 30 seconds, allowing the oil to attract to the magnet at the bottom. After 30 seconds, remove the 45 mL plastic test tube from the water.
8. The following steps pertain to the hydrophobic net method of oil removal.
    a. Create the hydrophobic net by spraying the Never Wet Hydrophobic Base Coat over the Top Fin Fine Mesh Net and letting it dry for 30 minutes in a well-ventilated area. Afterward, spray the Never Wet Hydrophobic Topcoat over the Top Fin Fine Mesh Net and let it dry for 30 minutes in a well-ventilated area.
    b. Submerge the hydrophobic net underneath the water. Use the net to “scoop” the oil from the surface of the water and let the water drain out the holes of the net as the oil beads up on the hydrophobic net surface.
    c. Lift the net out of the water and dispose of the oil from the net and any excess water by running water through the net. Dry the net using paper towel.
9. To conduct a control trial, follow steps 1-6 and then proceed to step 10 to measure the oil that is remaining in the container.
10. To measure the oil remaining in the container, put a funnel at the top of the self-constructed graduated cylinder (see Annex I). Pour the entire content of the container into the funnel slowly to reduce the formation of air bubbles. Allow the water and oil to separate for two minutes.
11. On the self-constructed graduated cylinder, using the mL lines, measure the oil that was separated from the water. See Figure 2 to view this process.
12. Pour the contents of the self-constructed graduated cylinder into the 38 cm. x 30 cm. x 23 cm. plastic container. This ensures that the olive oil is not poured down the drain.
13. The following steps detail how to clean the graduated cylinder after each trial.
    a. Pour 500 mL of tap water into the graduated cylinder.
    b. Place the graduated cylinder so that the cap opening faces the sink and twist the cap off to empty the water into the sink. Repeat this process twice.

c. Tie a 2.54 cm. x 12.70 cm. piece of white cloth onto the eye end of the cleaning rod. Insert the cleaning rod into the graduated cylinder and twist it to dry out the inside of the tubing. After use, untie the white cloth and throw it away.

14. Repeat steps 1-13 until 20 trials of the neodymium magnet method, 20 trials of the hydrophobic net method, and 10 trials for the controls are completed.

15. After all the trials have been conducted, use a paper cup and skim the surface of the 38 cm. x 30 cm. x 23 cm. container to collect the oil. Pour this recollected oil into a gallon Zip Lock bag with ten cups of cat litter. Skim the entire surface of the container five times and collect as much oil as possible. Throw the cat litter into the garbage and pour the remaining water down the drain.

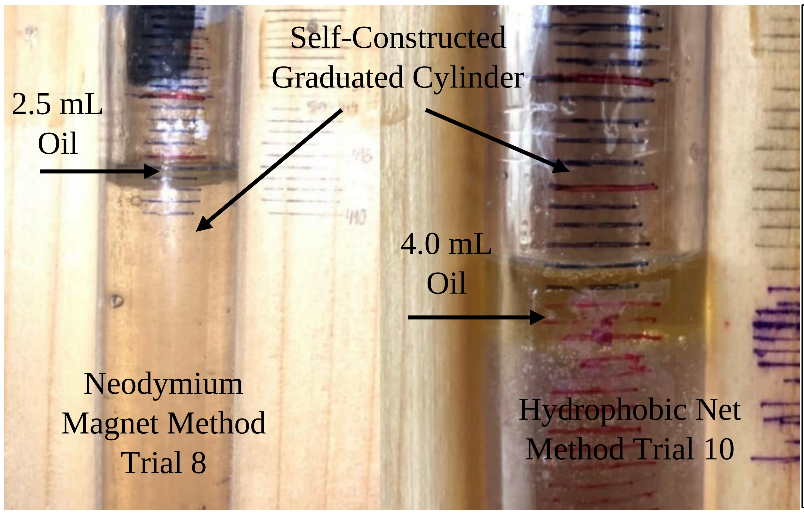


Figure 2. Collecting the Data

Figure 2 shows how the olive oil and water separate in the 0.5 L graduated cylinder that was constructed in Annex I. Due to this separation, the mL of oil in the graduated cylinder can be measured and recorded, and then subtracted from the initial 10 mL of oil that were added to the container to obtain the mL of oil that the collection method removed.

3. Results: In this experiment, two different methods of oil remediation were used to determine which method would be most effective at cleaning oil spills. To determine the most effective method, after applying the given recollection method, the remaining oil from each container was collected and measured using a self-constructed graduated cylinder. See the procedures for further explanation of the experimental setup.

Table 1
Milliliters of Oil Removed by Neodymium Magnet Method

Neodymium Magnet Oil Remediation Method		
Trial	**Oil Remaining (mL)**	**Oil Removed (mL)**
1	3.0	7.0
2	3.0	7.0
3	2.0	8.0
4	1.5	8.5
5	2.0	8.0

Trial	Oil Remaining (mL)	Oil Removed (mL)
6	1.5	8.5
7	2.0	8.0
8	2.5	7.5
9	3.5	6.5
10	2.5	7.5
11	3.0	7.0
12	1.5	8.5
13	1.5	8.5
14	1.5	8.5
15	2.5	7.5
16	3.0	7.0
17	2.0	8.0
18	2.0	8.0
19	2.0	8.0
20	1.5	8.5
Average	2.2	7.8

Table 1 shows the volume of oil that remained in the container and the volume of oil that was removed from the container, both measured in mL, after applying the neodymium magnet oil remediation method. There were 20 trials done for this method, with the average oil remaining in the container measuring at 2.2 mL, and thus the average oil removed from the container was 7.8 mL. Notice that trials 4, 6, 12, 13, 14, and 20 had the lowest volume of oil remaining in the container at 1.5 mL, and the neodymium magnet removed 8.5 mL of oil. In all these trials, when transferring the remaining oil and water from the container to the self-constructed graduated cylinder, the container was dumped into the funnel too quickly causing some of the liquid to overflow out of the graduated cylinder and onto the ground. Therefore, the low volume of oil remaining in the container could be due to some of the oil overflowing out of the funnel. Trial 9 had the greatest volume of oil remaining in the container at 3.5 mL, and the neodymium magnet removed 6.5 mL of oil. In this trial, the oil immediately spread along the sides of the container after injection, making it difficult to apply the Fe_3O_4 powder to all parts of the oil spill. Thus, the high volume of oil remaining in the container could be due to some of the Fe_3O_4 powder not attaching to the oil.

Table 3
Milliliters of Oil Removed by Hydrophobic Net Oil Method

Hydrophobic Net Remediation Method		
Trial	**Oil Remaining (mL)**	**Oil Removed (mL)**
1	4.5	5.5
2	5.0	5.0
3	4.0	6.0
4	3.0	7.0
5	3.5	6.5
6	3.0	7.0
7	3.0	7.0
8	2.5	7.5
9	3.0	7.0
10	4.0	6.0
11	3.5	6.5
12	4.5	5.5
13	4.0	6.0
14	4.0	6.0
15	3.5	6.5
16	3.5	6.5
17	3.0	7.0
18	3.5	6.5
19	4.5	5.5
20	2.5	7.5
Average	3.6	6.4

Table 3 shows the volume of oil that remained in the container and the volume of oil that was removed from the container, both measured in mL, after applying the hydrophobic net remediation method. There were 20 trials done for this method, with the average oil remaining in the container measuring at 3.6 mL, and thus the average oil removed from the container was 6.4 mL. Notice that trials 8 and 20 had the lowest volume of oil remaining in the container at 2.5 mL, and thus the hydrophobic net removed 7.5 mL of oil. In both these trials, the oil did not disperse, which enabled the hydrophobic net to easily collect the oil. Furthermore, in these trials, when transferring the remaining oil and water from the container to the self-constructed graduated cylinder, the container was dumped into the funnel too quickly causing some of the liquid to overflow out of the graduated cylinder. Therefore, the low volume of oil remaining in the container could be due to the oil staying in place and some of the oil overflowing out of the funnel. Trial 2 had the greatest volume of oil remaining in the container at 5.0

mL, and thus the hydrophobic net removed 5.0 mL of oil. In this trial, the oil immediately spread along the sides of the container after injection, making it difficult for the net to encompass all the oil to remove it. Thus, the high volume of oil remaining in the container could be due to the dispersion of the oil.

Table 5
Milliliters of Oil Removed Using No Oil Remediation Method (Control) Data

Control (No Oil Remediation Method)		
Trial	**Oil Remaining (mL)**	**Oil Lost (mL)**
1	7.0	3.0
2	7.0	3.0
3	6.0	4.0
4	6.0	4.0
5	7.0	3.0
6	7.0	3.0
7	6.0	4.0
8	6.0	4.0
9	7.0	3.0
10	6.0	4.0
Average	6.5	3.5

Table 5 shows the volume of oil that remained in the container and the volume of oil that was removed from the container, both measured in mL, when no oil remediation method was applied. There were 10 trials done for this method, with the average oil remaining in the container measuring at 6.5 mL, and thus the average oil removed from the container was 3.5 mL. Trials 3, 4, 7, 8, and 10 had the lowest volume of oil remaining in the container at 6.0 mL, whereas trials 1, 2, 5, 6, and 9 had the highest volume of oil remaining in the container at 7.0 mL, resulting in an average of 6.5 mL of oil remaining in the container. However, this means that 3.5 mL of oil was lost when no oil remediation method was applied. It can therefore be assumed that 3.5 mL of oil is lost in the transfer process from the container to the funnel, and from the funnel to the graduated cylinder. Thus, when looking at the data points for how much oil a specific oil remediation method removed, it is estimated that the value of oil removed is actually 3.5 mL lower than the value in the table.

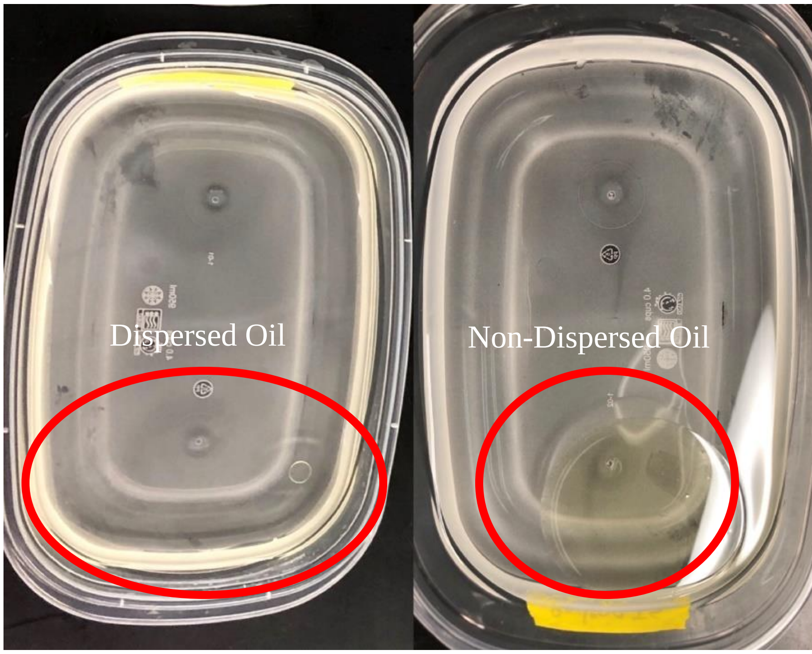


Figure 3. Dispersion of Oil Within the Container
The figure shows a side by side comparison of the saltwater solution when the oil disperses, compared to when the oil does not disperse. When looking at the right container the oil is much more contained and takes up a smaller surface area. Due to the smaller surface area it is easier for the small width of the hydrophobic net to collect the oil. The fact that the oil was more dispersed in some of the hydrophobic net trials, but less dispersed in others, could explain the variation in data.

5. Discussion: To ensure that the data collected was reliable, constants, controls, randomization, and repetition were utilized. To minimize the effect of lurking variables, the same concentration of oil was added to each container, the saltwater solution was always at room temperature (25 °C), and the same researcher injected the oil and applied the oil remediation method to each container. Furthermore, control trials were conducted, in which no oil remediation method was applied. This helped determine if the oil not remaining in the container was due to solely the oil remediation method applied, or if some oil was lost in the transfer process from the measuring cup to the container.

Moreover, the data was randomized in order to increase reliability and decrease the variability in the data. Finally, the experiment was repeated 20 times with each oil remediation method to provide assurance that the results from the experiment are valid and consistent, and to reduce variability in the data. This repetition combined with the constants, controls, and randomization ensured that the data collected was valid.

The oil removed by the neodymium magnet oil remediation method and the oil removed by the hydrophobic net oil remediation method can be compared to reveal which oil remediation method is most effective at removing oil from an oil spill. To do this, a two-sample *t* test will be used. A two-sample *t* test is an appropriate statistical test to analyze this data, as a two-sample *t* test allows two means of independent populations to be compared. In this experiment, the first population is the neodymium magnet trials and the second population is the hydrophobic net trials. However, before conducting a two-sample *t* test, all the necessary assumptions must be met.

The first assumption was that there are two simple random samples taken from two independent populations. This was met, as each method had an equal chance of being selected due to the randomization technique applied. The second assumption was that the samples used must be no more than one-tenth their population sizes. This was met as the population of all occasions in which the neodymium magnet and hydrophobic net oil remediation methods have been used is greater than 400 (the sample size of 20 for each method multiplied by 10). The final assumption was that the samples used in the two-sample *t* test were from normally distributed populations, or at least 30 samples were done. This experiment did not have 30 or more samples for each oil remediation method, meaning that the Central Limit Theorem could not be used to determine that the sampling distributions were normal. Box plots were used to determine if the samples collected were from normally distributed populations, shown in Figure 4.

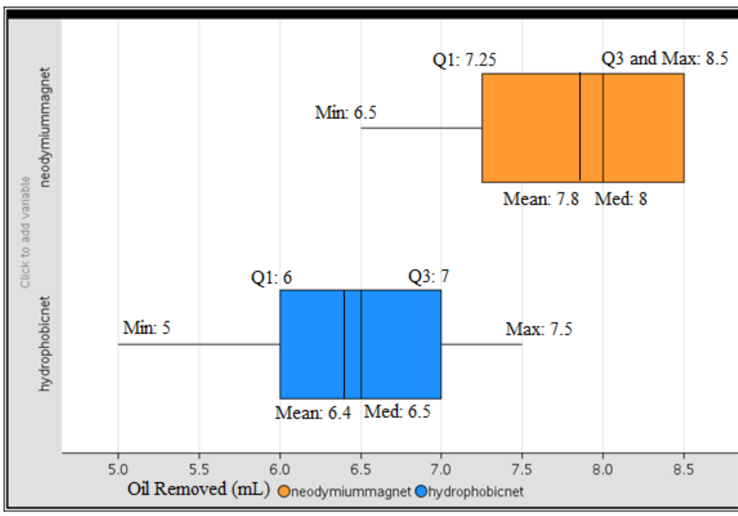


Figure 4. Oil Concentration Removed Using Each Method Box Plots

The box plot for the neodymium magnet method appears to be normal with minimal skew to the left because the mean is less than the median. The box plot for the hydrophobic net method also appears to be normal with minimal skew to the left, as again, the mean is less than the median.

Moreover, the box plot for the hydrophobic net method is furthest to the left, suggesting that the hydrophobic net removed less oil and was less efficient than the neodymium magnet approach. However, about 50% of the hydrophobic net data overlaps with the neodymium magnet data. Thus, the box plot alone cannot determine if the neodymium magnet method removed significantly more oil than the hydrophobic net method. Furthermore, for the neodymium magnet method, the median is 8.0 mL and the mean is 7.8 mL, and for the hydrophobic net method, the median is 6.5 mL and the mean is 6.4 mL. This suggests that the hypothesis predicting the neodymium magnet method would be most effective at removing oil could be correct, as the neodymium magnet method has both a higher mean and median than the hydrophobic net method. When looking at the box plots, since the samples can be considered to come from normally distributed populations, the two sample *t* test result should be reliable.

Figure 5 below shows the hypotheses to complete a two-sample *t* test comparing the mean volume of oil removed when using the neodymium magnet oil remediation method (μ_1) and the mean volume of oil removed when using the hydrophobic net oil remediation method (μ_2).

H_o: $\mu_1 = \mu_2$

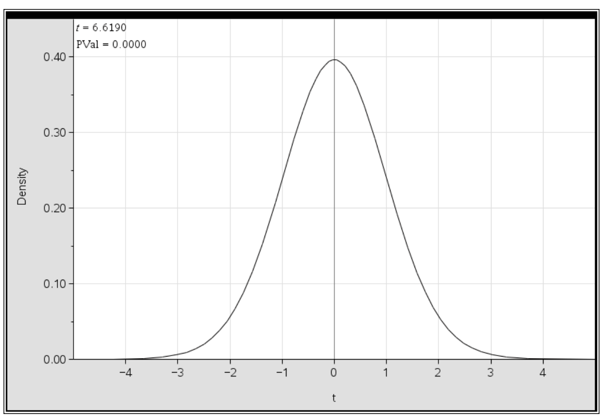
H_a: $\mu_1 > \mu_2$

Figure 5. Hypotheses for Statistical Test

As shown in Figure 5, the null hypothesis, H_o, states that the mean volume of oil removed when using the neodymium magnet oil remediation method is the same as that when using the hydrophobic net method of oil remediation. The alternative hypothesis, H_a, states that the mean volume of oil removed when using the neodymium magnet oil remediation method is greater than the volume of oil removed when using the hydrophobic net oil remediation method. Figure 6 shows the *t* value, the p-value, and the probability graph of the two-sample *t* test.

Figure 6. Probability Graph for Two-Sample *t* Test

Title	2−Sample t T..
Alternate..	μ1 > μ2
t	6.61905
PVal	4.21738E-8
df	37.6663
x̄1	7.8
x̄2	6.4
sx1	0.636603
sx2	0.699624
n1	20.
n2	20.



As shown in Figure 6, the *t* value was found to be 6.6190 and the p-value was found to be 4.2×10^{-8}. From the results of the two-sample *t* test, the null hypothesis is rejected because the p-value of 4.2×10^{-8} is less than the alpha (α) level of 0.05. There is evidence that on average, the neodymium magnet method removes a greater volume of oil from oil spills than the hydrophobic net method. If the null hypothesis was true, that is, if there really was no difference in the volume of oil removed when using the neodymium magnet method and when using the hydrophobic net method, then there would be almost no chance of getting a difference in volume of oil removed this extreme by chance. Since this is so unlikely to happen, the null hypothesis was rejected. When considering the small p-value of

4.2×10^{-8} and the rejection of the null hypothesis, it can be concluded that on average, the neodymium magnet method removes a significantly larger volume of oil than the hydrophobic net method, which supports the hypothesis.

The data collected supported the hypothesis, as adding the ferromagnetic material iron (II,III) oxide (Fe_3O_4) to the oil and then applying an external magnetic field with the neodymium magnet caused the oil to behave magnetically. Oil alone does not exhibit magnetic properties, but the addition of Fe_3O_4 powder and an external magnetic field allows the oil to behave in a magnetic manner. Magnetite, Fe_3O_4 powder, is a ferromagnetic material and on its own is not magnetic, but in the presence of an external magnetic field its domains align and magnetically attract to the magnetic field. The Fe_3O_4 powder particles then pull the oil particles with it due to Van der Waals' law, which states there is a relatively weak electric force that attracts neutral molecules to each other since one side of a molecule is always somewhat positive and the other negative, thus causing the opposite charges of the two molecules to align and create a net force. Therefore, in this experiment, when a magnetic field is applied to the oil and Fe_3O_4 powder combination, the neodymium magnet attracts the iron (II,III) oxide particles and the iron (II,II) oxide pulls the oil nanoparticles along with it, due to the weak force stated in Van der Waals law.[12]

Furthermore, the neodymium magnet method of oil remediation does not require the oil to stay in place, as the magnetic attraction will still be there even if the oil disperses. On the other hand, the hydrophobic net method will work most effectively if the oil remains in place and takes up less surface area, because it is easier for the small width of the hydrophobic net to encompass the entire oil spill as the net runs through the spill.[10] Therefore, the neodymium magnet method was able to, on average, collect more oil than the hydrophobic net method.

The results from this experiment do not agree with some existing research but do for other existing research in the field. A study done by Sachin Narayan[12], a high school student assisted by professor Debany Roy, Ph. D, utilized a net with Ultra Ever-Dry oleophobic and hydrophobic coatings for one removal method, and injected iron (II,III) oxide (Fe_3O_4) into an oil spill and used a neodymium magnet for another. He found that using the net method yielded 60.70% effectiveness and the neodymium magnet yielded 43.79% effectiveness.[12] These results disagree with this research, as this research found the neodymium magnet method to be more effective. However, this is because Narayan[12] utilized an oleophobic and hydrophobic coating rather just a hydrophobic coating, thus the surface of their net was able to repel water and the oil. Oleophobic surfaces repeal hydrocarbons like those found in oil.[4] Due to the size of the pores and the hydrophobic and oleophobic coating on Narayan's[12] net, the water was able to escape the net, but the oil remained inside the vicinity of the net for recapture. The oleophobic coating caused the oil to bead up on the surface of Narayan's[12] net so that it did not leak through the mesh of the net, however, in this experiment there was no oleophobic coating applied to the net. This allowed some oil to leak through the pores of the mesh net, and as a result less oil was able to be recaptured.

Although this research differed from Narayan's[12] research, it concurred with Ibrahim Ali Amar's[1] research, a professor in the department of chemistry at Sebha University in Sebha, Libya. Amar[1] applied cobalt ferrite ($CoFe_2O_4$) magnetic nanoparticles to oil to magnetize it and found that it created a considerable magnetic force that is strong enough to remove oil spills from a water surface.[1] Although this research utilized magnetite powder (Fe_3O_4) rather than cobalt ferrite ($CoFe_2O_4$) magnetic nanoparticles, this study confirmed that magnetizing oil is a possibility for effective oil remediation.

Further research could be conducted to expand upon this research and investigate more about cleaning oil spills. An experiment could be done using different chemicals with magnetic properties, including Fe_3O_4 and $CoFe_2O_4$, to determine which material is the safest for marine organisms and which material is the most attracted to neodymium magnets. These results could be utilized by environmental scientists, as it could help them determine which chemical should be used on a larger scale to remediate oil spills.

More research could also be conducted comparing the neodymium magnet method with a broader range of oil remediation methods, including bioremediation. Bioremediation involves the use of microorganisms, including *Pseudomonas fluorescens, Arthrobacter*, and *Burkholderia* to remove pollutants.[14] If these microorganisms are stimulated with nutrients, especially oxygen and nitrogen, they can destroy contaminants and use them for growth and reproduction. This is because contaminants, such as those in crude oil, provide a source of carbon, which is one of the fundamental aspects of forming new cell constituents and electrons for microorganisms.[9] Environmental scientists could compare the results from this research with future research on bioremediation to determine if the neodymium magnet method of oil remediation is truly the most effective, or if bioremediation may be a better option.

6. Conclusions: The hypothesis states that if the neodymium magnet method of oil remediation is used, then 5 mL of oil (the greatest volume of oil) will be removed from the water, when compared with a hydrophobic net. The hypothesis was accepted, because the neodymium magnet method removed an average of 7.8 mL of oil, but when considering the average residual of 3.5 mL of oil lost when no collection method was utilized, it removed an average of 4.3 mL of oil. On the other hand, the hydrophobic net method removed an average of 6.4 mL of oil, but again, when considering the average residual of 3.5 mL of oil lost when no collection method was utilized, it removed an average of 2.9 mL of oil. Therefore, the neodymium magnet method removed the greater volume of oil, which was close to 5 mL, confirming the hypothesis. Furthermore, the two-sample *t* test comparing the oil removed by the neodymium magnet and hydrophobic net removal methods resulted in a p-value of 4.2×10^{-8}, suggesting that the volume of oil removed for the neodymium magnet method was significantly greater than that removed for the hydrophobic net method, which also supports the hypothesis.

The results from this experiment have a great impact on the scientific community. Oil booms have historically been used to clean oil spills, however they only work if the oil is in one spot, if there are no rough sea waves, if there are no high wind velocities, and if it used within a few hours of the spill occurring, or else the spill becomes too large for oil booms to be effective. Dispersants have also historically been used to clean oil spills, but they are highly toxic to marine organisms.[18] Thus, it is imperative that oil spills are cleaned up using a better method, and this research determined that the neodymium magnet method of oil remediation is one such method. Exploration into areas of oil spills and oil remediation methods will help protect marine organisms and the environment from the threatening implications of oil spills, ensuring a cleaner world for humanity to inhabit.

7. References:

[1] Amar, Ibrahim Ali, et al. "Oil Spill Removal from Water by Absorption on Zinc-Doped Cobalt Ferrite Magnetic Nanoparticles." *Advanced Journal of Chemistry, Section A: Theoretical, Engineering and Applied Chemistry*, Sami Publishing Company (SPC), 1 Sept. 2019, www.ajchem-a.com/article_88429.html.

[2] Britannica, The Editors of Encyclopedia. "Ferromagnetism." *Encyclopædia Britannica*, Encyclopædia Britannica, Inc., 2 Mar. 2014, www.britannica.com/science/ferromagnetism.

[3] Ge, Jin, et al. "Pumping through Porous Hydrophobic/Oleophilic Materials: An Alternative Technology for Oil Spill Remediation." *Angewandte Chemie International Edition*, vol. 53, no. 14, 2014, pp. 3612–3616., doi:10.1002/anie.201310151.

[4] Hanson, Eric, Ph.D. "Ask the Expert: What Makes a Nanocoating Oleophobic?" *YouTube*. Aculon, 7 Oct. 2015. Web. www.youtube.com/watch?v=iFN9SaYBplg.

[5] "Heavy Oil vs. Light Oil." Legislative Brown, Mar. 2011, www.aoga.org/wp-content/uploads/2011/03/HRES-3.10.11-Lunch-Learn-BP-Heavy-Oil1.pdf

[6] Helmenstine, Anne Marie. "The Definition of Hydrophobic With Examples." *ThoughtCo,* ThoughtCo, 9 July 2019, www.thoughtco.com/definition-of-hydrophobic-605228.\

[7] "How Does Oil Impact Marine Life?" *NOAA's National Ocean Service*, 4 May 2010, oceanservice.noaa.gov/facts/oilimpacts.html.

[8] "How Do Oil Spills Happen?" *Office of Response and Restoration*, response.restoration.noaa.gov/training-and-education/education-students-and-teachers/how-do-spills-happen.html.

[9] "In Situ Bioremediation: When Does It Work?" at NAP.edu." *National Academies Press: OpenBook*, www.nap.edu/read/2131/chapter/4#17.

[10] Liu, Zhanfei, et al. "The Impact of Deepwater Horizon Oil Spill on Petroleum Hydrocarbons in Surface Waters of the Northern Gulf of Mexico." *Deep Sea Research Part II: Topical Studies in Oceanography*, Pergamon, 23 Jan. 2014, www.sciencedirect.com/science/article/abs/pii/S0967064514000277?via%3Dihub

[11] Miller, Carol. "Research Project Assistance." Message to Catherine August. 23 Sep. 2019. E-mail.

[12] Narayan, Sachin. "Deep Sea Oil Trap: An Underwater Cleanup System for Platforms and Ships to Contain and Recapture Oil Plumes." *The National High School Journal of Science*, 12 Nov. 2017, nhsjs.com/2017/deep-sea-oil-trap-an-underwater-cleanup-system-for-platforms-and-ships-to-contain-and-recapture-oil-plumes/.

[13] "Oil Tanker Spill Statistics 2018." *ITOPF*, www.itopf.org/knowledge-resources/data-statistics/statistics/.

[14] Peixoto, R. S., et al. "Petroleum-Degrading Enzymes: Bioremediation and New Prospects." *Enzyme Research*, vol. 2011, 2011, pp. 1–7., doi:10.4061/2011/475193.

[15] Roser, Max. "Oil Spills." *Our World in Data*, 5 Mar. 2013, ourworldindata.org/oil-spills.

[16] Thompson, Andrea. "FAQ: The Science and History of Oil Spills." *LiveScience*, Purch, 23 Apr. 2010, www.livescience.com/9885-faq-science-history-oil-spills.html.

[17] Wen, Christopher. "Viscosity." *Chemistry LibreTexts*, Libretexts, 5 June 2019, chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supple

mental_Modules_(Physical_and_Theoretical_Chemistry)/Physical_Properties_of_Matter/States_of_Matter/Properties_of_Liquids/Viscosity.

[18] Wise, James, and John Pierce Wise. "A Review of the Toxicity of Chemical Dispersants." *Reviews on Environmental Health*, U.S. National Library of Medicine, 2011, www.ncbi.nlm.nih.gov/pmc/articles/PMC6730675/.

8. Bibliograph

Burns, Kathleen, and Michael Harbut. "Crude Oil and Your Health." Science Corps, www.sciencecorps.org/crudeoilhazards-public.pdf.

Cressey, Daniel. "The Science of Dispersants." Nature News, Nature Publishing Group, 12 May 2010, www.nature.com/news/2010/100512/full/news.2010.237.html.

Laurén, Susanna. "What Are Surfactants and How Do They Work?" Surface Science Blog, blog.biolinscientific.com/what-are-surfactants-and-how-do-they-work.

"Why Is the Ocean Salty?" NOAA's National Ocean Service, National Oceanic and Atmospheric Administration, 14 Nov. 2008, oceanservice.noaa.gov/facts/whysalty.html.

9. Annex:

Annex I: Building Graduated Cylinder for Data Collection

Materials:

Pine Wood Backboard (8.26 cm x 10.80 cm x 107.95 cm)
(2) Pine Wood Sideboard (3.81 cm x 2.54 cm x 107.95 cm)
(2) Pine Wood Front Board (10.00 cm x 3.80 cm x 1.90 cm)
Cedar Wood Baseboard (50.17 cm x 13.97 x 2.54 cm)
UPD Clear Vinyl Tubing 2.54 cm I.D. x 3.18 cm O.D. (3.05 m long)
WATTS Nylon Hose Barb (25.00 mm x 20.00 mm)
White PVC Cap (19.05 mm)
(7) Grip Rite Drywall Screws (#6 size 3.18 cm)
(3) Irwin Quick Grip Clamp
Caliper (15.24 cm)
Titebond Original Wood Glue (236.59 mL)
(28) DeWalt Narrow Crown Staples 9 (3.18 cm)
Staple Gun
Tape Measurer
Nail Drill
Electric Miter Saw
Ruler (30 cm)

Procedures:

1. Cut a 1.067 m long section of the UPD Clear Vinyl Tubing with an electric miter saw.
2. At one end of the long clear vinyl tubing, insert the WATTS Nylon Hose Bard so that the elbow points outward at a 90º angle. Screw the PVC cap on the end of the WATTS Nylon Hose Bard.
3. With the measuring tape, measure a 8.26 cm x 10.80 cm x 107.95 cm pine wood rectangle and cut to size with an electric miter saw. This will be the backboard of the graduated cylinder.
4. With the measuring tape, measure two 3.81 cm x 2.54 cm x 107.95 cm pine wood rectangles and cut with an electric miter saw. These will be the sideboards around the vinyl tubing.
5. On the left side of the pine wood backboard, line up one of the pine wood side boards on top of the backboard so that their 107.95 cm length sides are lined up, with none of the sideboard overlapping on the outside edge of the baseboard. Apply a thin line of wood glue all the way down the back of the sideboard and glue in place.
6. Place three Irwin Quick Grip Clamps over the glued baseboard and sideboard to hold in place. Using the staple gun, insert 14 DeWalt Narrow Crown Staples into the back of the baseboard into the sideboard to secure it. Remove the Irwin Quick Grip Clamps.
7. Place the 3.05 m long UPD Clear Vinyl Tubing on the wood backboard so that the tubing is lined straight up next to the sideboard and clamp it in this position with two Irwin Quick Grip Clamps.
8. Repeat steps 5-6 on the right side of the baseboard to secure the tubing in-between the two sideboards.
9. Measure and cut two pine wood front boards (10.00 cm x 3.80 cm x 1.90 cm) with the measuring tape and electric miter saw.
10. At 20.40 cm from the top of the wood on the graduated cylinder, place the top edge on one of the pine wood front boards so that the 10.00 cm edge is across the front of the two sideboards crossing over the clear vinyl tubing. Using two Grip Rite Drywall Screws, screw each side of the front board into the left and right side of the sideboard. See Figure 7 for placement.
11. At 12.50 cm from the bottom of the wood on the graduated cylinder, place the top edge of the other pine wood front board and repeat step 10.
12. Steps 1-11 form the graduated cylinder to be used in the experiment.
13. Measure and cut the Cedar Wood Baseboard to 50.17 cm x 13.97 x 2.54 cm with a measuring tape and electric miter saw.

14. Stand the constructed graduated cylinder vertically in the center of the 50.17 cm side of the baseboard so the front edge of the graduated cylinder lines up with the front of the baseboard. On the back of the constructed graduated cylinder, with the nail drill, drill three Grip Rite Drywall Screws on a 45º angle down into the baseboard. See Figure 7 for the final graduated cylinder.

15. Pour 500 ml of water into the graduated cylinder. With a ruler and fine tip sharpie, mark on the tube and sideboard where the 500 mL of water lands at the top. Drain the water.

16. To make the 1 mL measurement mark on the tubing, set the Caliper to 3.00 mm distance; this is the space on the tubing that 1 mL takes up. Set the bottom edge of the caliper teeth in the middle of the 500 mL mark and score the tubing so that a line forms above the 500 mL mark. With the ruler, mark a straight line with the fine tip sharpie at this mark on the tubing, and with a pencil on the wood sideboard.

17. On the new mL mark created in step 16, set the bottom of the caliper on this mL line and score the tubing creating another mL line above the previous line. With the ruler and fine tip sharpie, mark a thin line along this score on the tubing, and with a pencil on the sideboard.

18. Repeat step 18, continuing up the tubing until 10 measurement lines are created up to 510 mL.

19. Repeat steps 17-18, but going down below the initial 500 mL mark so that it measures to 490 mL.

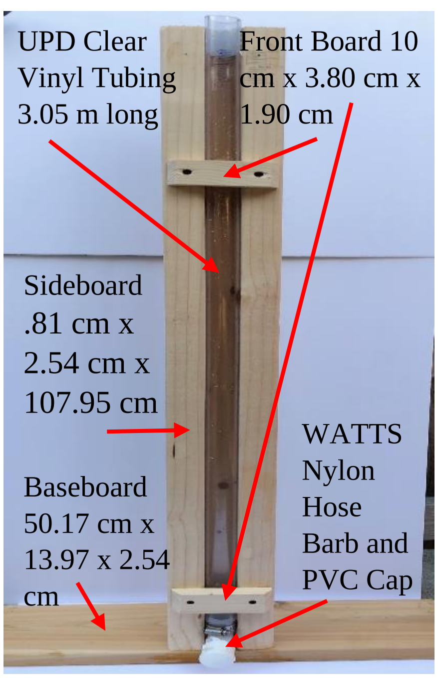


Figure 7. Graduated Cylinder

Figure 7. Constructed Graduated Cylinder

Figure 7 displays the graduated cylinder measuring device that was used to measure the oil remaining in the water boxes after one of the three oil remediation methods was used. This measurement was then used to determine how much oil was removed per trial. The Clear UPD Vinyl Tubing is placed vertically against the backboard, between two sideboards to support it.