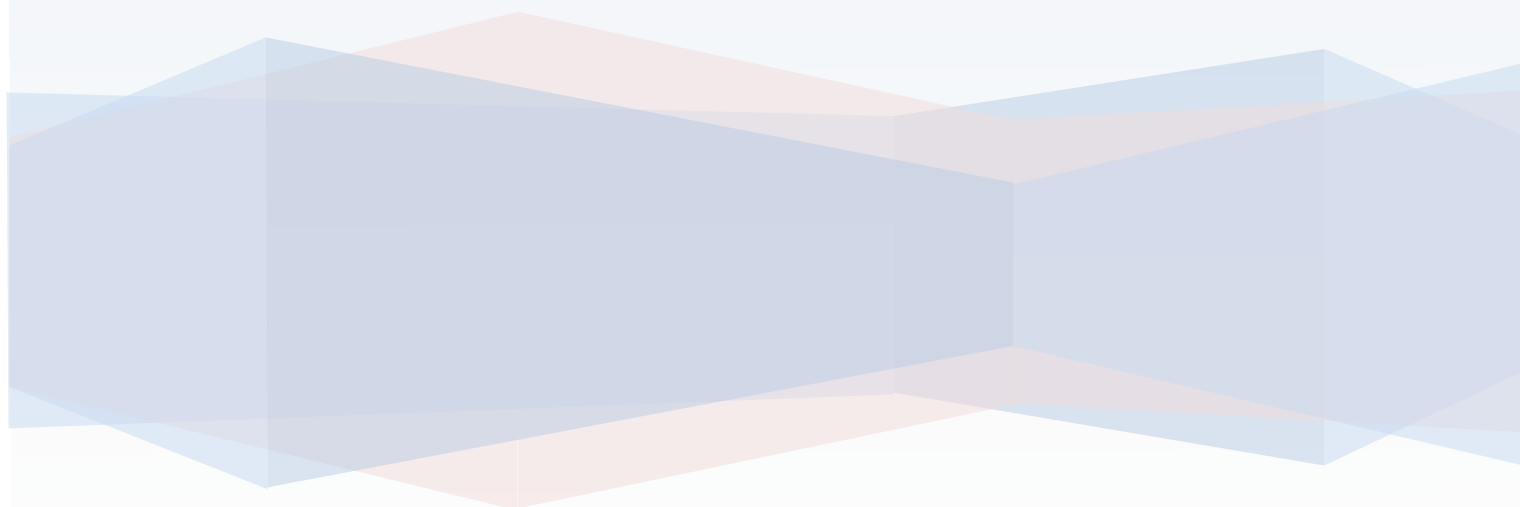


An Investigation of Multiwalled Nanotubes and Their Function in a Supercapacitor Based Ion Filter

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Abstract:

Researchers at the Indian Institute of Technology in Madras, India constructed a supercapacitor based water filter to remove metal ions from seawater and groundwater in order to produce drinkable water. Traditional methods of desalination are time consuming and inefficient, and the proposed filter aims to alleviate both problems. The electrodes used in the supercapacitor were made of multi-walled nanotubes coated with Fe_3O_4 nanoparticles. A Brauner, Emmett, Teller (BET) experiment and Cyclic Voltammetry scans were conducted to determine the electrochemical and physical properties of the Fe_3O_4 -multi-walled nanotubes. An Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) analysis was performed to determine the ion removal efficiency of the filter. The BET and Cyclic Voltammetry results indicated that Fe_3O_4 -multi-walled nanotube electrodes had large surface areas and capacitance. These results confirm that Fe_3O_4 -multi-walled nanotubes can be used as an effective adsorbent material for dangerous metal ions. The ICP-OES results indicate that the filter can remove roughly 60% of all metal ions in solution after 15 cycles.

Introduction:

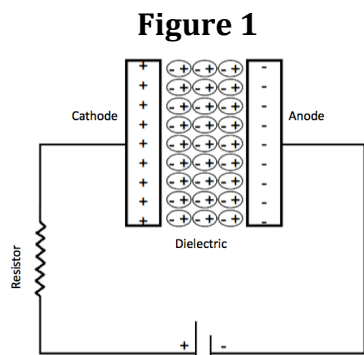
Water is the driving force behind all life on earth and is essential for human survival. Unfortunately, impurities found in water make over 97% of the world's water supply unfit for human consumption.¹ The major impurities that make drinking water so dangerous are metal ions such as sodium, magnesium, calcium, and arsenic. The first three metals are what make seawater salty and undrinkable, as salt water has a higher salinity than the urine that our kidneys produce and can cause dehydration and death when consumed.²

With a vast majority of the water supply occupying the oceans, humans must rely on the small amount of freshwater available on earth to survive. However, much of the fresh water is contaminated with cancer causing carcinogens like arsenic. Arsenic is an abundant metal in the earth's crust and it can be found in a number of oxidation states. The most common are the +5 and +3 states, which form arsenate

(AsO₄³⁻) and arsenite (AsO₃³⁻).¹ The ionic nature of both arsenate and arsenite make them very soluble in water; therefore, ground water has a tendency to dissolve arsenic ions as it flows through sediment and rocks underground. The highest levels of arsenic are found in Bangladesh, but arsenic contaminated water is also frequently found in other countries such as the United States, Mexico, Argentina, China and India.³ Short-term exposure to arsenic may cause vomiting, discoloration of skin, numbness of extremities, and stomach pain. Long-term exposure to arsenic can lead to many forms of cancer including skin, liver and lung cancer.³ The current maximum level of arsenic in drinking water in the US is 10 ppb.⁴ To ensure that drinking water stays below that threshold, technology must be developed to remove these dangerous ions from water.

Researchers from the Indian Institute of Technology Madras have recently developed a water filter that removes arsenic, sodium, magnesium, and calcium ions from seawater and groundwater. The filter utilized multiwalled carbon nanotubes (MWNT's) coated with Fe₃O₄ nanoparticles as the electrodes of a supercapacitor.¹ In order to understand the properties of a supercapacitor, it is first necessary to examine the basics of a traditional capacitor.

A traditional capacitor (Figure 1) is made of two conductive plates, or electrodes, very close to



Traditional Capacitor

A simple circuit diagram composed of two capacitor plates (the anode and cathode), a power source, and a resistor.⁵

each other, separated by a non-conductive dielectric material. As current runs to the two plates, electrons start to accumulate at one electrode and disappear from the other. The movement of electrons leaves one electrode positively charged (cathode) and the other negatively charged (anode). The charges that are formed amass on the surfaces of the electrodes where they have the greatest chance of interacting with the oppositely charged plate.⁵ This phenomenon is shown in figure 1. As the electrodes are charged, the potential difference, or voltage, between the

electrodes increases until the capacitor starts to conduct, or the electron flow to the electrodes stops. The amount of charge that the capacitor can carry is called capacitance, which increases as the surface area of the electrodes increase. This relationship is shown in equation 1:

$$C = \epsilon \frac{A}{D} \quad (1)^5$$

where C is capacitance, ϵ is a constant, D is the distance between electrodes and A is surface area.

A supercapacitor is simply a traditional capacitor that uses carbon nanotubes as electrodes.⁵ Carbon nanotubes have a considerable surface area, and therefore have a large capacitance when used as electrodes. The carbon nanotubes used in the Indian study were multiwalled nanotubes. Multiwalled nanotubes are comprised of layers of single-walled nanotubes, which are essentially sheets of graphene rolled up into long tubes. Carbon nanotubes are very conductive due to an extended π network that allows for the movement of electrons across the material.⁶

The charges that accumulate on the surface of the two supercapacitor plates will attract and adsorb ions from solution. The negatively charged plate will adsorb cations, and the positively charged plate will adsorb anions. The adsorption process occurs in two ways for the different ions that are adsorbed. To adsorb arsenic ions, a redox reactions between the electrode and arsenic ions occurs as follows:

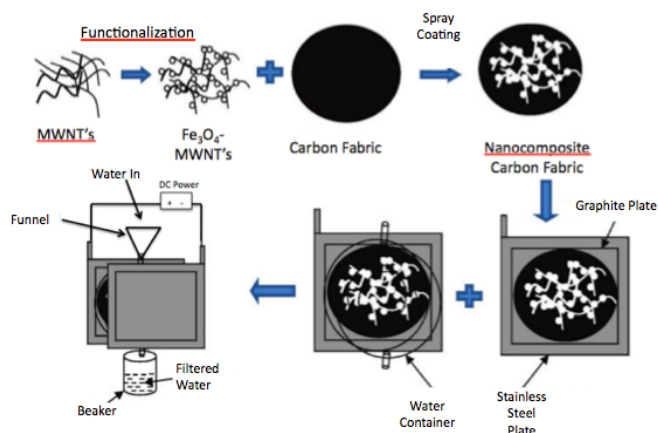


In both reductions, the product will adsorb onto the surface of the electrode and effectively be removed from the solution. The reduction reaction occurs for arsenic because the reduction potentials for both reactions are larger, 0.575 V and 0.250 V respectively⁷, than the reduction potential for the electrode, which is set at -1.0 V by the researchers. Reduction potentials measure how likely a reduction reaction is to occur. The more positive a value, the more natural it is for that specific reduction reaction to occur.

The sodium, magnesium, and calcium cations on the other hand have much lower reduction potentials (-2.714 V, -2.360 V, and -2.868 V)(Harris). Instead of undergoing a redox reaction, they will be adsorbed by the attractive electrostatic force between their positive charge and the negative charge of the electrode.

The supercapacitor filter developed for this research was powered with a potential of 1 V across

Figure 2



Supercapacitor Construction Process

Multiwalled nanotubes are functionalized with Fe_3O_4 particles and then sprayed onto a carbon fabric. The carbon fabric is then attached to a graphite plate, which is attached to a stainless steel plate, creating one electrode. Two electrodes are constructed and a current is run between them using a DC power source. Water is funneled between the two capacitors and is filtered into a beaker.¹

the two electrodes. The assembly of the proposed filter (Figure 2) begins with coating MWNT's with Fe_3O_4 and attaching the newly functionalized MWNT's to an inert carbon fabric to create a nanocomposite. The two electrode plates are then constructed by adding the nanocomposite to a stainless steel and graphite plate. The two plates are connected via a DC power supply and a conductive wire, and a plexiglas water container is placed between the two plates to hold the contaminated water.

Carbon nanotubes are the conductive framework for a supercapacitor and provide

sufficient adsorption sites for metal ions. Fe_3O_4 nanoparticles have separate adsorbent properties that have been studied extensively in the removal of large metal ions such as Cr(VI) , Cd(II) , and Cu(II) .⁸ Fe_3O_4 nanoparticles are able to effectively adsorb metal ions because of their high surface area to volume ratio and magnetic qualities.⁸ They are added to the electrodes of the supercapacitor to study any increase in capacitance or adsorption.

Calculating the surface area of the electrodes of a supercapacitor is important because capacitance is directly related to surface area. In order to calculate the surface area of the nanocomposite, a Brunaur, Emmett, and Teller (BET) surface area experiment was conducted. In a BET experiment, nitrogen gas is adsorbed onto the surface of the MWNT's and the volume of N₂ relative to the mass of adsorbent (cm³/g), is measured vs. the relative pressure to generate a plot. Temperature remains constant throughout the experiment.⁹ The relative pressure is the specific pressure measured during the experiment over the pressure required to achieve one layer of adsorbate (saturation pressure).¹⁰ The equation used to determine the surface area from the plotted data is called the BET equation (Equation 2),

$$\frac{1}{X[(P_0/P) - 1]} = \frac{C - 1}{X_m C} \left(\frac{P}{P_0} \right) + \frac{1}{X_m C} \quad (2)^9$$

where X is weight of N₂ adsorbed at a given relative pressure, X_m is the volume of gas adsorbed at standard temperature and pressure, P/P₀ is the relative pressure, and C is a constant. Plugging in data points from a BET plot to the BET equation will yield a straight line with the slope of $\frac{C - 1}{C * X_m}$, if the data points used are roughly between a relative pressure of 0.025 and 0.3.⁹ Past a relative pressure of 0.3, capillary condensation begins to occur and before 0.025, a monolayer is still forming. Capillary condensation occurs when the relative pressure is high enough to cause the condensation of nitrogen, which is not an adsorption process at all. To find the total surface area, S, the monolayer capacity, X_m was calculated from the slope and plugged into the surface area equation (Equation 2),⁹

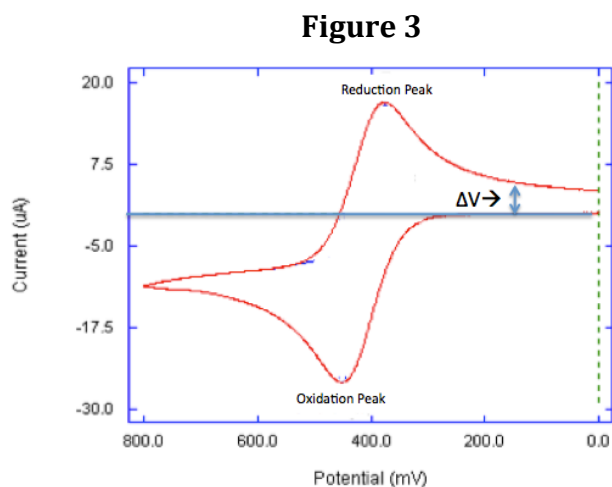
$$S = \frac{X_m L_{av} A_m}{M_v} \quad (3)^9$$

where S is surface area, L_{av} is Avogadro's number, A_m is the cross sectional area of N₂ and M_v is the molar volume.

Cyclic voltammetry (CV) was also used to analyze the supercapacitor capabilities of the filter. In CV, three electrodes are placed in an electrolytic solution: a working electrode, a reference electrode and a counter electrode. The reference electrode is held at a constant potential throughout the experiment. The voltage difference between the reference electrode and the working electrode is varied throughout the experiment by changing the potential at the working electrode. The counter electrode is used to keep the solution electrically neutral.

The potential between the working and reference electrodes can also be described as the available energy of electrons at the working electrode. This energy or voltage is changed at a specific rate, (V/sec) and in a specific direction. Typically, the voltage is scanned in the negative direction (reverse scan), from positive voltage to negative voltage first. After reaching a predetermined minimum voltage, the voltage scan

reverses direction until it reaches the original voltage applied. The two voltage scans are called the forward and reverse scan and together they make a cycle. The current at the working electrode is measured as a function of voltage and is plotted to form a voltammogram (Figure 3).¹¹



Typical Cyclic Voltammogram

This voltammogram initially scans from right to left in the positive direction. As the potential at the working electrode reaches roughly 430 mV, an oxidation occurs. During the reverse scan, left to right, a reduction peak occurs when the working electrode reaches a potential of roughly 400 mV. The ions in solution are being oxidized and reduced by the charged working electrode. The current is measured in the working electrode.¹⁰

Current at the working electrode is simply the movement of electrons to and from the electrode. A spike in current indicates a spike in electron flow, which implies an oxidation or reduction (redox) reaction is occurring at the surface of that electrode. In a redox reaction, one reactant is oxidized and loses electrons while the other is reduced and gains

electrons. A negative spike in current, shown at 430 mV in figure 2, indicates the oxidation of an analyte at the surface of the electrode. A positive spike in current, shown at 390 mV in figure 2, indicates the reduction of an analyte at the surface of the electrode. The voltages at which the peaks occur indicate the energy required to oxidize and reduce the particular ions being studied. Oxidation and reduction peaks will be analyzed in the CV plots to determine if ions in solution are undergoing redox reactions with the supercapacitor electrodes.

In addition to the oxidation/reduction peaks, the capacitance of the electrode can be calculated by measuring the vertical difference between the current during the forward and reverse scans. Capacitance is the ability for an electrode to store charge, and the more charge a capacitor can store, the more ions it's able to adsorb.¹ Capacitance, current, and scan rate can be related using the following equation:

$I = C * \frac{dV}{dt}$, where I is current, C is capacitance and dv/dt is the scan rate.¹² Any capacitor will have a constant capacitance. With a constant scan rate as well, the current would also be constant depending on the direction or sign of the scan rate. As the direction of the scan rate changes, so should the sign of the current. Therefore, the larger the capacitance, the larger the gap in current between the forward and reverse scans. One such gap has been indicated in figure 1 at a voltage of 100 mV.

Lastly, in order to determine the effectiveness of the proposed filter, inductively coupled plasma optical emission spectrometry, ICP/OES, analysis was performed. In this experiment, the sample in question was heated up to temperatures around 10,000 K. For comparison, the surface of the sun is roughly 5,800 K. Temperatures this high are reached by using an ICP torch, where argon gas is converted to an extremely hot plasma by introducing AC current through a copper coil at a frequency of 27 MHz. The changing electric and magnetic fields induced by the AC current cause the argon atoms to become ionized. Due to the alternating electric fields, the ionized argon atoms move so quickly and collide so frequently, that they induce temperatures much hotter than the sun.

Once the ICP torch is heated, the sample is introduced to the torch in aerosol form. At temperatures this high, electrons in typically stable metal ions like As (V) or Na (I) become excited to a higher energy level. The electrons are unstable at the higher energy state, and quickly release energy in the form of a photon to get back to their ground states. The wavelengths of the emitted photons are measured and matched to a specific metal ion. The intensity of the emitted light is directly proportional to the concentration of that ion in solution. In the case of the water filter, seawater and arsenic containing water was tested before and after filtration to determine the removal efficiency of the filter for a given metal ion.

This paper will examine the analytical techniques used to determine the properties of Fe_3O_4 -MWNT's and how those properties make them an ideal material for a supercapacitor based water filter. Additionally, the practicality and effectiveness of the proposed filter will be studied in order to determine long-term applications of the current research.

Results and Discussion:

BET:

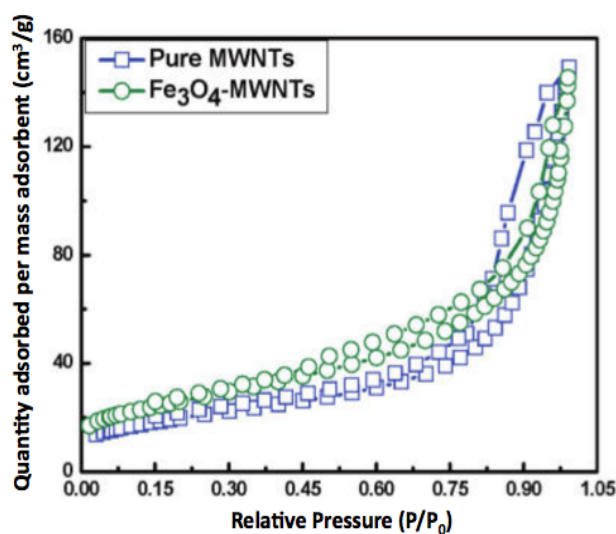
One important advantage of using MWNT's as an adsorbent material is the large surface area. Adsorption is a process that occurs at the surface of the adsorbent, so the greater the surface area, the greater amount of material that can be adsorbed. To calculate the surface area, a BET experiment was performed and the quantity of N_2 gas adsorbed vs. relative pressure, P/P_0 was plotted (Figure 4). Based upon the BET experiment shown in figure 4, a plot of the volume adsorbed for both pure MWNT's and Fe_3O_4 -MWNT's initially rose very slowly with increasing pressure until it reached a relative pressure of about 0.7. At this point capillary condensation occurred. During capillary condensation, the gas no longer adsorbs onto the Fe_3O_4 -MWNT's, but instead condenses, and the volume adsorbed rises exponentially.

In order to find the total surface area, the BET equation (Equation 2) was used to monitor how layers of nitrogen formed with increasing pressure. As discussed in the introduction, data points between

the relative pressures of 0.025 and 0.3 (pdf) should be used to construct a BET plot, which is analyzed to calculate the surface area. From this data, the two surface areas of 70.09 m²/g and 91.96 m²/g, Fe₃O₄-MWNT's and pure MWNT's respectively, were calculated (data not shown).

These calculated surface areas are significantly lower than the typical surface area of nanotubes. Single walled nanotubes (SWNT's), for example, have been shown to exhibit surface areas of over 1000 m²/g.¹³ One possible explanation for the low surface area may be that the MWNT's used in the BET

Figure 4



Plot of N₂ Adsorption vs. Relative Pressure

BET measurements for pure multiwalled nanotubes (Blue) and Fe₃O₄-Multiwalled nanotubes (Green). The multiwalled nanotubes were put in a pressurized space with isolated N₂ gas. As the pressure increased, the quantity of N₂ adsorbed was measured and plotted as a function of relative pressure.¹

experiment were already attached to the carbon fabric. The carbon fabric would have contributed to the overall mass of the adsorbent, but not the surface area, decreasing the area per gram calculation.

Although the Fe₃O₄-MWNT's were found to have a smaller surface area than pure MWNT's, it is important to note that before capillary condensation occurred, the Fe₃O₄-MWNT's (green line) had adsorbed more N₂ than the pure MWNT's (blue line). This data indicates that Fe₃O₄-MWNT's are actually the preferred adsorbent material. The reasoning behind these findings is that Fe₃O₄ has a high surface area to volume ratio;⁸ however, the results of the BET experiment are measured in a

surface area to mass ratio. Iron is much heavier than carbon and adding Fe₃O₄ nanoparticles to a carbon structure will significantly increase the mass of the electrode and therefore decrease the m²/g calculation. If

the BET experiment were set up to measure m^2/cm^3 (area/volume), the F_3O_4 -MWNT's would have a much larger surface area measurement than the pure MWNT's. Additional benefits of using F_3O_4 -MWNT's as supercapacitor electrodes were explored through cyclic voltammetry.

Cyclic Voltammetry:

MWNT's and their use in supercapacitors is not new technology, however, the article proposes that when standard MWNT's are decorated with Fe_3O_4 , they become more effective electrodes for a supercapacitor-based filter. To test the effectiveness of both MWNT's and Fe_3O_4 -MWNT's, cyclic voltammetry is performed. In the CV experiments, the voltammograms of the Fe_3O_4 -MWNT's were compared to the voltammograms of the carbon fabric and the pure MWNT's (Figure 5).

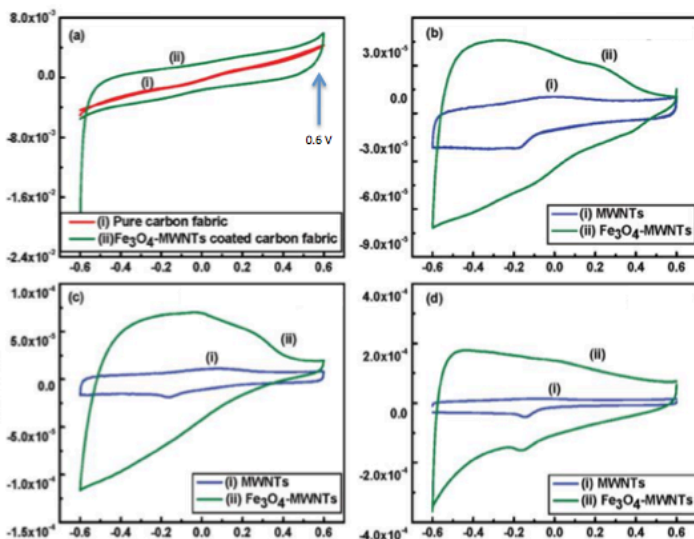
First, the chemical inertness of the carbon fabric substrate was tested in 5a. Following the plot from left to right, the carbon fabric scan (red), starts at a potential of -6.0 V and a current of roughly $-4\text{e-}3$ amps. As the voltage increases, so does the current. The change in current occurs because the carbon fabric is a conductive material and will therefore obey Ohm's Law: $V=I \cdot R$, where V is voltage, I is current and R is resistance.¹² As the voltage changes, the current changes with it because the resistance of the carbon fabric is constant. However, the change in current does not mean that charge is accumulating on the carbon fabric.

In fact, the scan indicates that the carbon fabric has no ability to store charge. When the voltage scan switches directions, indicated by the arrow at 0.6 V, the current did not change direction. Instead, the current stayed exactly the same, and followed the same path during the reverse scan as it did during the forward scan. Comparatively, during the Fe_3O_4 -MWNT scan, when the voltage scan changed direction at the arrow, the current reacted by changing direction or sign. As discussed in the introduction, the gap between the currents of the forward and reverse scan indicates the storage of charge by the electrode.

Figure 5a confirms that the carbon fabric substrate has no ability to store charge, and all the capacitive behavior in figures 5b-d comes solely from the nanotubes.

Figures 5b, 5c, and 5d show the capacitive behavior of pure MWNT's and Fe₃O₄-MWNT's in three

Figure 5



Current vs. Voltage Plots

Cyclic voltammograms plotted using different electrolytes and electrodes. (a): Electrodes of pure carbon fabric and Fe₃O₄-nanocomposite tested in a 1.0 M solution of NaOH with a scan rate of 10 mV/s. (b): Electrodes of multiwalled nanotubes and Fe₃O₄-multiwalled nanotubes tested in a sodium arsenate solution with a scan rate of 5 mV/s. (c): Electrodes of multiwalled nanotubes and Fe₃O₄-multiwalled nanotubes tested in a sodium arsenite solution with a scan rate of 5 mV/s. (d) Electrodes of multiwalled nanotubes and Fe₃O₄-multiwalled nanotubes tested in a seawater solution with a scan rate of 5 mV/s. ¹

different electrolytic solutions. The species in each solution were sodium arsenite, sodium arsenate, and typical seawater ions, which includes both forms of arsenic. As discussed in the introduction the capacitance of the capacitor is proportional to the gap in voltage between the forward and reverse scans.

The data shows that the

nanocomposite has the ability to store a much larger amount of charge than the pure MWNT's. In figures 5b-d, current measurements at the working electrode are always greater in the nanocomposite electrode than current measurements at

the pure MWNT electrode. The difference in currents indicates that more charge can be stored on the nanocomposite electrode than on the pure MWNT electrode. Current is a measurement of the flow of electrons, and a large current means that more electrons are moving towards or away from the surface of the nanocomposite at all times. If more electrons are moving to and from the electrode, the electrode has the capacity to store these charges and therefore has a larger capacitance. These findings were significant

because the more charge an electrode can hold, the more ions it can adsorb, regardless of surface area measurements.

The CV scans also gave the researchers proof that redox reactions occurred at the electrodes. The peaks that are seen in figures 5b-d on the pure MWNT scans are called oxidation and reduction peaks. Each peak indicates the oxidation or reduction of arsenic ions in solution. As the arsenic ions are reduced, they adsorb onto the surface of the electrode and are effectively filtered out of solution. As stated in the introduction, the arsenic ions are the only ions in the three solutions that can be oxidized or reduced because of the large negative reduction potentials of Ca(II), Na(I), and Mg(I).

Unlike figure 3 in the introduction, a spike in positive current indicates oxidation and a spike in negative current indicates reduction. This discrepancy arose because the researchers measured the current opposite of how it is typically measured. The oxidation and reduction peaks were easily observed on the pure MWNT's scans because they had a more steady and constant current. In the scans for the nanocomposite, it is much harder to observe the peaks because of the large fluctuations in current. The two most obvious peaks observed are the reduction peaks in the nanocomposite scan of 5d at -0.15 V, and the reduction peaks for the pure MWNT's scan of 5b and 5c at -0.18 V. All three peaks indicate the reduction of As(V) to As(III), or As(III) to elemental arsenic. In these reactions, electrons are transferred from the electrode to the arsenic ions at the surface of the electrode. Two oxidation peaks are also observed in the nanocomposite scans of figure 5b and figure 5c at 0.30V and 0.25 V respectively. These peaks represent the oxidation of elemental arsenic to As(III) and As(III) to As(V).

The observation of both oxidation and reduction peaks in the CV scans indicates that the adsorption process in the filter is reversible. If reverse voltage is applied, the electrodes can be washed free of any adsorbed ions. Therefore, the filter could be used many, many times before losing its ability to filter.

An interesting observation to note in figure 4 is the difference in the axes of 5b-5d. Figure 5d has a maximum current of well over -2.0×10^{-4} A. The maximum current in 5c is roughly half of the maximum at 5d

at -1.0×10^{-4} A, and the maximum current in 4b is even smaller at -8×10^{-5} A. The difference in current in these three voltammograms is independent of the electrode; instead, it is dependent on the ions in solution. Although the concentrations of each electrolytic solution are not provided in the article, it is assumed that the concentration of ions in the seawater is likely much higher than the concentration of ions in prepared arsenic solution. A higher concentration of ions means that at the surface of the electrode there will be more ions to counter the charge that is created to induce a voltage. In order to produce the desired voltage, the power source must create an additional charge at the surface of the electrode to account for the opposing charges of the ions. The extra charge that the power source produces increases the current in the electrode, which is why in figure 5d the current readings are amplified. The difference between 5b and c is harder to explain. One theory is that the reduction of As(V) to As(III) that occurs in 4b is a two electron process while the reduction of As(III) to As(0) that occurs in 4c is a three electron process. More electrons are used in the reduction in 4c, therefore the current increases as more electrons are brought to the electrode to complete the reduction process.

The sodium, magnesium, and calcium ions are not adsorbed through redox reactions, but instead through an attractive electrostatic force between the cations and the negatively charged electrode. The effectiveness of all adsorption processes was studied through an ICP-OES experiment.

ICP Analysis:

In order to test the efficiency of the water filter, ICP analysis was performed on three separate solutions, after 1, 5, 10, 15, and 20 cycles through the filter (Figure 6). The ICP data gives the concentration of ions in any given solution, and the % removal is found using equation 4:

$$\% \text{ Removal} = \frac{(C_0 - C_f) * 100}{C_0} \quad (4)$$

where C_0 is the initial concentration of any particular ion in solution and C_f is the concentration of the same ion after filtration. In figure 6i, sodium arsenate contaminated water with an arsenic concentration of 400

ppm was filtered and after 15 cycles, 58% of the arsenate and 61% of the sodium was removed, leaving a

168 ppm arsenic. In figure 6ii, sodium

arsenite contaminated water with an

arsenic concentration of 400 ppm was

filtered and after 15 cycles, 67% of the

arsenite and 65% of the sodium were

removed, leaving a 132 ppm arsenic

solution. In figure 6iii, seawater was filtered,

and after 20 cycles (five more than the

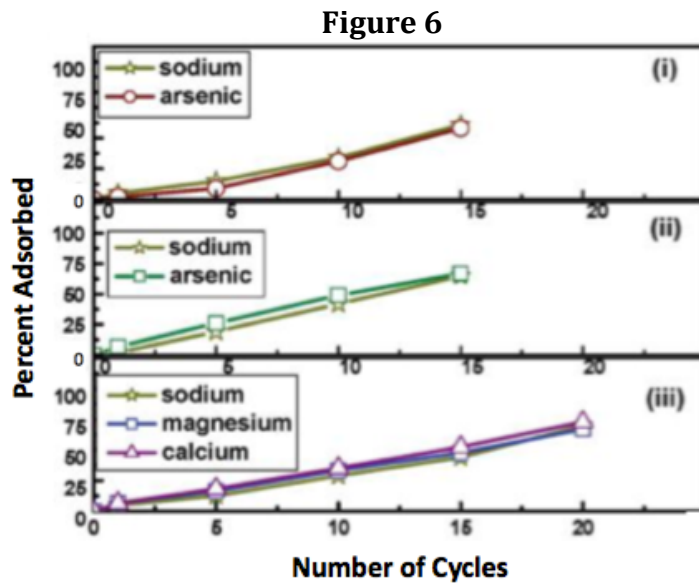
arsenic trials) 70% of sodium, 67% of

magnesium and 73% of calcium were

removed. The initial concentrations of each

ion were 9870, 1750 and 540 ppm for

sodium, magnesium and calcium



Removal Efficiency Plot

In all three plots, the concentration of each ion listed was tested through ICP-OES analysis after 5, 10, 15 and 20 cycles through the filter. (i): Removal efficiency plot of sodium arsenate containing water (ii): Removal efficiency plot of sodium arsenite containing water (iii): Removal efficiency plot of seawater.¹

respectively. While the filtration of the seawater would decrease the salinity enough to make the water drinkable, the final concentration of arsenic is still thousands of times larger than the EPA limit of 10 ppb. Further research is necessary to determine if the filter would be able to remove arsenic below the EPA level.

In all three trials, the different ions in solution were adsorbed at roughly a constant efficiency of 3.4 to 4.5 % removed per cycle. This data suggest that all ions had an equal affinity towards the two Fe₃O₄-MWNT's electrodes. The heavier ions many have been expected to have a harder time moving to the electrically charged electrode, but it is important to remember that adsorption occurs at the surface of the electrodes. If the ions aren't already within the immediate area of the electrode surface, they will not be adsorbed. Therefore, the fact that all ions were adsorbed in equal amounts is to be expected.

Another oddity in the ICP data is that adsorption does not decrease as the concentration decreases and the pores on the nanotubes are filled. The data in figure 6 show a nearly constant slope from start to finish for all three experiments. As the concentration of the ions decreased and the surfaces of the electrodes were filled with adsorbate, the percent removed per cycle should decrease dramatically. However, the data suggest that the filter was washed between each cycle. If the electrodes were cleaned between each cycle, all sites would be open and ready to adsorb during the next cycle.

Conclusion:

The research presented in this article is both promising and disheartening for the case of the supercapacitor based water filter. The CV scans show that the Fe_3O_4 -MWNT's have a large capacitance and that the adsorption process is reversible. This data is significant because it shows that the filter could be re-used after a simple wash and that the Fe_3O_4 -MWNT's are preferable over pure MWNT's, in that they have a larger capacitance and are therefore able to adsorb a greater amount of metal ions.

The surface areas of each electrode were calculated to be $70.09 \text{ m}^2/\text{g}$ for the Fe_3O_4 -MWNT's and $91.96 \text{ m}^2/\text{g}$ for the pure MWNT's. Although this number is higher than a typical capacitor plate, the results are extremely small for any carbon nanotube. The data may have been skewed because the carbon fabric was included in the surface area calculation, but it stands to reason that if the surface area of the electrodes could be improved, the efficiency of the entire filter would also improve.

The data concerning the removal efficiency of the filter when tested with seawater and arsenic contaminated water was unfortunately insufficient. In the future, conducting multiple ICP analyses would be valuable in determining the potential of this technology. In these analyses, variables such as the initial volume of water, the ion concentration, the number of washes, and the type of filter (Fe_3O_4 -MWNT's or pure MWNT's) would be changed. The second analysis should also record how long each filtration cycle lasts so a rate of filtration can be established (% removed/min). All of these changes to the original experiment would contribute to the practicality of the proposed filter and help develop a commercial prototype.

The technology described throughout this article has the potential to become a successful technique in water filtration for years to come. However, more work is necessary to determine the appropriate uses for the water filter. In theory, a supercapacitor will work as a filtration device for ions. The Fe_3O_4 -MWNT's provide a large surface area for charge to accumulate, while metal ions in water will have the tendency to adsorb to the electrodes via a redox reaction or through electrostatic force. However, the scale and timeline in which the process could be repeated cannot be determined until future research is completed. Until these key details are addressed, it is impossible to judge the usefulness of such technology. If the filtration process could be repeated with high volumes of water in a relatively short period of time, this product could revolutionize the water industry and the entire human population would reap the benefits.

The negative ethical implications of using a MWNT supercapacitor filter are small and would deal almost entirely with disposal of waste. Nanotubes are relatively new technology; therefore long term environmental effects of releasing carbon nanotubes into the environment have not been studied extensively. However, single-walled nanotubes have been shown to have a negative impact on the bacterial life in aquatic systems soon after contamination.¹⁴ There may be additional negative impacts that have not been discovered yet. Although negative consequences are a possibility, research for this project should continue because of the potential benefits. If this project were to be successfully pursued, the 3% of drinkable water on earth would become 100%. Anyone stranded at sea could drink the water that was previously poisonous. Entire communities that are struggling with thirst would have a new source of water to use, and many years down the road, farmers experiencing drought could be able to use seawater to water their crops. This technology has the potential to save a countless number of lives, and for that reason, it should continue to be explored and studied extensively.

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