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**Advanced Faraday Cage Measurements of
Charge, Short-Circuit Current and Open-Circuit Voltage**

by
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Submitted to the Department of Electrical Engineering and Computer Science
in partial fulfillment for the degree of
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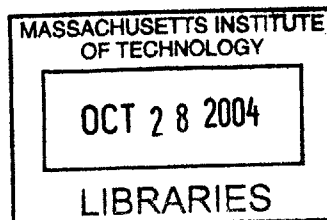
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BARKER

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Abstract

This thesis is devoted to Faraday cage measurements of air, liquid, and solid dielectrics. Experiments use pressurized air with fixed Faraday cage electrodes, and a moving sample of liquid and solid dielectrics between two Faraday cup electrodes. Extensive experiments were conducted to understand the source of the unpredictable net measured charge.

In the air experiment, the Faraday cage consists of a hollow, cylindrical, gold-plated brass electrode mounted within a gold-plated brass hermetic chamber that connects with earth ground. Measurements of transient current at various temperatures and humidity during transient air pressure change are presented. The flow of electrode current is shown not to be due to capacitance and input offset voltage changes, since the calculated value is on the order of 10^{-16} Amperes which is much less than the measured currents of order 10^{-13} Amperes. By controlling the internal relative humidity of air in the Faraday cage, and from the measurements of current using dry nitrogen, we confirm that the absence of moisture causes no current to flow. Amplitude of the measured current is found to be dependent upon the internal relative humidity. Repeatedly, polarity reversals were observed to occur, in part due to galvanic action between dissimilar metals as water condensed upon the insulating surface between them. At a low temperature with a small pressure change, only one pulse of current was observed to occur but, with a pressure change of more than 10psi, two opposite polarity pulses of current were shown to occur almost simultaneously. A small pressure increase only caused a pulse of negative current, and a small pressure decrease only caused a pulse of positive current. A pressure increase of more than 10psi above atmospheric pressure caused both positive current and negative current pulses with the negative pulse larger than the positive pulse. A pressure decrease of more than 10psi below atmospheric pressure also caused both positive current and negative current pulses with the positive current larger than the negative current pulse. Experiments showed that the negative current was generated by the galvanic action between the two dissimilar metals in the triaxial connector connecting the center electrode of the electrode chamber with the electrometer, as water condensed. Positive current could have been produced by the evaporation of moisture from the center electrode of the electrode chamber. Dew point analysis is performed to show that for water to condense on metallic surfaces, it is not necessary to reach the dew point. The

calculated dew point temperature is lower than the temperature at which the water condenses upon the electrode surfaces.

In the liquid and solid dielectric experiments, we use a patented Faraday cage which is composed of two identical in-line hollow, gold-plated Faraday cup electrodes that enclose the samples which move between them during each measurement under computer control. We conducted charge measurements using various electrometers to rule out the possibility of false instrument readings due to input offset voltage and other experimental effects. One wire mesh style of Faraday cage connected with an electrometer was also used to measure the charge.

The liquid dielectrics are distilled water, tap water, Sargasso Sea water, and 0.9% NaCl solution which are contained in a 30mL polyallomer centrifuge tube, and they are found to maintain distinct negative non-zero equilibrium charge values. For each of the samples, measurements of charge, open-circuit voltage, and capacitance as a function of temperature are presented. Charge and open-circuit voltage measurements are found to be dependent upon temperature. The solid dielectrics tested were Teflon and Acrylic of cylindrical shape with diameter of about 2cm and length of about 10cm. Charge measurements are presented for each of the solid dielectrics after they were triboelectrically charged by rubbing. They were then subjected to an increased temperature to increase the rate of charge decay.

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I hope I have acknowledged every single person who has contributed to prepare this thesis. In the mean time, I hope I have tried my best to please them through the research product that is presented in this thesis. I wish the reader will find the material contained in this thesis an enjoyable one and something contributory to the existing knowledge present in the human society. My father has recently taught me one thing, and that is, whatever research work I undertake it must be “SMART.” The word “SMART” is expressed as follows: specific, measurable, achievable, realistic, and tangible. I can concede that the work contained in this thesis follows the theme of “SMART.”

May God help all of us to arrive at our final objective!

Imagination is more important than knowledge.

Albert Einstein.

I never see what has been done; I only see what remains to be done.

Marie Curie.

Chapter 1

Introduction to the Measurements of Electrical Charge

1.1 Review of Faraday Cage Measurement Principles

1.1.1 *Faraday cage and Electroscope*

A Faraday cage is an electrically conducting enclosure with no holes. If a Faraday cage metal enclosure is initially uncharged and electrically grounded, any charge that is put inside creates an image charge of opposite sign that distributes itself upon the inside surface of the conductor so that the electric field within the cage metal remains zero. In the absence of charge within the Faraday cage, even if the Faraday cage is placed within an electric field region, there will be no electric field inside. The Faraday cage acts as an electrostatic shield to any exterior electric field. The electric field outside of a grounded Faraday cage is unaffected by any charge that is put inside. A Faraday cage when connected to an electroscope can measure charge. An electroscope is a device which indicates the amount of electrostatic charge present on the device by utilizing electrostatic repulsion of hanging metal leaves such as in a gold leaf electroscope. The electroscope shown in Figure 1.1 is composed of a conducting plate at the top, an insulating stand for support, and a needle or a vane which is electrically connected to the support stand and can rotate about its pivot [1]. The plate, support stand, and the needle are all composed of a conducting material permitting electrons to flow and any charge on the electroscope to be distributed. An insulating sleeve surrounds the support stand to electrically isolate the plate, stand, and needle from the grounded can. In the presence of charge on the electroscope, the needle shows a deflection related to the amount of charge present.

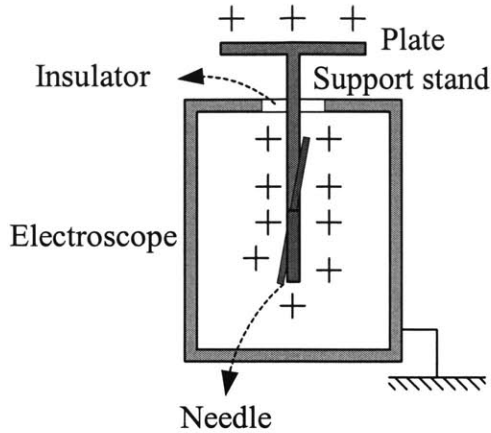


Figure 1.1: An electrostatic shield measures the amount of charge present on its electrode from a needle deflection.

1.1.2 Faraday’s Ice-Pail Experiment

This thesis research uses a “Faraday Cage” method to measure the charge flow, short-circuit current, and open-circuit voltage caused by pressurized air and by liquid or solid dielectrics as they enter or exit a grounded Faraday cage chamber. This research is sponsored by Mr. Thomas Peterson, Jr., who similarly measured charge flow as liquid and solid materials entered and left a Faraday cage. The motivation for the research is to learn the cause of such charge flows, which is not predicted by conventional theory.

Our research protocols originate with Michael Faraday’s “ice pail experiment,” which was conducted in 1843. The ice-pail experiment can be described as:

1. Faraday took a neutral empty metal ice pail (Faraday cage) that was electrically isolated but connected to an uncharged electrostatic shield as shown in Figure 1.2.

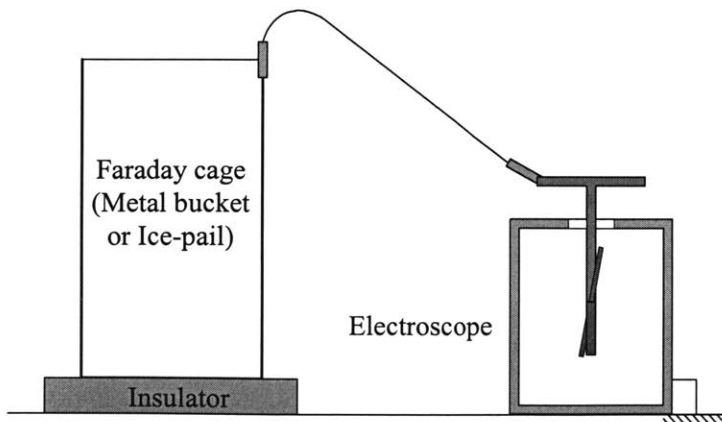


Figure 1.2: An uncharged electrically isolated metal ice pail is connected to an uncharged grounded electrostatic shield so that there is no deflection by the needle.

- Next, he suspended a charged metal ball by a long silk thread into the electrically isolated metal ice pail (Faraday cage). This caused the needle of the electroscope to deflect as shown in Figure 1.3. The charged metal ball with charge $-q$ induced a charge of opposite sign but of total equal magnitude upon the inside surface of the metal ice pail, $+q$, causing a total charge of the same sign and of equal magnitude, $-q$, on the outer surface of the ice pail and on the electroscope, assuming no charge was initially present. The degree of deflection of the needle was independent of the location of the charged ball within the Faraday cage.

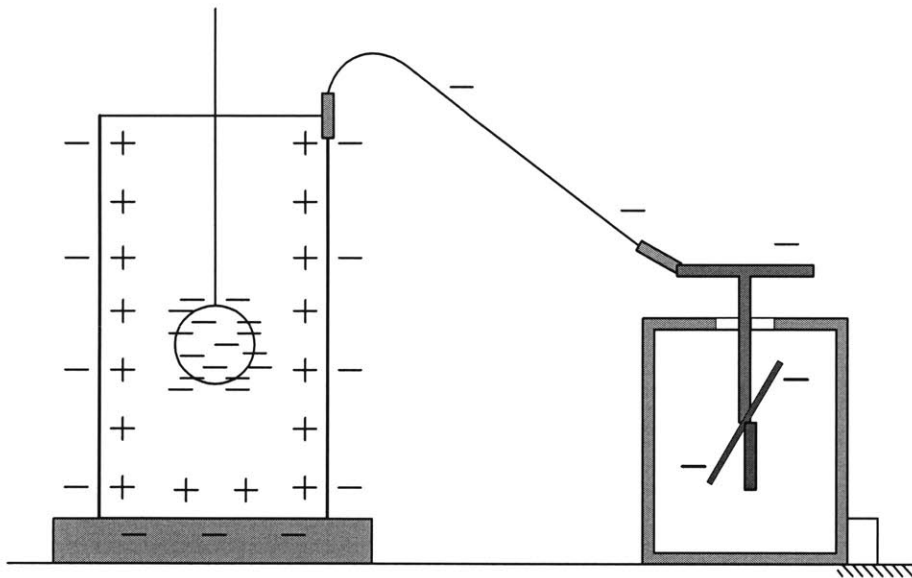


Figure 1.3: A negatively charged ball inside the electrically isolated metal ice pail (Faraday cage) induces positive charge but of total equal magnitude on the inside surface of the pail. The total negative charge on the ball appears on the outside surface of the electrically isolated pail and on the electroscope causing the needle to deflect.

- When the metal ball was withdrawn from the pail, but without touching the pail, the needle of the electroscope fell back to its original zero charge position as shown in Figure 1.4.

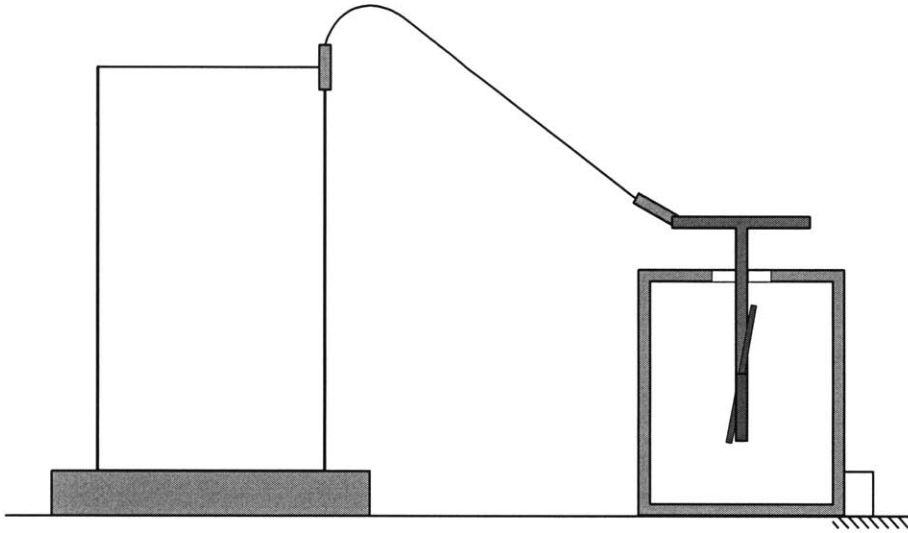


Figure 1.4: The charged ball is withdrawn from the pail without touching it, and the needle returns to its zero charge position.

4. When the charged ball in Figure 1.3 first touched the metal bucket and then the ball was completely removed, the electrostatic needle remained in its deflected position. The ball lost its charge to the metal ice pail and electrostatic as shown in Figure 1.5.

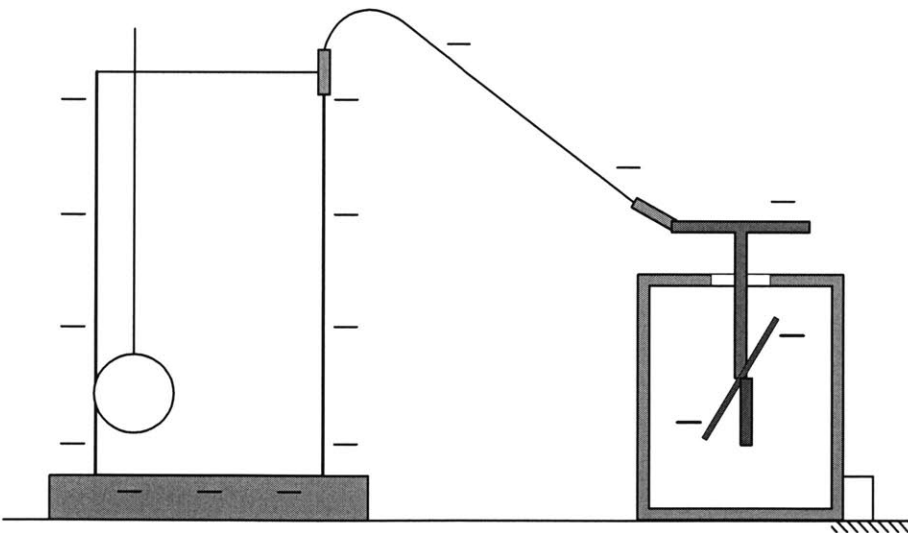


Figure 1.5: Touching the metal pail neutralizes the previously charged ball and the inside surface of the pail. Charges on the outside surface of the metal pail and on the electrostatic remain unchanged. The needle remains in the deflected position.

5. After withdrawing the ball, all the original charges on the outside surface of the metal pail and on the electroscope remain unchanged, causing the needle to remain in the deflected position shown in Figure 1.6.

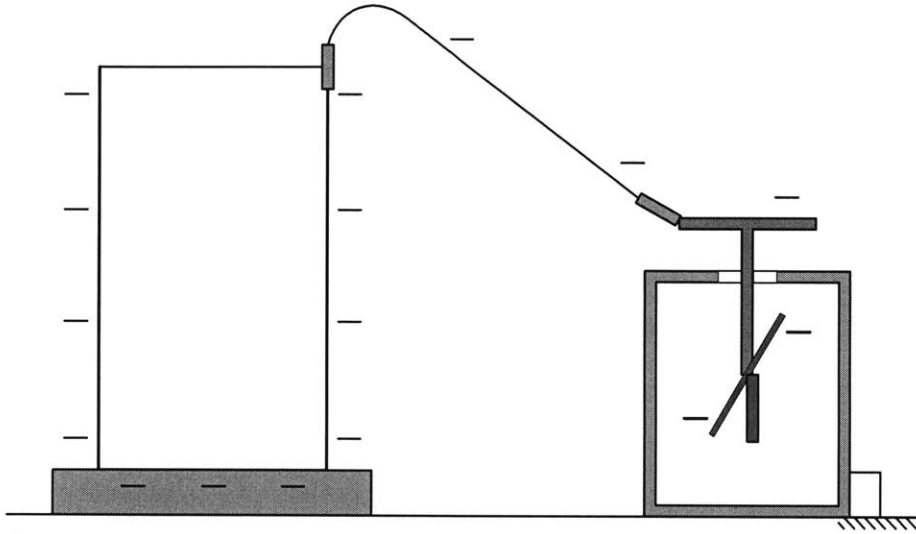


Figure 1.6: After touching the metal pail shown in Figure 1.5, the ball is removed. Removing the ball, leaves the charges unchanged on the outside surface of the metal pail and on the electroscope. The ball is neutralized, but the metal pail and electroscope contain the total charge which causes the needle in the electroscope to show a deflection.

Faraday concluded that when a charged object is left for an indefinite period of time within a grounded metallic enclosure, but without touching the metal wall, the charge on the object eventually decays to zero due to charge leakage through the slightly conducting air. In the proposed research, we have observed a new phenomenon with the tested materials where they maintain a non-zero equilibrium charge value. Water (distilled water, tap water, sea water and 0.9% NaCl solution) and other solid dielectric samples are kept at electrical equilibrium within grounded metallic shields for an extensive period of time, but when placed within a Faraday cage they are found to contain a net negative charge of order 10^{-9} Coulombs. Estimation of the capacitance of Faraday's apparatus and electroscopes used during his time period demonstrates that we are now able to exceed his measured sensitivity by a factor of 10^5 [2]. The purpose of this research is to understand the origin of these anomalous results and determine if they are physically correct or due to experimental artifacts.

1.2 Review of Past Research

Mr. Thomas Peterson conducted Faraday cage experiments using air, distilled water, glycerol and methanol. He used a Faraday cage with a fixed electrode for pressurized air dielectric measurements, and a moving sample between Faraday cup electrodes for testing liquid and solid dielectrics.

From his air experiments, he noted that a transient change in pressure caused a flow of current. He hypothesized that a change in air pressure caused a change in the charge density of air which induced a flow of electrode current. From these measurements, it appeared that the earth's surface could possess a permanent negative charge as proposed by Peltier [3, 4]. Thus, he concluded that air may contain a previously unmeasured non-zero equilibrium charge [4].

He also conducted experiments bringing distilled water, glycerol, and methanol into the Faraday cage. He found these liquid dielectrics to possess a net negative charge even after keeping them inside the Faraday cage for a long time period [2]. He noted the dependence of temperature upon the measured charge value of distilled water as shown by his electrometer. The value of measured charge of each tested sample appeared to be a function of its relative dielectric permittivity, which is a function of temperature [2]. He hypothesized that water and air may contain non-zero equilibrium charge [2, 4].

He hypothesized that if the atmosphere and waters of the earth's surface contain previously unnoticeable charge values [4], the non-zero charge values could be translated mathematically to a "non-zero ground potential" value defined as follows, "absolute zero ground potential is achieved throughout the volume of a shielded and grounded homogeneous dielectric when its net volume space charge is absolutely charge neutral at equilibrium" [2].

1.3 Overview of this Thesis

This thesis focuses on the theoretical and experimental analyses of the Faraday cage measurements obtained from air experiments, water (distilled water, tap water, Sargasso Sea water and 0.9% NaCl solution) experiments, and experiments using solid dielectrics.

Chapter 1 has reviewed Faraday cage principles, Faraday's Ice-Pail experiments and recent research conducted by Mr. Peterson.

Chapter 2 presents theory, calculation, and measurement results obtained from the transient air pressure experiments. Atmospheric air confined in the Faraday cage is pressurized using a hand pump and transient measured current is measured at various temperatures and humidity. Polarity and magnitude of the measured current of air are found to be dependent upon internal relative humidity and internal temperature of the Faraday cage. Transient pressure and current data were acquired by controlling the ambient and internal temperatures and internal relative humidity of the Faraday cage. Calculated values of current due to changes in air permittivity and in electrometer offset voltages are presented and shown to be negligible compared to the measured current. The permittivity of air was taken as a measured function of temperature, pressure and relative humidity. Transient pressure and current data obtained by drying air or by replacing atmospheric air with dry nitrogen show that the measured charge flow is a function of moisture in the chamber air.

Chapter 3 describes the apparatus and experimental method used for a small closed volume of water or solid dielectrics to be placed within or removed from a Faraday cup electrode. Preliminary charge values are presented using various water dielectrics of differing conductivity and solid dielectrics from two differently constructed Faraday cages.

Chapter 4 focuses on the analysis of measurements using distilled water, tap water, Sargasso Sea water (near Bermuda), and 0.9% Sodium Chloride (NaCl) solution. A plot of the variation of charge and voltage with time and variation with temperature is presented and Arrhenius activation energy is calculated. Measured charge values using different grounding metal screws within the water samples are also presented and compared. Measured capacitance values for the water dielectrics are presented. The calculated values for charge and voltage measurements are in good agreement with the measured values.

Chapter 5 analyzes the results obtained using solid samples of Teflon and Acrylic. Charge and voltage are plotted with time and variation of temperature. Triboelectric

charging as a function of temperature is described with Teflon and Acrylic being contacted with a wide variety of other insulators.

Finally, chapter 6 summarizes the results of this research and discusses suggested future research. The thesis also contains appendices describing important details of all experiments.

Appendix A explains the procedure of how to acquire waveforms from the Tektronix TDS 1012 oscilloscope by the computer terminal and how to store and recall the temperature data from the 2001 Digital Multimeter.

Appendix B contains a plot of dielectric constant as a function of pressure, temperature and humidity; it contains a plot of the variation of saturated vapor pressure with temperature and a plot of the variation of dielectric permittivity with temperature for saturated water vapor.

Appendix C explains the procedure of how to program the 2001 Digital Multimeter to control the motion of the sample inside the Faraday cage, to configure channels to record the temperature, to record the temperature after the RTD (resistance temperature detector) is connected, to use the channels to record both internal temperature of the Faraday cage and room temperature, and a description of required changes in the Testpoint program when one wants to switch from acquiring charge values to voltage values or vice versa.

SI units are used throughout the thesis.

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Chapter 2

Faraday Cage Measurements

of Short Circuit Current and Open Circuit Voltage with Transient Air Pressure, Temperature, and Humidity

2.1 Background to the Experiment

A “Faraday Cage” method was used to measure transient charge flow from a pair of electrodes as the pressure of the air dielectric was being changed using a hand pump. A cylindrical electrode was located at the center of a surrounding grounded coaxial cylindrical electrode which acted as a Faraday cage, also called here as an “electrode chamber”. The center electrode was virtually grounded through a Keithley 617 electrometer which could measure the transient current flow from the electrode. The 617 electrometer was also used to measure the transient open circuit voltage of the center electrode. The Faraday cage was connected to a pump chamber via a plastic conducting hose which could change the air pressure in the electrode chamber.

Measurements showed that changing the air pressure with the hand pump caused electrode current to flow. Related previous research by Peterson hypothesized that a change in air pressure caused a change in the volume charge density in air which caused the flow of electrode current, but that original work had not noted the effects of temperature and humidity on the amplitude and polarity of the current. In this research investigation, we scrutinized the current pulse amplitude and polarity as a function of transient pressure, relative humidity, and ambient and instantaneous temperatures of both pressure and electrode chambers.

Initial oscilloscope and electrometer measurements showed the polarity of current to be dependent upon temperature. From the MIT measurements, it was consistently observed that an increase in pressure caused a positive pulse of current for temperatures greater than 20°C and a negative pulse of current for temperatures less than 20°C. Similarly, a decrease in pressure caused a negative pulse of current for temperatures greater than 20°C and a positive pulse of current for temperatures less than 20°C.

Through conducting many experiments, it is concluded that water vapor, evaporation, relative humidity, and other moisture effects contributed to this polarity effect. In order to note the effect of humidity, a Honeywell humidity sensor of HIH-3610 series was installed in a new electrode chamber in September 2003. The main objective of this research experiment was to determine if measured transient currents were due to pressure, temperature and humidity changes which could change the relative dielectric permittivity of air; were due to space charge effects in air; or were due to evaporation and condensation.

2.2 Experimental Method

The equipment that comprises the experiment is shown in Figure 2.1: pump chamber, pressure transducer, electrode chamber, 617 Keithley electrometer, Sensotec sensor to display the pressure, and a Tektronix TDS 1012 digital storage oscilloscope.

A schematic of the experiment showing the electrical connections between the devices is shown in Figure 2.2. The air pump was used to manually increase or reduce the air pressure by moving the handle (located at the very top of the pump chamber) up and down. Moving the handle up and down changed the volume of air in the pump chamber. Pulling the handle upwards caused the pressure in the electrode chamber to be reduced, and pushing the handle downwards caused the pressure in the electrode chamber to rise approximately proportional to the total change in air volume. A pressure transducer, Sensotec model TJE/3883-02TJA, measured the absolute pressure of the air in the chamber. The digital value of the pressure was displayed by the Sensotec GM-A Sensor. A Tektronix TDS 1012 two channel oscilloscope was used to display the pressure and current waveforms. One of the channels was connected to the analog output of the Keithley 617 electrometer to record the flow of current between the electrode and ground. The Keithley 617 electrometer analog output in current measuring mode had a scale of 1V to equal 1pA of measured current. The output from the pressure transducer was connected to the other channel of the oscilloscope using an additional BNC to BNC cable. The calibration was set so that 1psi was equivalent to 0.1 volts of output signal. Initially, the pressure was a little above 15psi which corresponded to a value of around 1.5 volts. Finally, a computer was connected to the oscilloscope for data acquisition. Using the

Tektronix “Wavestar” software the waveforms from the oscilloscope could be acquired and be transferred to the computer terminal. The procedure of how to acquire data from the oscilloscope and transfer it to the computer is described in Appendix A.

Peterson had hypothesized that when the pressure changes, the volume charge density of air that is confined in the electrode chamber also changes [1]. If the air sample were to contain net electrical charge, then according to the induction law of electrostatics, the electrical charge of the air sample should induce a charge of opposite sign upon the surrounding metal surfaces. Since a change in pressure caused the volume charge of the air to change, it also changed the induced surface charge distribution on the electrodes. The electrode charge flowed as a current between the electrodes and ground [1]. This current was measured by the 617 electrometer that virtually grounded the center electrode. Another 617 electrometer was connected in parallel to the first electrometer to record the corresponding value of the potential difference. The value of current recorded by the current measuring 617 electrometer did not change when the voltage measuring 617 was connected indicating that the second electrometer did not load the first electrometer. An increase in pressure to about 35psi from about 15psi caused the voltage to increase to about 0.11mV from about 0.08mV.

To record the ambient temperature and humidity, a Thermo-Hygrometer was used. To display the internal temperature of the chamber, a RTD (resistance temperature detector) was installed inside the pump chamber since the internal temperature of electrode chamber and pump chamber are virtually equal. The Thermo-Hygrometer had been used to record the ambient temperature, before using the RTD. We used two types of two-wire RTD. The insulated RTD was used to measure the ambient temperature, and the non-insulated RTD inside the pump chamber was used to measure the internal temperature. To display the temperature, a 2001 Digital Multimeter was used. It was programmed to display up to two decimal values, making it preferable to the Thermo-Hygrometer in terms of accuracy. The procedure of how to program the 2001 multimeter to record both internal temperature and room temperature is described in Appendix C. The internal humidity was recorded using a Honeywell humidity sensor, HIH-3610 series. The waveform was then viewed on the oscilloscope.



Figure 2.1: A picture of the devices being used in the air charging experiments.

1. Keithley 617 electrometer for measuring current
2. Sensotec GM-A sensor for displaying pressure in psi
3. Pump chamber (the longer one, with black handle at the top)
4. Electrode chamber (Faraday cage)
5. Pressure transducer of Sensotec model TJE/3883-02TJA
6. Tektronix TDS 1012 digital oscilloscope

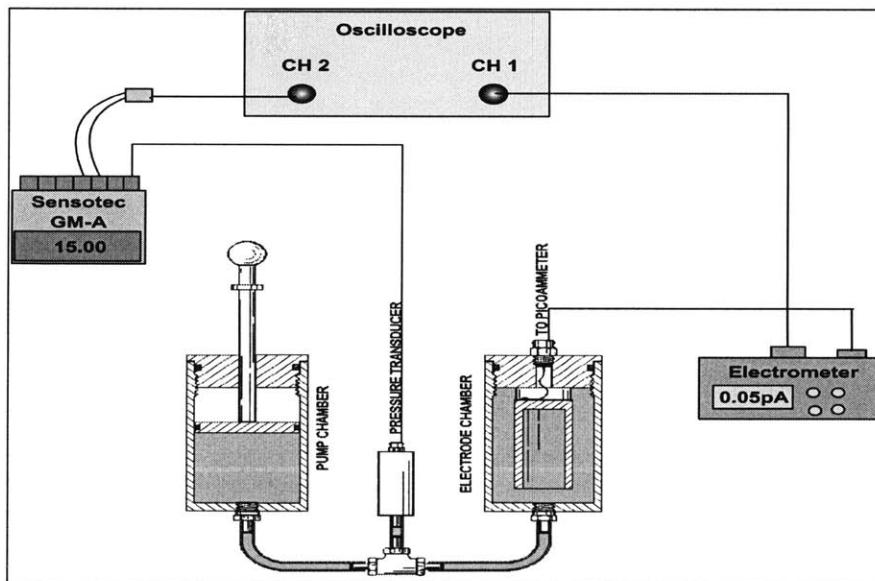


Figure 2.2: A schematic of the air experiment showing the electrical connections between the devices. The electrometer was used to display the value of current, voltage and charge when the pressure was applied using the hand pump. The electrode chamber was connected to the pump chamber and the electrometer. The waveform of current or voltage was then viewed on the oscilloscope. The Sensotec pressure transducer, TJE/3883-02TJA, was used to convert the pressure to voltage, and the waveform was then displayed on the oscilloscope. The Sensotec GM-A sensor was used to display absolute pressure of the chamber in psi.

2.3 Current Measurements at Ambient Temperature with Original Electrode Chamber

Temperature and ambient relative humidity were recorded for each of the current measurements as pressure was changed. Two different sets of data with opposite polarity current for the same pressure change are presented for temperatures above and below 20°C. For both sets of measurements shown in Figures 2.3 and in 2.4, the upper trace on channel #2 is the pressure waveform, and the lower trace on channel #1 is the electrode current. The pressure waveforms show that there was a small amount of air leakage during the experimental time of around eight seconds. This was demonstrated after increasing or decreasing the pressure and keeping the pump handle in the same position. Additionally, the triaxial shielded lead which connected the electrode chamber to the electrometer was vibration sensitive and must not be moved during the measurements to avoid jitter on the current trace.

2.3.1 *Current measurements at temperatures less than 20°C*

From the measurements conducted with the old electrode chamber during winter 2002-2003 we noticed that when the ambient temperature or internal temperature was below 20°C, there was a polarity reversal which meant an increase in pressure resulted in a negative pulse in electrode current, and a decrease in pressure yielded a positive pulse in electrode current. For this set of data an increase in pressure with corresponding negative current caused the center electrode to have a decrease in negative charge or an increase in positive charge, and a reduction in pressure caused the center electrode to have an increase in negative charge or a decrease in positive charge as shown in Figure 2.3. These observations were observed repeatedly. Additionally, when the temperature was much below 20°C, a very small change in pressure caused a relatively large flow of electrode current. Here, on average, for this set of data, the pressure rose to a value of 19.6 psi and was reduced to a value of 12.8 psi. There is an adjustment screw located at the very top of the pump chamber, and the change in pressure is a function of that screw tightness. After unscrewing it, it was possible to raise the pressure to a value of about 35psi. Data measurements of pressure and the electrode current shown in Figure 2.3 and Figure 2.4 were taken from 10 degrees Celsius to 23 degrees Celsius with an increment of every 1 degree Celsius. The ambient temperature was increased with a portable room

heater and a heat gun. The room heater was placed on the floor, and the heat gun was used to directly heat the chambers. Data was taken when only the room heater was used and when both heat gun and the room heater were used. This process, however, was a tiresome one as it usually took 30 to 60 minutes to raise the ambient temperature by only 1°C.

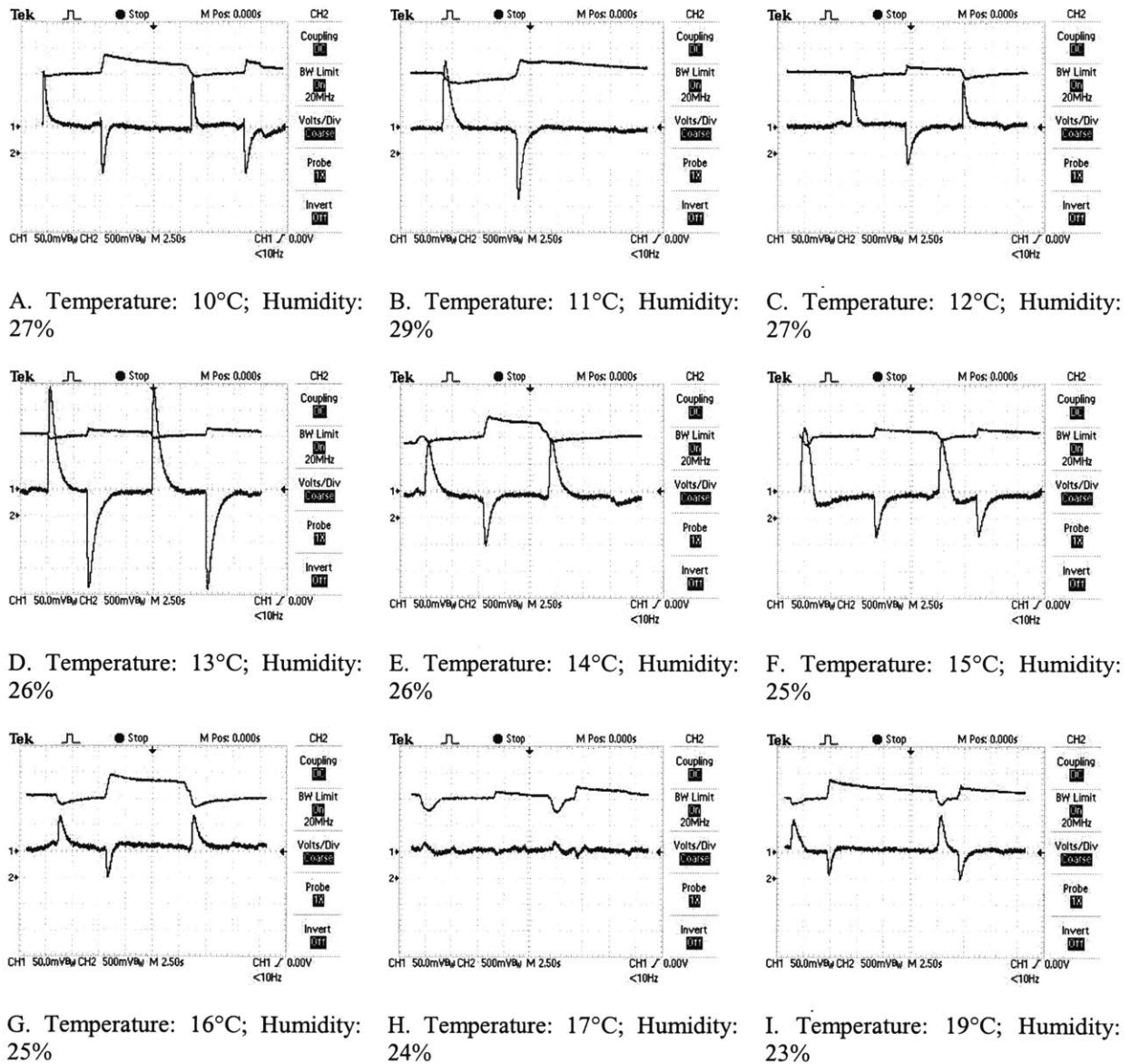


Figure 2.3: Transient pressure and current data for forced ambient air into the electrode chamber with ambient temperatures less than 20°C where a pressure increase caused the current to decrease, and a pressure decrease caused the current to increase.

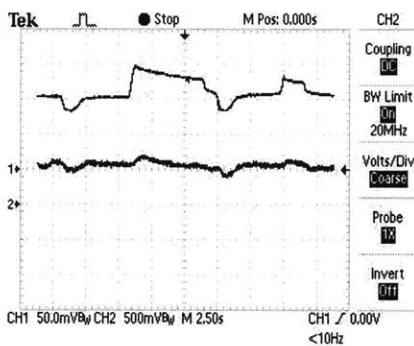
Pressure scale: Ch 2. 5.0 psi per 500 mV division (Upper Waveform).

Current scale: Ch 1. 0.05pA per 50 mV division. (Lower Waveform).

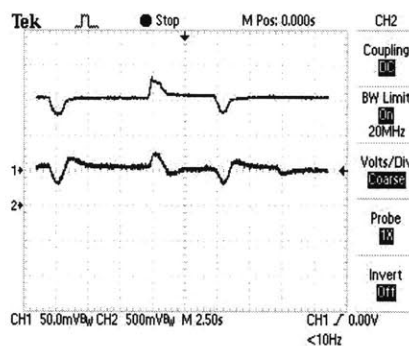
Time scale: 2.5s per division.

2.3.2 Current measurements at temperatures greater than 20°C

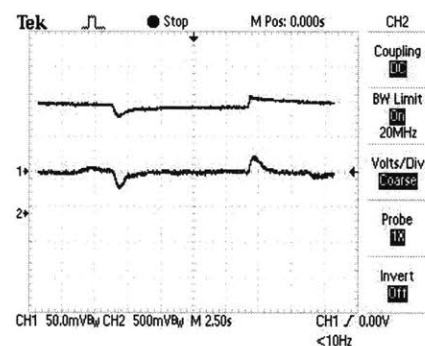
For the second set of measurements shown in Figure 2.4, a positive increase in pressure caused a positive increase in current, and a decrease in pressure caused a negative current. Because the current was directed into the 617 as verified by a 9V battery, a positive current caused an increase in negative charge on the center electrode or a decrease in positive charge on the center electrode. When the handle was released from raising or reducing the pressure, the current approached zero. Figure 2.4 measurements were taken when the temperature was at 20°C or above.



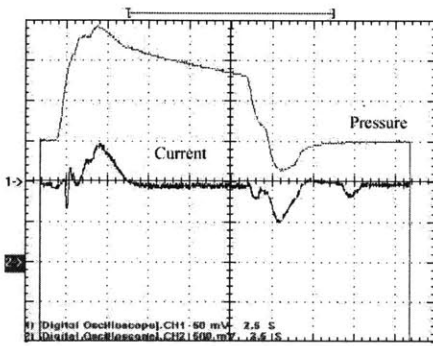
A.
Temperature: 20°C
Humidity: 22%



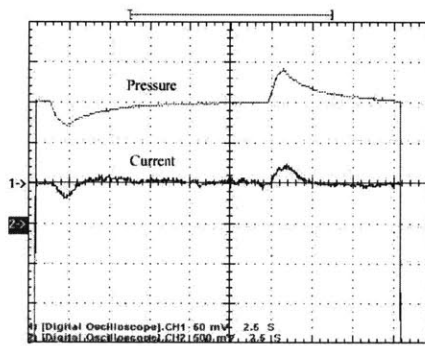
B.
Temperature: 20°C
Humidity: 37%



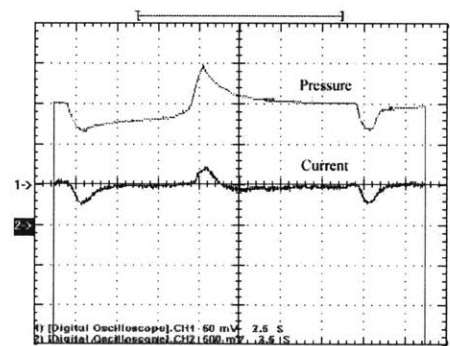
C.
Temperature: 20°C
Humidity: 32%



D.
Temperature: 21.50°C
Humidity: 24%



E.
Temperature: 22.71°C
Humidity: 25%



F.
Temperature: 23.51°C
Humidity: 24%

Figure 2.4: Transient pressure and current data for forced air into the electrode chamber where ambient temperatures was greater than 20°C. Increasing/decreasing pressure causes the same variation (increasing/decreasing current). Pressure scale: Ch 2. 5.0 psi per 500 mV division (Upper Waveform). Current scale: Ch 1. 0.05pA per 50 mV division (Lower Waveform). Time scale: 2.5s per division.

2.4 Temperature Control

Since it was observed that temperature was a strong factor that contributed to the polarity reversal for the measurements conducted during winter 2002-2003, further measurements were conducted with better control of the internal temperature of the chambers. Heating tape around the electrode chamber and the pump chamber was used with thermocouple control as shown in Figure 2.5.

For temperatures below 20°C, raising the internal air temperature with heating tape, the magnitude of the current reduced with change in air pressure. For 20°C and above, an increase in pressure caused a positive pulse of electrode current and a decrease in pressure caused a negative pulse of electrode current. During these measurements, the magnitude of current was small as shown in Figure 2.6. We, however, only used the non-insulated RTD to display the internal chamber temperature as it was being warmed with heating tape connected to the temperature controller, and we used the Thermo-Hygrometer to record the ambient temperature. In the measurements shown in Figures 2.3 and 2.4, the temperature was controlled with a heat gun and a portable room heater, and it took about 30 to 60 minutes to increase the temperature by only 1°C with the heat gun; whereas, in the measurements shown in Figure 2.6, the internal temperature was controlled with heating tape, and it took only about 2 to 3 minutes to increase the internal temperature by 1°C.

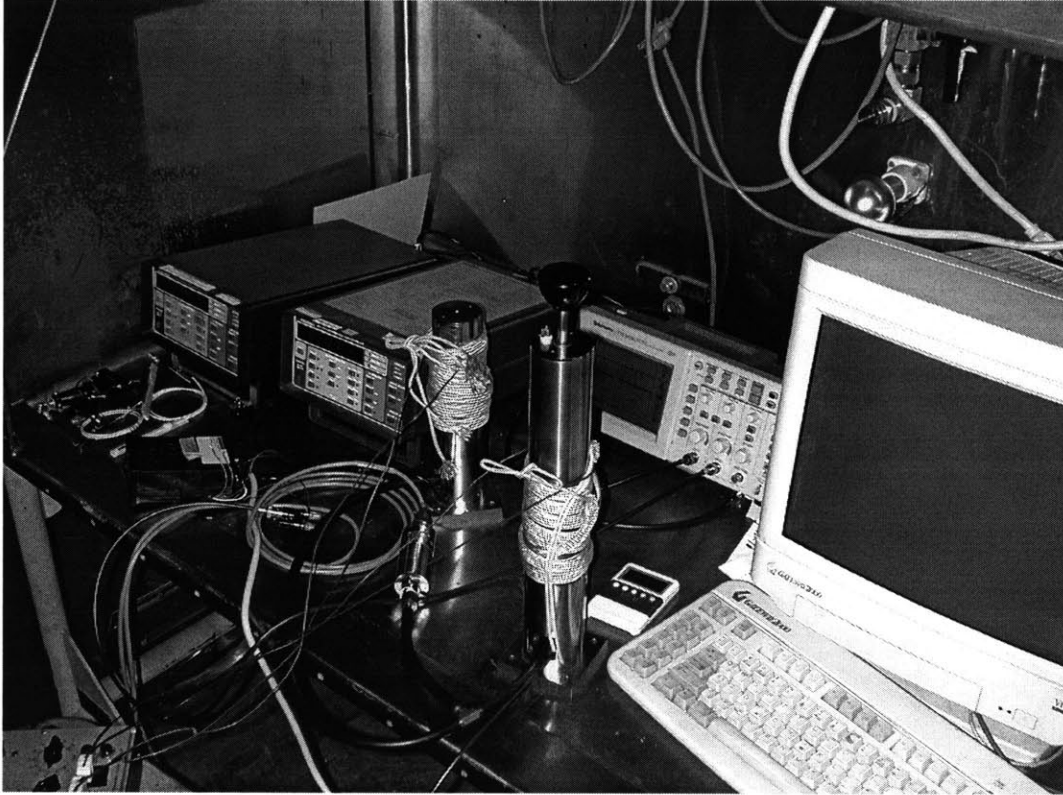


Figure 2.5: Set up of the experiment to control the internal temperature of the chambers. Data was taken using the heating tape wrapped around the electrode chamber and the pump chamber to measure the effect of warming up both chambers using the temperature controller.

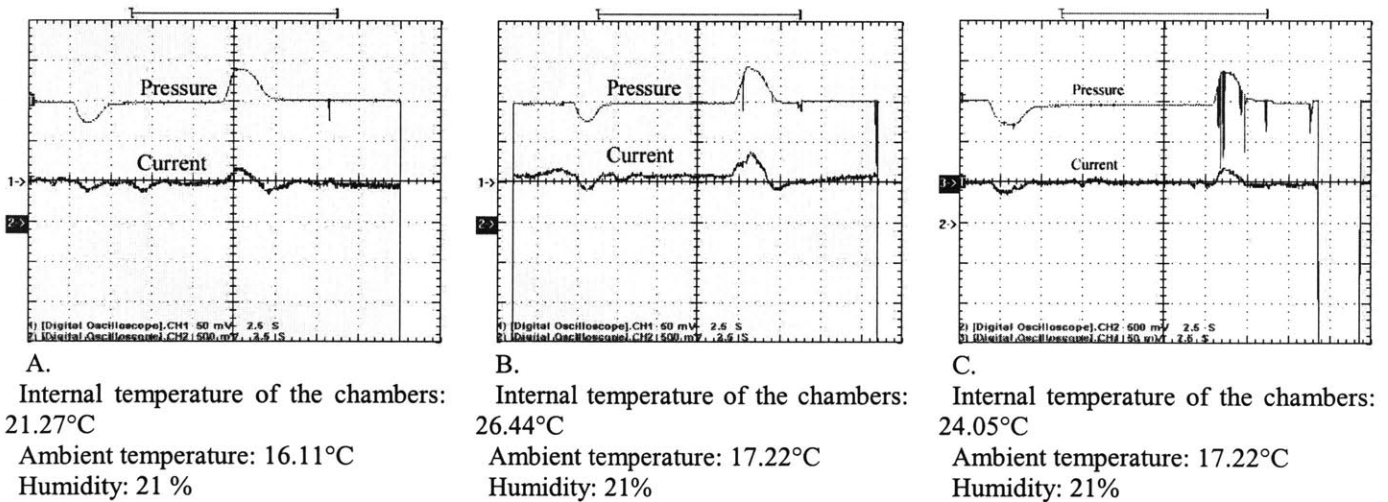


Figure 2.6: Transient pressure and current data using heating tape wrapped around the electrode chamber and pump chamber for internal temperature increased above 20°C with an ambient temperature of less than 20°C.

Increasing/decreasing pressure causes the current to increase/decrease for temperatures greater than 20°C.

Pressure scale: Ch 2. 5.0 psi per 500 mV division.

Current scale: Ch 1. .05pA per 50 mV division.

Time scale: 2.5s per division.

2.5 New Current and Humidity Measurements at Ambient Temperature

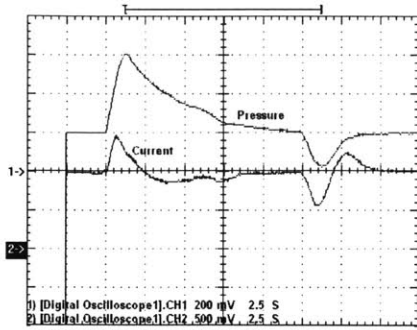
A new electrode chamber was used after September 2003 which had a Honeywell humidity sensor. The plastic conducting hose is connected from the pump chamber to the top of the electrode chamber. Variation of current with a change in pressure is shown in Figure 2.7. An increase in pressure caused an increase in current, and a decrease in pressure caused a decrease in the current value as was obtained from the results shown in Figures 2.4 and 2.6. Here, no heating tape or room heater was needed to raise the electrode chamber temperature as the ambient temperature was greater than 20°C.

In the previous measurements, because of the absence of a humidity sensor, we were not able to note the variation of humidity with a transient pressure change; whereas, in this new chamber we can. Variation of humidity inside the chamber with change in pressure is shown in Figure 2.8. For all three measurements, an increase in pressure caused the relative humidity inside the chamber to increase. For the measurements shown in Figure 2.8(A,B,C), the initial relative humidity was about 36.07 %, 36.07 %, and 52.04 % respectively. When the pressure was increased to about 25 psi, 26 psi, and 25 psi, the relative humidity increased to about 52.04 %, 52.04 %, and 60.03 % for the measurements shown in Figure 2.8(A,B,C) respectively. The voltage output is converted to relative humidity using the following expression [2]:

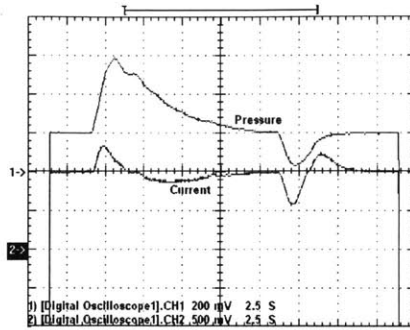
$$RH = (V_{out} - 0.871) / 0.0313 \quad (1)$$

Therefore, 0 % humidity records as 0.871 V.

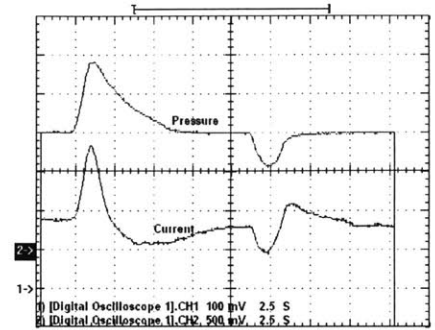
Since the TDS 1012 is a two-channel oscilloscope, we can only take two measurements at a time. Variation of current and humidity with change in pressure is shown in Figure 2.9. An increase in pressure caused both current and relative humidity inside the chamber to increase, and a decrease in pressure caused both current and relative humidity inside the chamber to decrease. Measurements shown in Figure 2.8 were performed to note the variation of humidity alone with change in pressure. Measurements shown in Figure 2.9 were performed to note the variation of both humidity and transient current with a transient pressure change.



A.
Ambient Temperature: 26.97°C



B.
Ambient Temperature: 26.97°C



C.
Ambient Temperature: 25.01°C

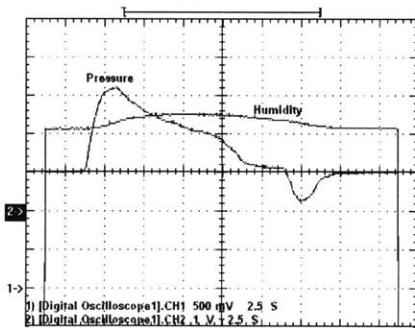
Figure 2.7: New transient pressure and current data for forced air into the electrode chamber with humidity sensor installed and with ambient temperatures greater than 20°C.

Increasing/decreasing pressure causes the current to increase/decrease.

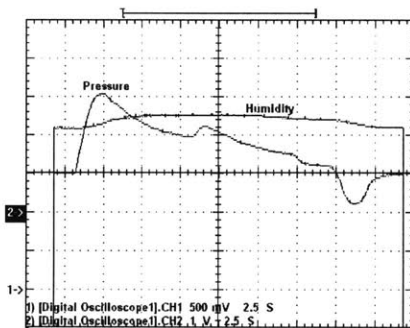
Pressure scale: Ch 2. 5.0 psi per 500mV division

Current scale: Ch 1. 0.2pA per 200mV division (A&B); 0.1pA per 100mV division (c)

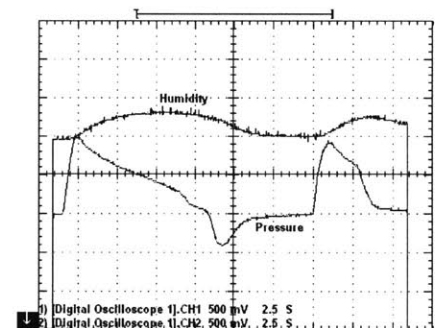
Time scale: 2.5s per division.



A.
Ambient Temperature: 26.97°C



B.
Ambient Temperature: 26.97°C



C.
Ambient Temperature: 25.01°C

Figure 2.8: Transient pressure and humidity data for forced air into the electrode chamber with ambient temperatures greater than 20°C.

Here, because of the presence of a humidity sensor in this new Faraday cage, we are able to measure the variation of humidity with transient pressure change.

Increasing/decreasing pressure caused the same variation in humidity (increase/decreasing).

Pressure scale: Ch 1. 5.0 psi per 500 mV division

Humidity scale: Ch 2.

Time scale: 2.5s per division.

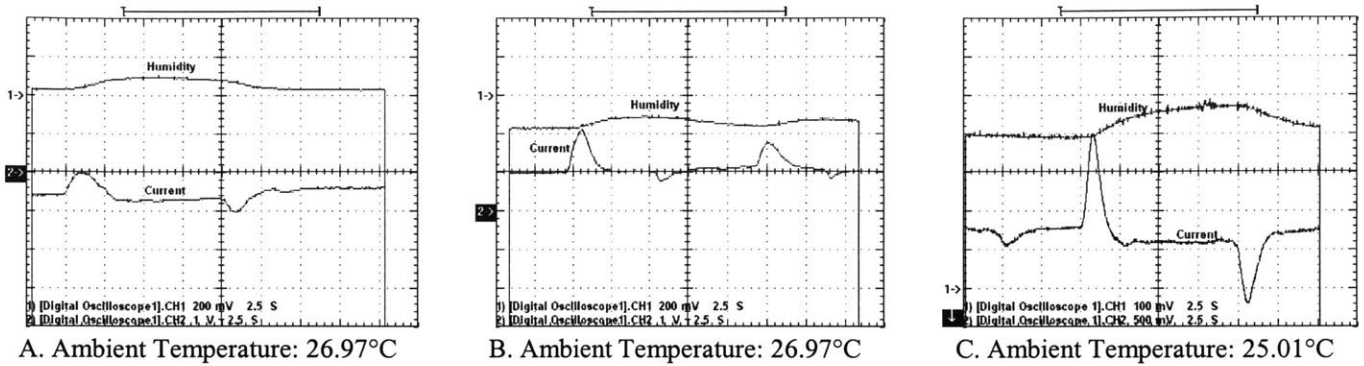


Figure 2.9: Transient current and humidity data for forced air into the electrode chamber with ambient temperatures greater than 20°C with variation in pressure.

Increasing/decreasing pressure causes the same variation (increasing/decreasing current and increasing/decreasing humidity).

Current scale: Ch 1. 0.2pA per 200 mV division (A&B); 0.1pA per 100mV division (C).

Humidity scale: Ch 2.

Time scale: 2.5s per division.

2.6 Current and Humidity Measurements at Ambient Temperature Performed in Cleveland, Ohio

Measurements of current and humidity with variation in pressure were also conducted by Mr. Peterson in his laboratory at Cleveland, Ohio. Following the observation of reverse polarity from the measurements performed at MIT, variation of current with a change in transient pressure was also performed in Cleveland at low ambient temperatures as shown in Figure 2.10. We note that there are two pulses of current which occurred subsequent to one another with change in pressure. An increase in pressure caused both a positive pulse of current and then a negative pulse of current. The difference between this data and the data shown in Figure 2.3 is that here the change in pressure is larger. Since the pressure change in Figure 2.3 was small, only one pulse of current was observed. The reverse polarity was also observed in Cleveland at low temperatures; however, because the pressure change was larger two pulses of electrode current occurred with one being higher amplitude than the other one. As temperature began to increase, the negative pulse of current with an increase in pressure or the positive pulse of current with a decrease in pressure began to reduce in amplitude. Finally, the negative pulse of current or the positive pulse of current disappeared when the temperature reached about 18°C. There are two sources acting behind the positive pulse

of current and the negative pulse of current which will be discussed in detail in the next section.

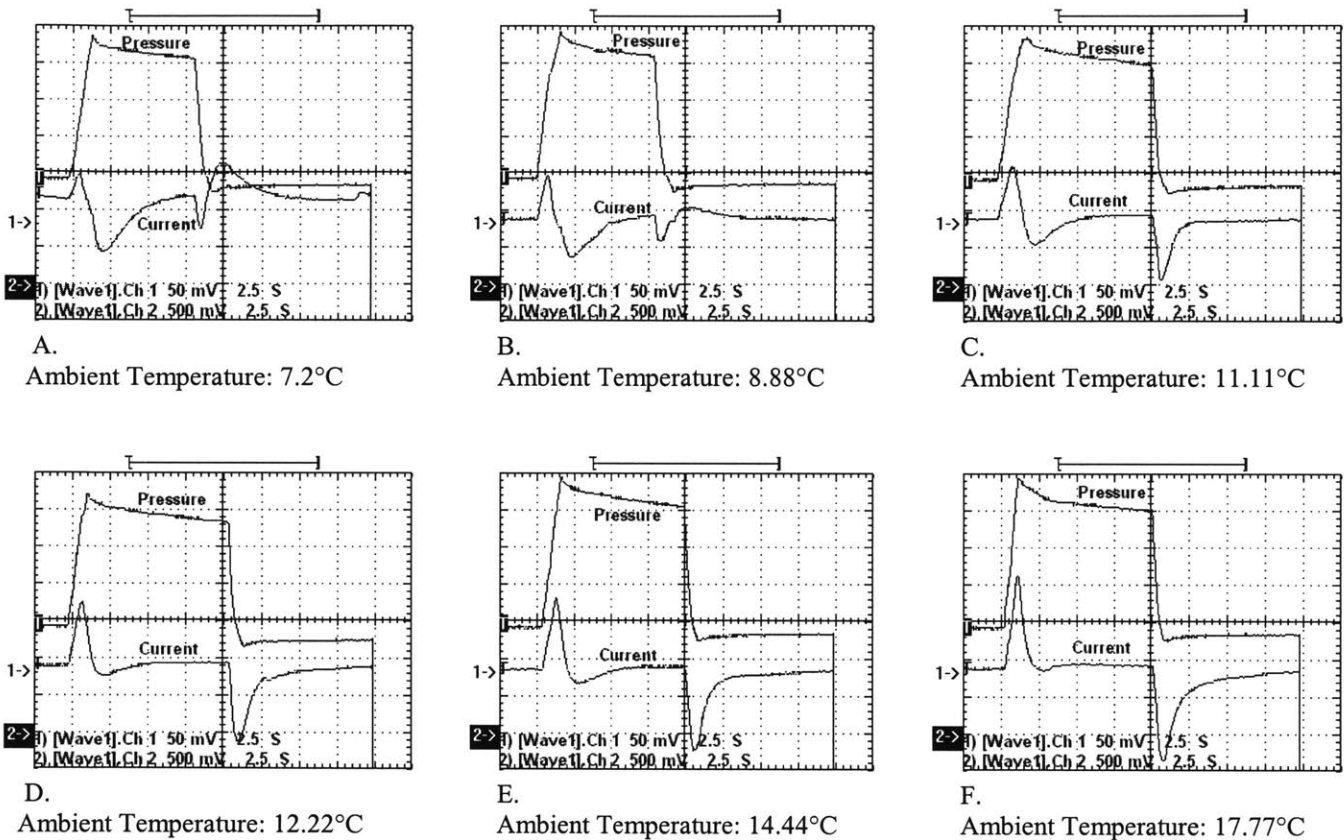


Figure 2.10: Peterson's measurements of transient pressure and current data for forced air into the electrode chamber at low ambient temperatures. Internal temperatures of the chambers were not controlled like the measurements in Figures 2.4 and 2.7 had been controlled.

Initially, a pressure change caused both positive and negative electrode current. As temperature began to increase, the negative electrode current due to pressure increase and the positive electrode current due to pressure decrease began to reduce in amplitude.

Pressure scale: Ch 2. 5.0psi per 500mV division.

Current scale: Ch 1. 0.05pA per 50mV division.

Time scale: 2.5s per division.

Figure 2.11 shows the variation of current with pressure change at a warmer ambient temperature where the pressure increase caused completely positive electrode current and a pressure decrease caused negative electrode current.

Variation of humidity inside the chamber with a change in pressure is shown in Figure 2.12. Like the measurements shown in Figure 2.8, both of the measurements in Figure 2.12 show that an increase in pressure caused the relative humidity inside the chamber to increase. For the measurements shown in Figures 2.12A and in 2.12B, the

initial relative humidity was about 45.65 % and 39.02 % respectively. When the pressure was increased to about 33 psi and 35 psi, the relative humidity increased to about 61.62 % and 68.01 % for the measurements shown in Figures 2.12 A and B respectively.

Variation of current and humidity with change in pressure is shown in Figure 2.13. An increase in pressure caused both current and relative humidity inside the chamber to increase, and a decrease in pressure caused both current and relative humidity inside the chamber to decrease like the measurement shown in Figure 2.9.

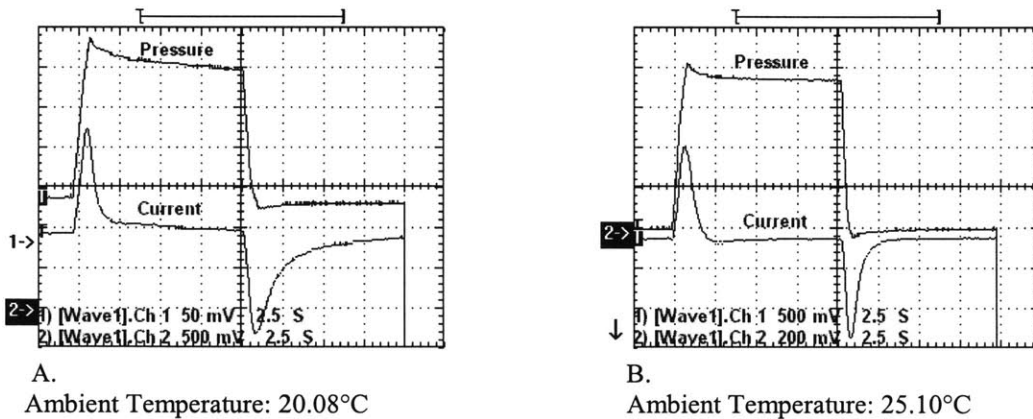


Figure 2.11: Peterson’s measurements of transient pressure and current data for forced air into the electrode chamber at low ambient temperatures. An increase/decrease in pressure caused the electrode current to increase/decrease.

Pressure Scale: Ch2. 5.0psi per 500mV division.

Current Scale: Ch1. 0.05pA per 50mV division (A) and 0.2pA per 200mV division (B).

Time Scale: 2.5s/division.

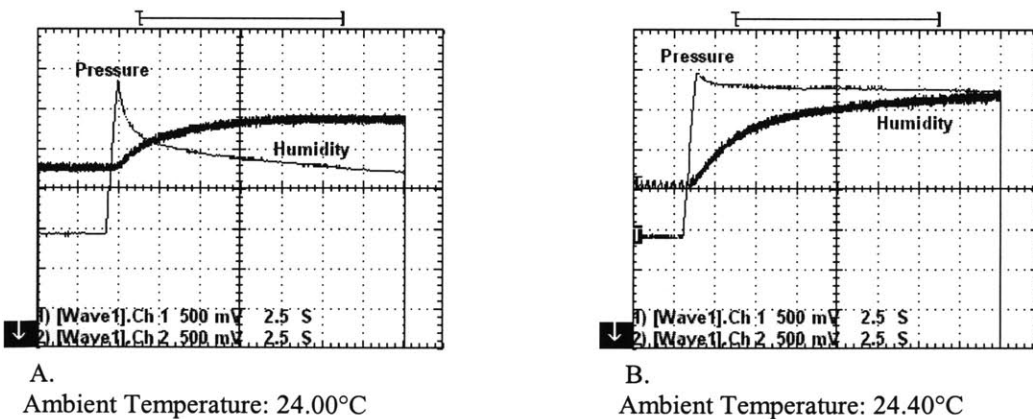


Figure 2.12: Peterson’s measurements of transient pressure and humidity data for forced ambient air into the electrode chamber with ambient temperatures. The measurement result is similar to the MIT measurement shown in Figure 2.9. Increasing/decreasing pressure caused the same variation (increasing/decreasing humidity). Pressure scale: Ch 1. 5.0 psi per 500 mV division. Humidity scale: Ch 2. 15.97% per 500mV division.

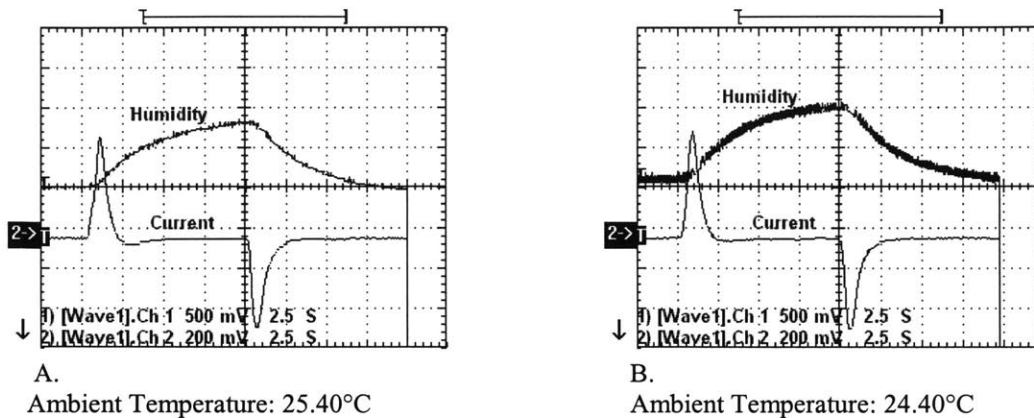


Figure 2.13: Peterson's measurements of transient current and humidity data for forced air into a Faraday cage with ambient temperatures. The measurement result is similar to the MIT measurement of transient current and humidity as shown in Figure 2.10.

Increasing/decreasing pressure causes the same variation (increasing/decreasing current and increasing/decreasing humidity). The humidity sensor has a slow response time. Current scale: Ch 2. 0.2 pA per 200 mV division. Humidity scale: Ch 1. 15.97% per 500mV division. Time scale: 2.5s per division.

2.7 Reasons behind the Polarity Reversal

Reverse polarity was observed to occur consistently when the temperature was low. At a small pressure increase, the positive current was so small compared to the negative current, that only the negative current pulse was observed. Similarly, at a small pressure decrease, the negative current was much smaller than the positive current making only the positive current pulse visible. On the other hand, at a large pressure increase or decrease two simultaneous opposite polarity current pulses were observed to occur. As the temperature was increased, ultimately, a pressure increase only caused a positive current and a pressure decrease only caused a negative current. Here, two sources of current acted to yield a positive and a negative current. Positive electrode current could be caused by the action of moisture on the center electrode of the electrode chamber, and the negative electrode current could be caused by the galvanic action between the two dissimilar metals in the BNC Pomona 4388 triaxial connector which connects the center electrode of the electrode chamber to the 617 electrometer. The triaxial connector contains a nickel-plated, brass-threaded case and two solder posts of gold-plated beryllium. Between the metal components lies an insulation surface. To

confirm this galvanic mechanism, the posts and case were dipped in a beaker containing distilled water, and we found that they produced a current of $-1.3\mu\text{A}$ and an open-circuit voltage of -140mV . So, it appears probable that the positive current is produced from the center electrode of the electrode chamber and the negative current is produced from the triaxial connector. To further prove this reasoning, the center terminal of the triaxial connector was disconnected from the center electrode of the electrode chamber. After that, a wetted paper towel was placed on the center electrode. Then, increasing the pressure caused a negative flow of current as was originally generated by the triaxial connector as shown in Figure 2.14. As water condensed upon the triaxial connector, a galvanic negative current of high amplitude was generated; thus, it concealed the positive current pulse. So in our previous experiments, when the temperature was low, water that condensed upon the triaxial connector generated the negative pulse. With increasing temperature, the water evaporated so that the current from the center electrode was the only pulse. This experiment showed the cause behind the polarity reversal at low temperatures to be due to galvanic action of dissimilar metals in the triaxial connector.

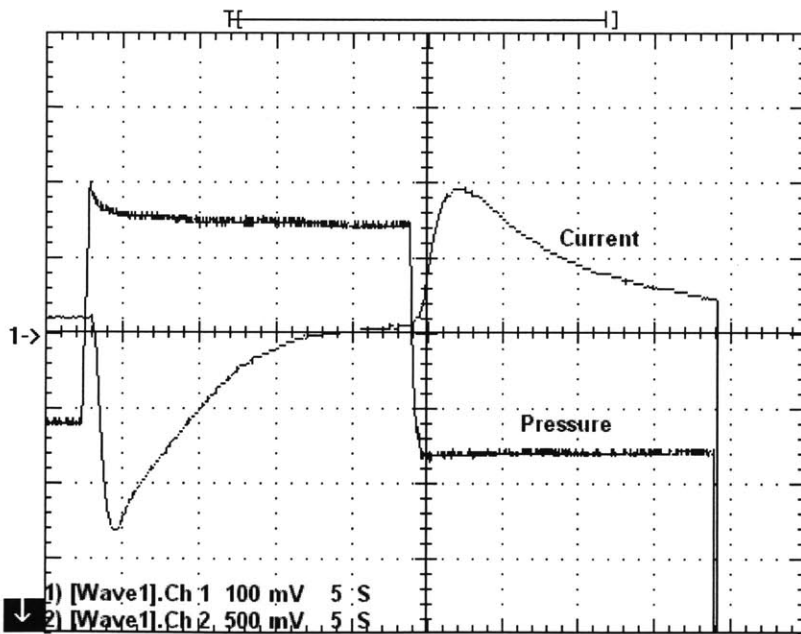


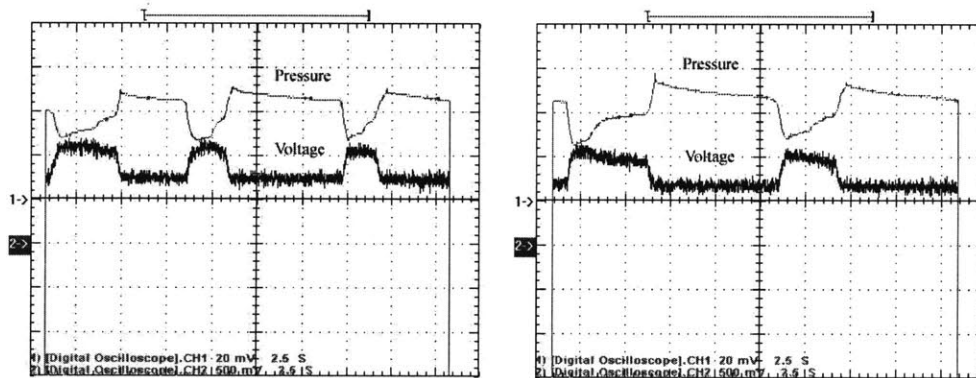
Figure 2.14: After disconnecting the center terminal of the triaxial connector from the center electrode of the electrode chamber, a negative current occurred with a pressure increase and a positive current with a pressure decrease. This experiment proved that galvanic action between dissimilar metals in the triaxial connector was the cause of polarity reversal. Ambient Temperature was 25.60°C .

Pressure Scale: Ch2. 5.0psi per 500mV division.

Current Scale: Ch1. 0.1pA per 100mV division. Time Scale: 5.0s per division.

2.8 Open-Circuit Voltage Measurements

An open circuit voltage was measured using the previously used current measuring Keithley 617 electrometer by switching to voltage mode from current mode. These measurements were taken while another 617 electrometer was connected in parallel which was used to note the variation of input offset voltage with change in pressure. The transient pressure waveforms for the open circuit voltage are shown in Figure 2.15 and are similar to the waveforms for the current. These measurements were taken when the temperature was below 20°C. With an increase in pressure, the voltage decreased; with a decrease in pressure, the voltage increased. When the pressure was not changed at ambient temperature, open circuit voltage was observed to be around 7.0mV as shown in Figures 2.15A and in 2.15B. When the pressure was decreased from atmospheric pressure to about 12 psi, the voltage increased to about 25 mV and 24 mV for the measurements shown in Figures 2.15A and 2.15B respectively. In the absence of another electrometer being connected in parallel, the value doesn't reach any stable value according to the observations. The value of open circuit voltage keeps rising.



A.
Ambient temperature: 16.11°C
Humidity: 22 %

B.
Ambient temperature: 16.11°C
Humidity: 22 %

Figure 2.15: MIT measurements of transient pressure and voltage data for forced air into the electrode chamber with ambient temperatures below 20°C.

Increasing/decreasing pressure caused the opposite variation (decreasing/increasing voltage).

Pressure scale: Ch 2. 5.0 psi per 500 mV division.

Voltage scale: Ch 1. 20 mV per division.

Time scale: 2.5s per division.

2.9 Dew point Analysis

In Section 2.8, we discussed the possible reasons behind the polarity reversal. We showed that the negative current was due to condensation of water on the triaxial connector and the positive current was due to the presence of water on the center electrode of the electrode chamber. Here we calculate the dew point to determine the temperature that water starts to condense on the electrode surface. Dew point is defined as the temperature at which the air must be cooled at a constant pressure and with a constant amount of water vapor in order to reach saturation. Saturation is reached when the air contains the maximum amount of water vapor which is when the rate of evaporation is equal to the rate of condensation. At saturation, for every molecule of liquid evaporating, a molecule of vapor condenses. Water vapor begins to condense when the temperature reaches the dew point or below. Relative humidity depends on two factors, namely, moisture and temperature. We calculate the dew point using the Clausius-Clapeyron equation [3].

Relative humidity is expressed as:

$$\left(\frac{E}{E_s}\right) \times 100\% = RH \quad (2)$$

where “ E ” denotes the partial vapor pressure, and “ E_s ” denotes the saturated vapor pressure. Vapor pressure represents the ambient pressure which is due to the fraction of water vapor in the air, and the saturated vapor pressure represents the maximum vapor pressure that the air can contain at a given temperature.

The Clausius-Clapeyron equation is expressed as:

$$E = E_o \times \exp \left[\left(\frac{L}{R_v} \right) \times \left\{ \left(\frac{1}{T_o} \right) - \left(\frac{1}{T_d} \right) \right\} \right] \quad (3)$$

and

$$E_s = E_o \times \exp \left[\left(\frac{L}{R_v} \right) \times \left\{ \left(\frac{1}{T_o} \right) - \left(\frac{1}{T} \right) \right\} \right] \quad (4)$$

Here, E_o denotes the reference saturation vapor pressure at a reference temperature; usually taken at 0°C. At 0°C, $E_o = 0.611$ kPa.

L denotes the air latent heat of vaporization; $L = 2.5 \times 10^6 \frac{J}{Kg}$.

R_v denotes the gas constant for water vapor; $R_v = 461 \frac{J}{Kg.K}$.

Thus, $\left(\frac{L}{R_v}\right) = 5423 \text{ K (Kelvin)}$.

T_o denotes the reference temperature. For our calculations, we use $T_o = 273 \text{ K (Kelvin)}$.

T_d denotes the dew point temperature in the Kelvin scale.

T denotes the ambient temperature in the Kelvin scale.

A plot of the variation of saturated vapor pressure, E_s , with temperature T is in Appendix B. Using (3) and (4), we solved for the dew point temperature denoted as T_d . For instance, measurements shown in Figure 2.4E were performed at a temperature of 22.71°C or 295.71 K at a relative humidity (RH) of 25%. Substituting the given values in (3) and (4) we obtain,

$$E = 0.611 \times \exp \left[(5423) \times \left\{ \left(\frac{1}{273} \right) - \left(\frac{1}{T_d} \right) \right\} \right] \quad (5)$$

$$E_s = 0.611 \times \exp \left[(5423) \times \left\{ \left(\frac{1}{273} \right) - \left(\frac{1}{295.71} \right) \right\} \right] \quad (6)$$

Substituting the value of relative humidity in (2) we obtain,

$$\frac{E}{E_s} \times 100\% = 25\% \quad (7)$$

By substituting (5) and (6) into (7), the dew point temperature in (5) was calculated as $T_d = 274.93 \text{ K}$ or equivalently 1.93°C; theoretically, this is the temperature to what the air inside the chamber must be cooled, in order to reach saturation.

We, however, noted that water condenses on the triaxial connector or on the center electrode surface of the electrode chamber at a higher temperature than this calculated value. The reason behind this could be that the water doesn't necessarily have to reach the dew point to condense on metal surfaces. It is known that layers of water coat metal surfaces as a function of humidity, temperature and pressure. When metal ions are dissolved in water, Nernst voltage is generated to the extent that space charge and electric

potential difference are formed between the water layer and the metal [4]. R. Strömberg weighed the adsorbed water film on gold, and he found it to be 6Å when the relative humidity was 40%, 21Å at a relative humidity of 80%, and 64Å at a relative humidity of 100% [5]. At no humidity, there was no layer of water present. Therefore, for water to condense on the metal surfaces, it is not necessary to reach the dew point.

2.10 Relationship between Change in Pressure and the Electrode Temperature

Changing the transient air pressure caused the transient internal temperature of the chamber to change. With an increase in pressure, the internal temperature increased, and with a decrease in pressure the internal temperature decreased. The temperature was recorded using the Keithley 2001 digital multimeter. The 2001 multimeter was used to store and recall data. Necessary steps for storing and recalling the temperature data are illustrated in Appendix A.

Variations of the air temperature with time in the electrode chamber with multiple changes in pressure are shown in Figure 2.16. The initial temperature was 28.22°C. Initially, upon increasing the pressure, the internal temperature rose to a value of 29.87°C, and the elapsed time was 3.499sec. After that, the temperature dropped a little. Then, the pressure was raised again, which in turn, caused the internal temperature to rise. The internal temperature was increased from 29.82°C to 30.44°C and the elapsed time was 1.647sec. After that, the pressure was decreased which caused the internal temperature to decrease from 30.44°C to 30.00°C, and the elapsed time was 1.1 sec. The process of increasing and decreasing the pressure was performed repeatedly for 18.19 sec. The pressure was increased initially by almost 15 psi which caused the internal temperature to increase significantly.

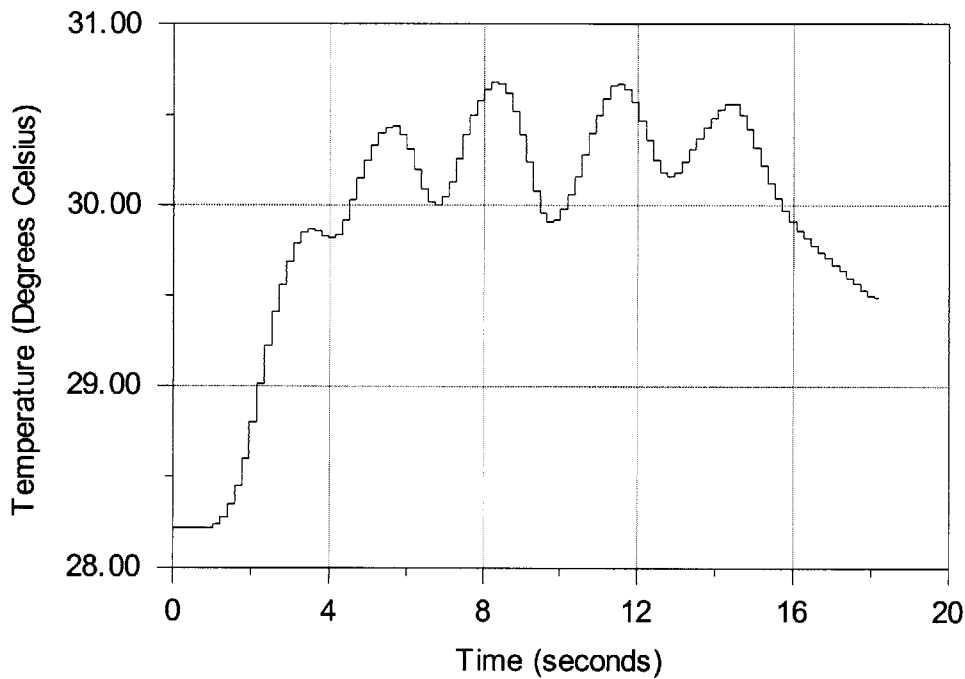


Figure 2.16: Measurement of internal air temperature vs. time in the electrode chamber with repeated changes in pressure between 15psi and 35psi.

2.11 Theoretical Current Due to the Changes in Capacitance and Input Offset Voltage

The polarity effects of the electrode current as a function of temperature, relative humidity, and pressure was a major focus of this research. A change in these parameters could also contribute to a change in the relative dielectric constant of the environment in the chamber. A change in the dielectric constant also changes the capacitance which can cause an electrode current to flow. A change in the voltage also contributes to the flow of current. The relationship between charge and voltage is expressed as:

$$Q = CV \tag{8}$$

where Q denotes the charge; C denotes the capacitance; V denotes the voltage.

Current, I , is defined as:

$$I = \frac{dQ}{dt} \tag{9}$$

Substituting (8) into (9) we obtain,

$$I = \frac{dQ}{dt} = \frac{d}{dt}(CV) = C \frac{dV}{dt} + V \frac{dC}{dt} \quad (10)$$

For fixed electrode geometry, the change in capacitance, C , is due to changes in relative dielectric constant where the relative dielectric constant, itself, depends on the pressure (P), temperature (T), and the internal relative humidity (RH). So, we define the capacitance, C , as:

$$C = \varepsilon_r(P, T, H)C_0 \quad (11)$$

where C_0 is the vacuum capacitance. The voltage measuring electrometer that was connected in parallel to the current measuring electrometer showed a value of 0.08mV. Changing the pressure to about 35psi caused the voltage value to increase by only 0.03mV. Even though the change in voltage was very small, we still must account for such a change. Taking account of the change in air pressure, temperature, and relative humidity, the relative dielectric constant also changes and so the capacitance in (11) would also change. The second term on the right hand side of (10) using (11) can be expressed as:

$$V \left(\frac{dC}{dt} \right) = VC_0 \frac{d\varepsilon_r}{dt} = VC_0 \left(\frac{\partial \varepsilon_r}{\partial P} \frac{dP}{dt} + \frac{\partial \varepsilon_r}{\partial T} \frac{dT}{dt} + \frac{\partial \varepsilon_r}{\partial H} \frac{dH}{dt} \right) \quad (12)$$

Substituting (12) into (10) we obtain,

$$I = VC_0 \left(\frac{\partial \varepsilon_r}{\partial P} \frac{dP}{dt} + \frac{\partial \varepsilon_r}{\partial T} \frac{dT}{dt} + \frac{\partial \varepsilon_r}{\partial H} \frac{dH}{dt} \right) + \varepsilon_r C_0 \frac{dV}{dt} \quad (13)$$

where $\varepsilon_r C_0$ is the air capacitance and has a measured value of 129×10^{-12} F or 129pF.

From the transient pressure air measurements, we found that changing the pressure using the hand pump caused a flow of electric current and caused changes in the internal temperature and internal relative humidity.

To determine whether the measured current was significantly due to the changes in the dielectric permittivity of air, we calculated the current using three methods. The first method used to calculate the current assumed the air to be dry; thus, the dielectric permittivity is taken to be only a function of temperature and pressure. The second method and the third method have taken account of the dielectric permittivity of air to

also be a function of humidity. We have used the temperature, humidity, and pressure values from the measurements shown in Figures 2.11B, 2.12B, 2.13B and 2.16.

2.11.1 First Method

In this first method, the relative dielectric constant has been taken to be a function of pressure and temperature.

The formula used to calculate the relative dielectric permittivity for dry air has been taken from [6] and is expressed as:

$$\frac{\epsilon_r(P, T) - 1}{\epsilon_r(P = 760, T = 20) - 1} = \frac{P}{760[1 + .003411(T - 20)]} \quad (14)$$

where P is the pressure in mmHg, and T is the temperature in °C. Here, $\epsilon_r(P = 760, T = 20) = 1.0006$.

Solving (14) for ϵ_r of air yields:

$$\epsilon_r(P, T) = \frac{P(0.0006)}{708.1528 + 2.59236T} + 1 \quad (15)$$

We have used the measurement values shown in Figure 2.11B. Using (14) in (13) and the given values for voltage, rate of change of voltage, and vacuum capacitance, the current can be calculated. It took 10 seconds to increase the pressure from atmospheric pressure to about 35 psi, and that caused the current to reach 0.4pA in a time of 5.0 seconds. From the measurement of variation of temperature with change in pressure, we noted the temperature to change by 1.65°C in 3.499 seconds. Mathematically, we express the rates of change of pressure and temperature as:

$$\frac{dP}{dt} = \frac{(1809.52 - 760)}{10} = 104.95 \text{ mmHg/s}; \quad \frac{dT}{dt} = \frac{1.65}{3.499} = 0.47^\circ\text{C/s} \quad (16)$$

Using (15), at a temperature of 26.05°C and a pressure of 1809.52mmHg, we calculate the change of relative dielectric constant with respect to pressure and temperature as:

$$\frac{\partial \epsilon_r}{\partial P} = 7.73 \times 10^{-7} (\text{mmHg})^{-1}; \quad \frac{\partial \epsilon_r}{\partial T} = -4.67 \times 10^{-6} (^\circ\text{C})^{-1} \quad (17)$$

The measured rate of change in voltage is:

$$\frac{dV}{dt} = \frac{0.03 \times 10^{-3}}{5.0} = 6.0 \times 10^{-6} \text{ V/s} \quad (18)$$

Then, substituting the values from (16) to (18) and the air capacitance value into (13) we calculate the value of current due to capacitance and voltage changes to be,

$$I = (0.08 \times 10^{-3})(129 \times 10^{-12}) \left[(7.73 \times 10^{-7})(104.95) + (-4.67 \times 10^{-6})(0.47) \right] + (129 \times 10^{-12})(6.0 \times 10^{-6})$$

$$= 7.748 \times 10^{-16} \text{ A} \quad (19)$$

The measured value of current was about $0.4 \times 10^{-12} \text{ A}$, so, this calculated value is much smaller than the measured value. This means that there was more flow of current and charge within the electrode chamber than be accounted for by changes in capacitance and input offset voltage changes. Here, the dielectric permittivity has been taken to be only a function of temperature and pressure. A plot of the variation of dielectric constant with pressure and with temperature is in Appendix B. The following two methods will additionally take account of the dependence of dielectric permittivity upon the humidity.

2.11.2 *Second Method*

In this second method, the relative dielectric constant is taken to be a function of pressure, temperature and internal relative humidity.

In this second method, Smith's equation will be used to calculate the relative dielectric permittivity for moist air [7, 8]:

$$\epsilon_r = \frac{1}{1 + 4 \times 10^{-6}} \left\{ \frac{77.6}{T} \left(P + 4810 \cdot \frac{P_p}{T} \right) \cdot 10^{-6} + 1 \right\}^2 \quad (20)$$

where T denotes the absolute temperature (K); P denotes the pressure in millibars; p_p denotes the partial pressure of water vapor in millibars. (1 millibar (mbar) = 1 hectopascal (hPa) = 100Pa); (133.322 Pa = 1 mmHg).

The partial pressure, p_p is related to relative humidity and saturated vapor pressure by (2), where p_p was denoted as E in (2). Bolton's equation [8,9], can be used to calculate the saturated vapor pressure, E_s in (2) at temperature T , and expressed as:

$$E_s = 6.112 \times e^{\frac{17.67T}{243.5+T}} \quad (21)$$

where E_s denotes the saturated vapor pressure. Substituting (21) in (2) for E_s yields the partial pressure, p_p , and then substituting the result into (20), we can express (20) as:

$$\varepsilon_r = \frac{1}{1 + 4 \times 10^{-6}} \left\{ \frac{77.6}{T + 273.15} \left(P + \frac{4810}{t + 273.15} \cdot \frac{H}{100} \cdot 6.112 \times e^{\frac{17.67T}{243.5+T}} \right) \cdot 10^{-6} + 1 \right\}^2 \quad (22)$$

In (22), H denotes the relative humidity and T is in degrees Celsius. We have used the pressure, temperature, and humidity values of the measurements shown in Figures 2.11B to 2.13B and 2.16. For the variation of transient pressure with transient current, we used the measurement shown in Figure 2.11B. For the variation of transient pressure with humidity we used the measurement shown in Figure 2.12B, and for the variation of transient current and humidity with transient change in pressure we used the measurements shown in Figure 2.13B. Upon increasing the pressure to 35psi, the relative humidity increased from 39.02% to 68.01%, and the time elapsed was 5.0 seconds as shown in Figure 2.13B. Using (22) in (13) and the given values for voltage, rate of change of voltage, and vacuum capacitance, the current can be calculated. Rates of change in pressure, temperature, and humidity with respect to time are calculated as:

$$\begin{aligned} \frac{dP}{dt} &= \frac{(2412.488 - 1013.247)}{10} = 139.924 \text{ hPa/s}; & \frac{dT}{dt} &= \frac{1.65}{3.499} = 0.47^\circ\text{C/s} \\ \frac{dH}{dt} &= \frac{(68.01 - 39.02)}{5.0} = 5.79\%/s \end{aligned} \quad (23)$$

Using (22) at a pressure of 2412.488hPa, a temperature of 26.05°C, and at a humidity of 68.01%, we calculate the change of relative dielectric constant with respect to pressure, temperature, and humidity as:

$$\frac{\partial \varepsilon_r}{\partial P} = 5.19 \times 10^{-7} (\text{hPa})^{-1}; \quad \frac{\partial \varepsilon_r}{\partial T} = 5.86 \times 10^{-6} (^\circ\text{C})^{-1}; \quad \frac{\partial \varepsilon_r}{\partial H} = 2.81 \times 10^{-6} \quad (24)$$

Then, substituting the values from (18), (23), (24) and the air capacitance value into (13) we calculate the value of current to be,

$$\begin{aligned} I &= \left(0.08 \times 10^{-3} \right) \left(129 \times 10^{-12} \right) \left[\left(5.19 \times 10^{-7} \right) (139.924) + \left(5.86 \times 10^{-6} \right) (0.47) + \left(2.81 \times 10^{-6} \right) (5.79) \right] + \\ &\left(129 \times 10^{-12} \right) \left(6.0 \times 10^{-6} \right) = 7.749 \times 10^{-16} \text{ A} \end{aligned} \quad (25)$$

Even after considering the dependence of dielectric permittivity upon humidity, the value of current calculated in (25) is about the same as (19). The measured value of current is much higher than the calculated value. A plot of the variation of dielectric constant with pressure, humidity, and with temperature is in Appendix B.

2.11.3 Third Method

Like the second method, in this third method, the relative dielectric constant is taken to be a function of pressure, temperature and internal relative humidity.

In this second method, Lea's equation will be used to calculate the relative dielectric permittivity for moist air [10, 11], and it is expressed as:

$$\epsilon_r = 1 + \frac{211}{T} \left[P + \frac{48E_s}{T} H \right] 10^{-6} \quad (26)$$

where T denotes the absolute temperature (K); P denotes the pressure in mmHg; E_s denotes the saturated water-vapor pressure at temperature, T and the saturated water-vapor pressure is in mmHg; H denotes the internal relative humidity in percent.

Like the first two methods, we have used the pressure, temperature, and humidity values from Figures 2.11B to 2.13B. For the variation of transient pressure with transient current, we used the measurement shown in Figure 2.11B. For the variation of transient pressure with humidity we used the measurement shown in Figure 2.12B, and for the variation of transient current and humidity with transient change in pressure we used the measurement shown in Figure 2.13B. Using (26) in (13) and the given values for voltage, rate of change of voltage, and air capacitance, the current can be calculated. We express the rates of change of pressure, temperature, and internal relative humidity as:

$$\begin{aligned} \frac{dP}{dt} &= \frac{(1809.52 - 760)}{10} = 104.95 \text{ mmHg} / s; & \frac{dT}{dt} &= \frac{1.65}{3.499} = 0.47^\circ \text{C} / s; \\ \frac{dH}{dt} &= \frac{(68.01 - 39.02)}{5.0} = 5.79\% / s \end{aligned} \quad (27)$$

This method yielded the same values as the values obtained from the second method.

Since $1 \text{ mmHg} = 1.33 \text{ hPa}$, upon multiplying $\frac{dP}{dt}$ from (27) we also get $139.92 \text{ hPa} / s$ which is the same as (23). Using (26) at a pressure of 1809.52 mmHg , a temperature of 26.05°C , and at a humidity of 68.01% , we calculate the change of relative dielectric constant with respect to pressure, temperature, and humidity as:

$$\frac{\partial \epsilon_r}{\partial P} = 7.05 \times 10^{-7} (\text{mmHg})^{-1}; \quad \frac{\partial \epsilon_r}{\partial T} = -5.56 \times 10^{-6} (\text{K})^{-1}; \quad \frac{\partial \epsilon_r}{\partial H} = 2.86 \times 10^{-6} \quad (28)$$

Then, substituting the values from (18), (27), (28) and the air capacitance value in (13) we calculate the value of current to be,

$$I = \left(0.08 \times 10^{-3}\right) \left(129 \times 10^{-12}\right) \left[\left(7.05 \times 10^{-7}\right) (104.95) + \left(-5.56 \times 10^{-6}\right) (0.47) + \left(2.86 \times 10^{-6}\right) (5.79) \right] + \left(129 \times 10^{-12}\right) \left(6.0 \times 10^{-6}\right) = 7.749 \times 10^{-16} A \quad (29)$$

The value obtained in (29) is the same as the values obtained in (25) and in (19). Even after considering the dependence of dielectric permittivity upon humidity, the value of current calculated in (29) or (25) is about the same as (19). The measured value of current is much higher than this calculated value. We, therefore, have confirmed that the measured current cannot be due to the change in the dielectric permittivity of air and variations in electrometer offset voltage since the measured current value is much higher than the calculated value. The measured current was $4.0 \times 10^{-13} A$.

2.12 Dependence of the Flow of Electrode Current on Humidity

One of the main objectives of this research was to examine the source of the flow of electrode current. An experiment was performed where the flow of electrode current was found to be dependent upon the internal relative humidity of the electrode chamber. The internal humidity was increased by passing air through a closed beaker containing water. This beaker was connected to the electrode chamber through a hose. In the presence of moisture in the chamber, a small increase caused a large flow of electrode current. Figure 2.17 shows such a large variation of current with small transient pressure change, and it was taken when the internal relative humidity was 36.07%. The internal relative humidity was increased to 52.04%, where a pressure change from the atmospheric pressure to about 21psi caused a large positive electrode current flow change of 0.25pA. The reason behind such a large flow of electrode current in the presence of moisture in the chamber could be related to the high conductivity or high relative dielectric constant of water.

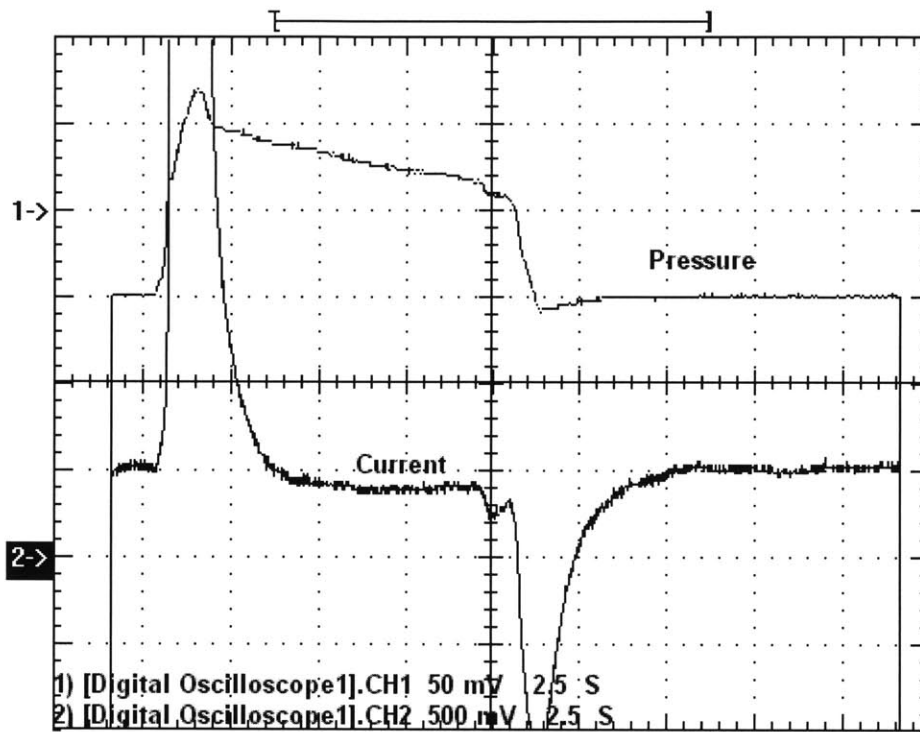


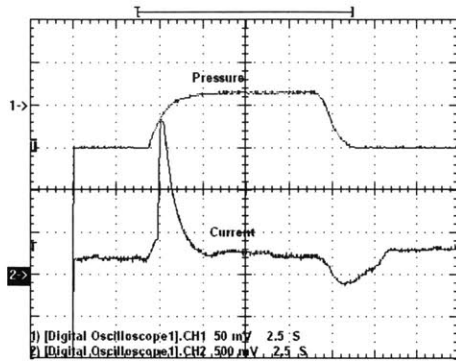
Figure 2.17: Transient pressure and current data taken at an ambient temperature of 31.30°C and at an internal relative humidity of 36.07%. Relatively large variation of electrode current was produced even with this small change in pressure.

Pressure Scale: 5.0psi per 500mV division.

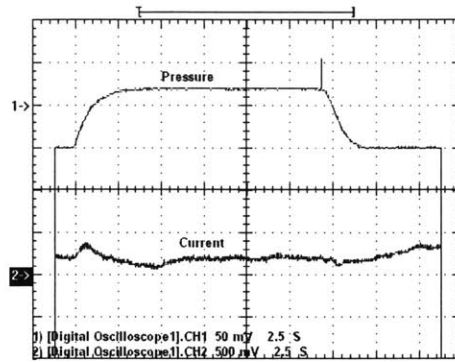
Current Scale: 0.05pA per 50mV division.

Time Scale: 2.5s per division.

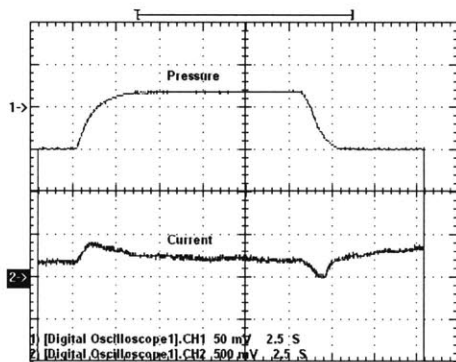
After increasing the internal relative humidity to 52.04%, the internal relative humidity was reduced to 13.70% by removing the in-line water beaker and replacing it with a closed cylindrical tube containing desiccant, Drierite (anhydrous CaSO_4). From 13.70%, the internal relative humidity was further reduced to 2.52% in steps. Figure 2.18 shows the dependence of amplitude of electrode current on humidity. As humidity was being reduced, the amplitude of electrode current was also reducing. At 2.52%, a change in pressure did not cause any appreciable change in the amount of current flow. Therefore, this experiment confirms the flow of electrode current to be significantly dependent upon internal humidity. Here, the pressure was controlled using an electric pump.



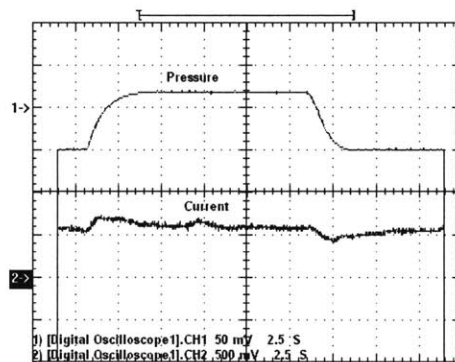
A.
Internal humidity: 13.70%



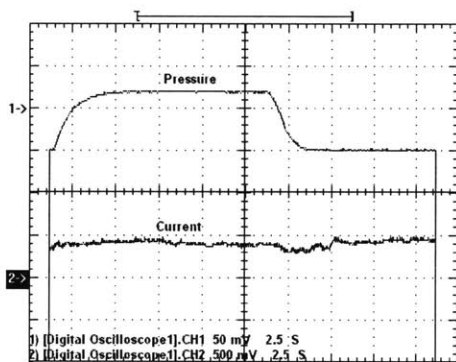
B.
Internal humidity: 10.51%



C.
Internal humidity: 7.31%



D.
Internal humidity: 4.12%



E.
Internal humidity: 2.52%

Figure 2.18: Transient pressure and current data where the current was dependent upon the internal relative humidity. As the humidity was being reduced, amplitude of the current was also being reduced.

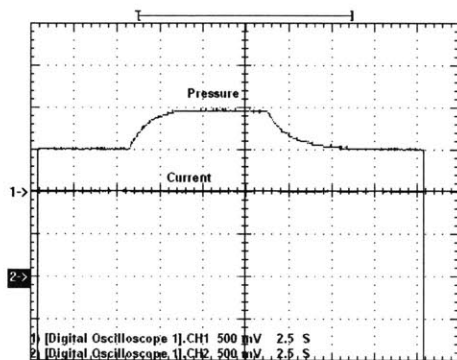
Pressure Scale: 5.0psi per 500mV division.

Current Scale: 0.05pA per 50mV division. Time Scale: 2.5s per division.

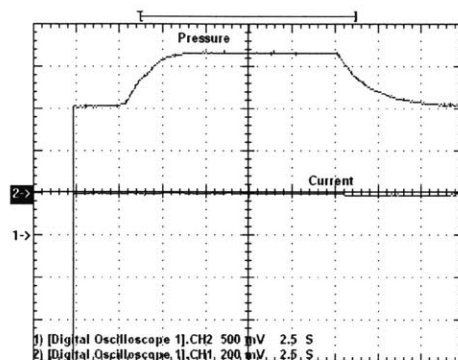
2.13 Measurements Using Dry Nitrogen

Measurement of transient current with transient pressure change was also performed replacing air with dry nitrogen as shown in Figure 2.19. A pressure change did

not cause any appreciable flow of current; the current was essentially zero. This verifies the results shown in Figure 2.18 that the amplitude of electrode current is primarily due to moisture effects. The pressure change was controlled using the valve in the nitrogen gas cylinder.



A.
 Ambient Temperature: 29.57°C
 Pressure Scale: Ch2. 5.0psi per 500mV division
 Current Scale: Ch1. 0.5pA per 500mV division



B.
 Ambient Temperature: 21.20°C
 Pressure Scale: Ch1. 2.0psi per 200mV division
 Current Scale: Ch2. 0.5pA per 500mV division

Figure 2.19: Transient pressure and current data using dry nitrogen. A pressure change did not cause any significant flow of current.
Time Scale: 2.5s per division.

2.14 Discussion

Theoretical calculations using three methods as described in Section 2.11 have shown that the flow of electrode current is not due to changes in capacitance and input offset voltage as had been anticipated. Calculations using each of the three methods provided essentially the same value of capacitive current which is much smaller than the measured value.

This research has proven that the flow of electrode current in the electrode chamber is primarily due to moisture effects. One experiment used water and Drierite to control the humidity in the electrode chamber. A closed beaker containing water was connected to the electrode chamber through a hose to increase the humidity. In the presence of moisture in the electrode chamber, even a small change in pressure caused a relatively large flow of electrode current. Such a large flow could be related to the high dielectric constant or conductivity of water. Then, a closed cylindrical tube containing Drierite was used to reduce the humidity. As humidity was being reduced, the current pulse was also reduced. Finally, at a humidity of about 2.52%, a change in pressure

caused only a minute flow of electrode current as shown in Figure 2.18E. Measurements of current due to changes in humidity are shown in Figures 2.17 and 2.18. The second experiment replaced ambient air with dry nitrogen. This measurement is shown in Figure 2.19 where a change in pressure also did not cause any appreciable flow of current. Hence, these two experiments prove that the reported charging phenomenon is due to atmospheric humidity.

The polarity of electrode current with transient pressure change was also shown to vary with temperature. Figures 2.3 and 2.4 show that the polarity of current changed at about 20°C. When the temperature was measurably below 20°C, an increase in pressure caused a negative flow of current, and a decrease in pressure caused a positive flow of current. When the temperature was about 20°C, polarity of the current reversed to match the sign of variation of the pressure. Now, when the pressure change is more than about 10psi above atmospheric pressure, at a low temperature of about less than 20°C two simultaneous pulses of electrode current were observed to occur as shown in Figure 2.10. As temperature was increased, the negative pulse with an increase in pressure started to disappear. Finally, when the temperature was about 18°C, an increase in pressure caused only a single pulse of positive electrode current, and a decrease in pressure caused only a single pulse of negative electrode current. At a low temperature less than 20°C, the negative electrode current with an increase in pressure was shown to be the dominating pulse, and at a high temperature greater than 20°C, the positive electrode current with an increase in pressure was shown to be the dominating pulse. The reason behind the polarity reversal around 20°C wasn't understood at first. Further experiments confirmed that the positive current and negative current resulted from two different mechanisms. The positive current was produced from the condensation of water on the center electrode of the electrode chamber, and the negative current was generated by galvanic action in the triaxial connector that connected the center electrode of the electrode chamber to the electrometer as discussed in detail in Section 2.7. There could also be a possibility that the polarity reversal could be related to changes in the state of the water molecules of the surface layer *i.e.* monomolecular, multilayer, or more complex bound and ordered droplets [12].

Dew point analysis was discussed in Section 2.9 where we found that the calculated dew point was much lower than the expected value. We, however, discussed in Section 2.9 that, it is not necessary to reach the dew point for water to condense on metal.

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Chapter 3

Faraday Cage Measurements of Liquid and Solid Dielectrics: Experimental Methods and Apparatus

3.1 Faraday Cage Experimental Method of Solid and Liquid Dielectrics

Charging phenomena using water and solid dielectrics were measured in another type of Faraday cage apparatus. Figure 3.1 shows the components that were used in this measurement method. The computer which was used to acquire the charge and voltage values is not shown.

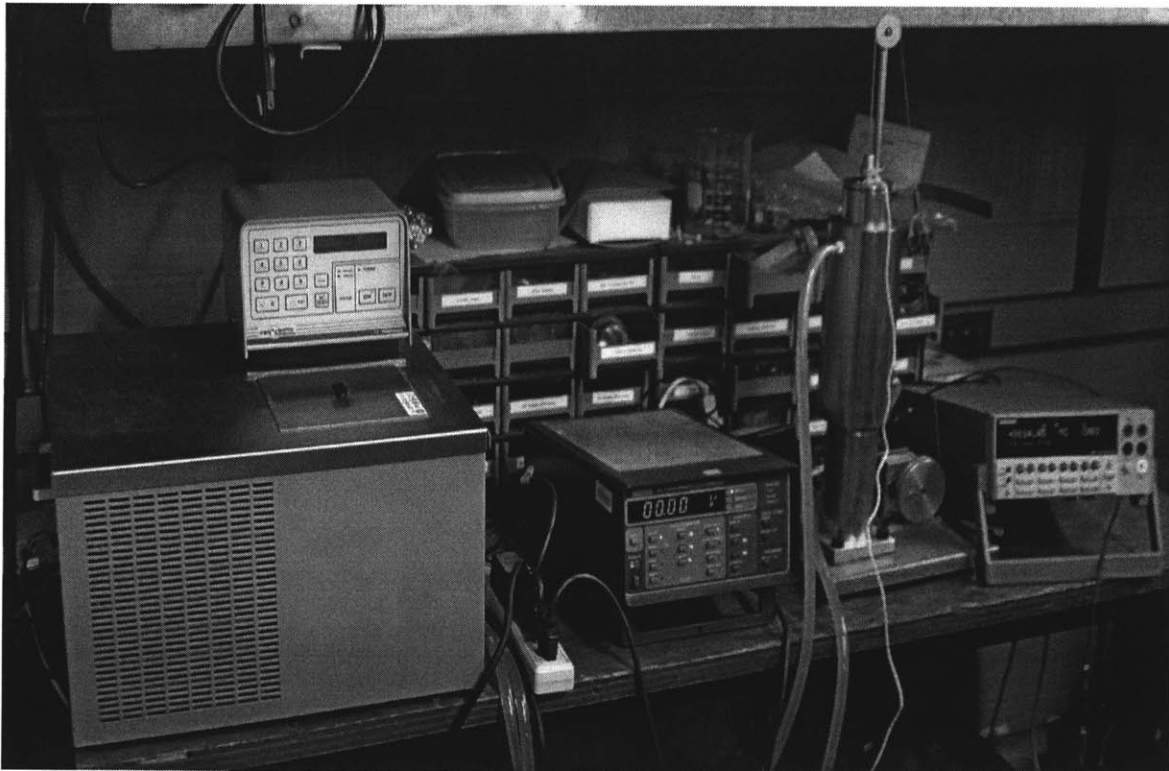


Figure 3.1: A picture of the Faraday cage apparatus used for measuring charge and open-circuit voltage using liquid and solid dielectrics. The temperature controller (leftmost), Keithley 617 electrometer, Faraday cage, and 2001 digital multimeter (rightmost) are shown.

Figure 3.2 shows a schematic of the experiment to show the electrical connections between the devices. Measurements of charge and voltage using the liquid and solid dielectrics that will be described in the following two chapters follow the experimental method that is described here. Charge and voltage measurements were performed in a patented [1], gold-plated Faraday cup device contained in a grounded Faraday shield. There are two aligned hollow Faraday cup gold-plated brass electrodes where the upper electrode is permanently grounded and the lower electrode is grounded between measurements by the zero check input of a Keithley 617 electrometer. A diagram of the internal structure of the Faraday cage is shown in Figure 3.3. Liquid dielectric samples are contained within 30mL Nalgene Polyallomer centrifuge tubes, which are moved up and down between these two Faraday cup electrodes without making any contact with the electrode surfaces during the motion. A metal grounding screw is sealed through the tube cap. This holds the dielectric to a gold-plated motor-controlled rod, and the metal grounding screw makes contact between the water dielectrics and the earth ground throughout the experiment. The solid dielectric samples are of circular cross-section and are transported between Faraday cup electrodes without contacting the electrode surfaces as well. The top part of the solid dielectrics is threaded to be tightened into a cap. The same motor controlled rod that holds the water dielectrics is also used to hold the solid dielectrics. When operating in the Coulomb mode, the 617 electrometer measures the charge of the dielectric as it leaves the lower electrode for the upper electrode; when operating in the Voltage mode, the 617 electrometer measures the open-circuit voltage.

When the polarity shown by the electrometer is positive, after the sample comes to rest within the upper Faraday electrode, the sample is negatively charged since it induced a positive charge on the inner surface of the lower electrode which flowed through the electrometer to ground as the sample left the lower electrode. Similarly, when the polarity is shown to be negative after the sample comes to rest within the upper Faraday electrode, the sample is positively charged since it induced a negative charge on the inner surface of the lower electrode. For instance, after the distilled water sample comes to rest within the upper Faraday electrode, the polarity of the charge value shown by the electrometer is positive, and when it reenters the lower electrode, the polarity of

the charge value is negative but of equal magnitude. Therefore, the distilled water is negatively charged when kept in a Polyallomer centrifuge tube.

The sample moving between the lower Faraday electrode and the upper Faraday electrode is held in equilibrium with the potential of the earth, since the upper electrode is permanently earthed [2]. The sample could be moved in three ways. One way is by activating a switch in the motor relay. Pressing the switch in the motor relay allows the sample to ascend, and releasing it allows it to descend. The second way to control the motion is to program the 2001 Digital Multimeter's digital I/O port which is used to control external digital circuitry. Detailed instructions of how to program the 2001 Digital Multimeter to control motion of the sample is given in Appendix C. The third way of controlling the sample motion is automatic which is performed through a computer using the Testpoint data acquisition tool. It can also create a user interface. To run this experiment automatically, it is programmed to acquire data every sixty-seconds. Some of the functions within the program need to be changed when going from the charge measurements to the voltage measurements, which is described in Appendix C.

In order to determine the effect of temperature upon the magnitude of charge and open-circuit voltage of each of the samples, a water circulator and jacket are used as a temperature controller. This water circulator, which is used as a temperature controller, is used to warm up the internal environment of the Faraday cage as well as to cool it. It can be set to any desired temperature over a specified range for every sample which is tabulated in the manual [3]. The Faraday cup electrodes and values of charge or voltage of liquid or solid dielectrics depend on the thermal conductivity of the air within the shield [4]. For the experiments conducted, once the internal temperature reached the desired temperature, it was allowed to stay constant for some time and then the temperature controller was turned off to allow the internal temperature to return to room temperature. The charge and voltage of the sample was recorded on a computer disk, and after the experiment was completed, the values were copied to Statmost to plot the variation of charge or voltage as a function of temperature and time. Statmost is an integrated statistical analysis and graphics package.

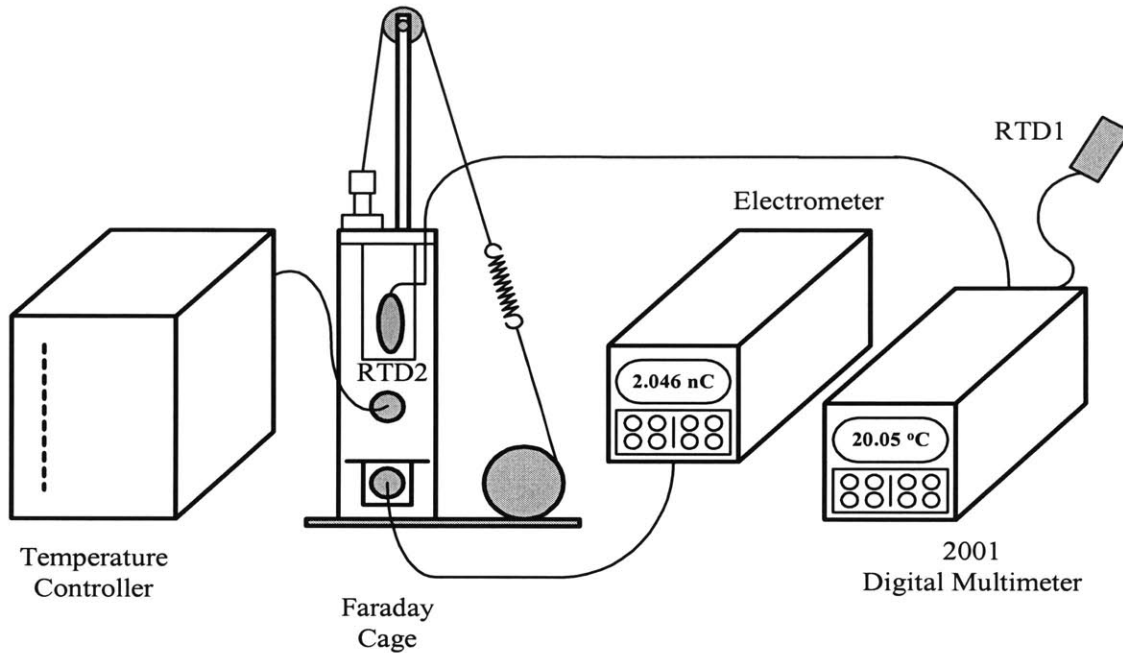


Figure 3.2: A schematic of the equipment along with the Faraday cage used in the liquid and solid dielectric experiments. The Faraday cage contains two aligned hollow cylindrical Faraday cup electrodes. The lower Faraday cup electrode is connected to the electrometer to show charge and voltage values. The 2001 Digital Multimeter is used to display the room temperature and internal temperature of the Faraday cage through RTD1 and RTD2 respectively. The temperature controller is used to warm or cool the internal temperature of the Faraday cage for measurements of the temperature effect on charge and open-circuit voltage measurements.

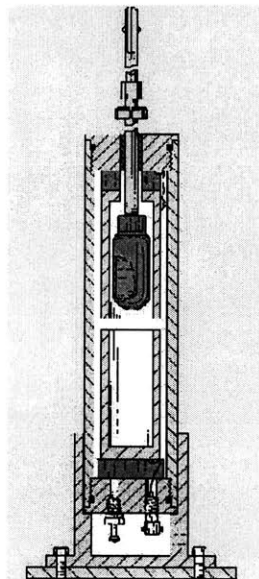


Figure 3.3: A schematic of the internal structure of the Faraday cage where liquid and solid dielectrics were moved between two Faraday cup electrodes [1]. This Faraday cage chamber consists of two Faraday cup electrodes. The upper electrode is permanently grounded, and the lower electrode is virtually grounded through the electrometer. The lower electrode is connected to the electrometer using a triaxial cable.

3.2 Charge Measurements Using Two Faraday Cages

In the MIT High Voltage Research Laboratory (HVRL), we conducted our measurements using the patented Faraday cage where the picture of the experimental method is shown in Figure 3.1 and the internal structure of the Faraday cage is shown in Figure 3.3. A traditional wire mesh style Faraday cage, as shown in Figure 3.4, was obtained from the Electrical Engineering and Computer Science (EECS) Department at MIT for comparing with the charge values of water and solid dielectrics measured by the electrometer using the patented Faraday cage by Peterson as shown in Figure 3.3. To perform our measurements using the EECS Faraday cage, we suspended our tested materials with a thread into the metal screen cage; whereas, with the measurements performed using the Peterson Faraday cage the tested materials were moved between two Faraday electrodes and in a more controlled way as described in Section 3.1. We could determine the effect of temperature upon the magnitude of charge and open-circuit voltage for the tested materials using the Peterson Faraday cage, but the Faraday cage shown in Figure 3.4 is not advanced enough to allow control of temperature. Additionally, the open top of this Faraday cage did not absolutely enclose the tested samples so electrometer measurements fluctuated. The Peterson Faraday cage measured very stable values. Nevertheless, the mesh enclosed Faraday cage allowed an independent verification of the experimental method performed using the Peterson Faraday cage.

Many measurements using the Peterson Faraday cage had been performed at different time periods before the preliminary measurements conducted using the EECS Faraday cage. Average charge measurement values conducted using the Peterson Faraday cage in the laboratory, and charge measurement values conducted using the EECS Faraday cage and different materials are shown in Table 3.1. Measurements conducted using the EECS Faraday cage was performed on December 4th, 2003.

The values can be seen to be different using the two Faraday cages. The values obtained using the EECS Faraday cage cannot be taken as accurate because of the open top. The experimental method using the EECS Faraday cage was much less controlled than the experimental method using the Peterson Faraday cage. Additionally, the values obtained using the Peterson Faraday cage which are listed in Table 3.1 are average

values. Nevertheless, this indicates that the values obtained using the Peterson Faraday cage was not due to any experimental artifacts.

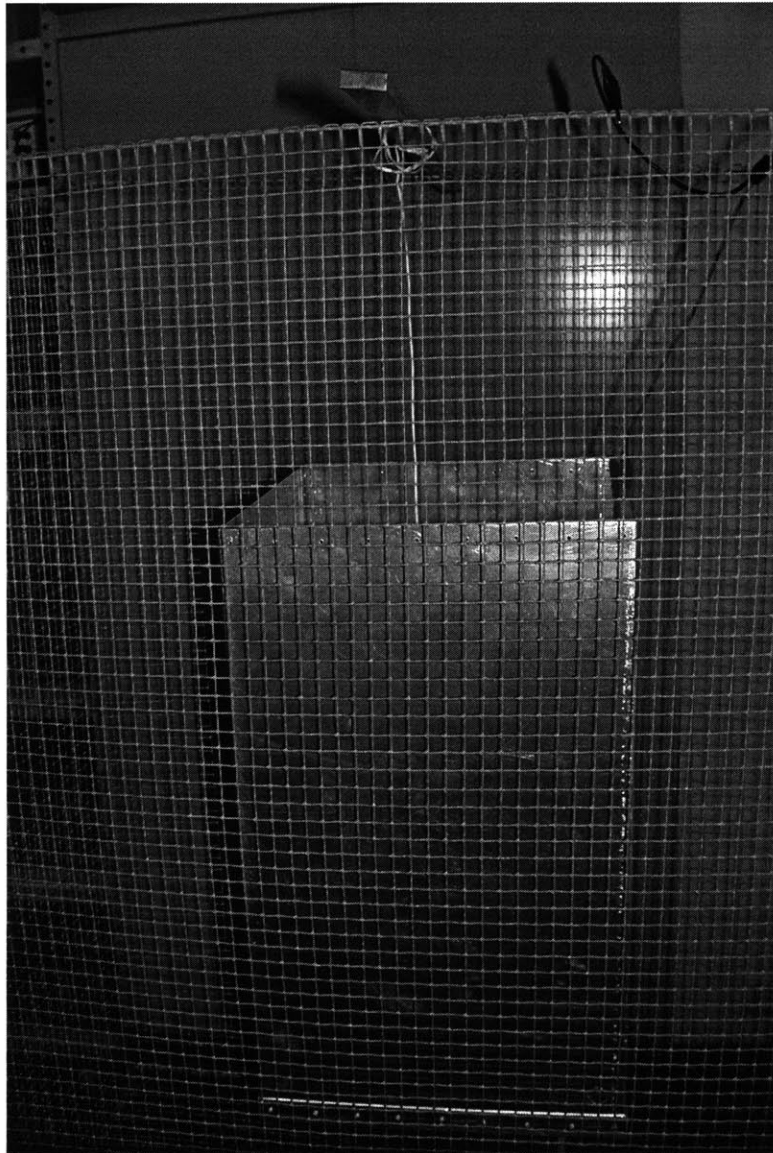


Figure 3.4: A picture of the Faraday cage from the EECS Department at MIT. Tested materials were suspended with a thread into the metal screen cage, and then the values of charge were recorded as shown by the Keithley 617 electrometer.

Table 3.1 Charge (nC) measurements using two different Faraday cages and a 617 electrometer

<i>Faraday cage</i>	<i>Peterson Distilled water</i>	<i>MIT Distilled water</i>	<i>Sargasso Sea water</i>	<i>Tap water</i>	<i>Teflon</i>
Peterson	-1.78	-2.36	-1.17	-4.37	-6.65
EECS	-1.04	-1.20	-0.62	-1.0	-4.0

3.3 Charge Measurements Using Different Electrometers

To ensure the values shown by the 617 electrometer were not false readings due to input offset voltage or other experimental effects, charge measurements were made using different electrometers. Measurements using the Peterson Faraday cage containing Acrylic, Teflon and Peterson Distilled water were performed on December 10, 2003. Measurements using the Peterson Faraday cage containing MIT distilled water, Sargasso Sea water and tap water were performed on December 16, 2003. Two more Keithley 617 electrometers and one Keithley 614 electrometer were used. The charge values are tabulated in Table 3.2 using different electrometers. Within experimental error all electrometers showed essentially similar values.

Table 3.2. Charge (nC) values using different Keithley electrometers

<i>Electrometer</i>	<i>Peterson Distilled water</i>	<i>MIT Distilled water</i>	<i>Sargasso Sea water</i>	<i>MIT Tap water</i>	<i>Teflon</i>	<i>Acrylic</i>
#1 617	-0.39	-4.57	-1.23	-3.23	-6.23	-0.93
#2 617	-0.40	-4.53	-1.25	-3.21	-6.21	-0.93
#3 617	-0.41	-4.45	-1.24	-3.15	-6.10	-0.89
614	-0.39	-4.56	-1.27	-3.21	-6.22	-0.93

3.4 Discussion

The experimental method of charge and voltage measurements used on the liquid and solid dielectrics was described. Measurement of charge was conducted on the tested materials using two different Faraday cages to confirm validity of the results. The totally enclosed Peterson Faraday cage was more reliable than the open top EECS wire mesh style Faraday cage. The tested liquid dielectrics were distilled water, tap water and Sargasso Sea water, and the tested solid materials were Teflon and Acrylic. Additionally, to determine the validity of the values shown by the 617 electrometer that was usually used for the experimental method described in Section 3.1, we performed electrical charge measurements on tested materials using two more 617 electrometers and one 614 electrometer. The charge values measured by the electrometers were essentially identical, indicating that the Peterson Faraday cage and the electrometer that were usually used to

perform charge and voltage measurements of the tested materials provided repeatable and reproducible values.

References

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Chapter 4

Advanced Faraday Cage Measurements

of Charge and Voltage

Using Distilled water, Tap Water, Sargasso Sea Water, and 0.9% Sodium Chloride Solution

4.1 Conductivity Measurements

Conductivity of each of the water samples was measured using a Model 142 Orion conductivity meter by employing Orion 2-electrode conductivity cells [1]. Results are tabulated in Table 4.1.

Table 4.1 Conductivity measurements

Distilled water (mS/cm)	Tap water (mS/cm)	0.9% NaCl solution (mS/cm)	Sargasso Sea water (mS/cm)
.0116@ 22.70°C	0.12 @ 24.7°C	0.992 @ 22.20°C	0.46@ 23.70°C

4.2 Charge Measurements Using Distilled water

The experimental method of measuring charge was described in detail in Chapter 3. Distilled water was contained in a 30cc Polyallomer centrifuge tube inside the Faraday cage. Measurements of charge were conducted using the distilled water provided by Mr. Peterson from Cleveland, Ohio and using the distilled water provided by MIT. The first charge measurement was performed using the distilled water provided by Mr. Peterson in the beginning of February 2003, and the value shown by the electrometer was about -2.0nC. On February 27, 2003 the value of charge was measured again, and the recorded value of the charge as shown by a 617 Keithley electrometer when in the Coulomb mode was -2.04nC. The MIT distilled water was put inside the Faraday cage on August 20, 2003. The initial value was -1.28nC at a room temperature of 35.28°C. The next measurement using the Peterson distilled water was conducted on July 29, 2003. This

time the charge value was about -1.24nC at a room temperature of 33.31°C . It is in reasonable agreement with the value of charge obtained from the MIT distilled water.

4.2.1 Charge Measurements Using Different Metal Grounding Screws

To better understand the source of the charge we measure using the distilled water, we performed an experiment of charge measurement of distilled water using different metal grounding screws. The two metal grounding screws we used were brass and stainless steel. For distilled water, using a brass grounding screw, we obtained a charge value of -1.7nC , and using a stainless steel grounding screw, we obtained a charge value of -2.04nC . The values are similar which means the source of the charge is not significantly dependent upon galvanic action. Each time we introduce any sample to a Faraday cage, we put more charge onto the surface from handling, and this could be attributed to the difference in reading.

4.2.2 Measurement of Charge Using the Peterson Distilled Water

A measurement of the variation of charge with temperature change as a function of time is shown in Figure 4.1. The initial value was -1.21nC at a room temperature of 31.33°C . The temperature controller was set to 60°C . With an increase in temperature, the value of charge also started to increase. For the first 30 minutes, the value of measured charge was slightly increasing and decreasing, but after 30 minutes the value of charge started to exhibit a steady increase with an increasing temperature. It took a little more than four hours for the internal temperature to reach a peak temperature of 59.24°C when the measured charge was about -1.237nC . An increase in the negative charge of the distilled water with temperature increase could possibly be attributed to the disruption of hydrogen bonding [2]. For about 200 minutes, the value of charge was approximately constant with a constant temperature. Then, with a decrease in temperature the value of charge started to decrease. At around 350 minutes into the experiment, the temperature controller was turned off to allow the internal temperature to return to room temperature. At 483 minutes, the experiment was stopped, and so the entire experiment took a little more than eight hours. The final value of the magnitude of charge was about -1.21nC which was about its original room temperature value. We, therefore, conclude that the value of measured charge of distilled water is temperature dependent when contained in a Polyallomer centrifuge tube.

4.2.3 First Measurement of Charge Using the MIT Distilled Water

A measurement of charge was also conducted using the MIT distilled water sample. The initial value of charge was about -1.28nC at a room temperature of 35.28°C . This value was close to the value shown by the 617 electrometer using the Peterson distilled water as described in Section 4.2.2.

A measurement of the variation of charge with temperature is shown in Figure 4.2. Here, the initial value was -1.27nC at a room temperature of 33.49°C . The temperature controller was set to 65°C . From the graph, we note that at the beginning for a short period of time, the value of charge did not exhibit any temperature dependence. Then it started to increase with an increase in temperature. It took about four hours for the internal temperature to reach a peak temperature of 65.28°C when the charge value was about -1.35nC . Similar to the measurement performed using the Peterson distilled water shown in Figure 4.1, in the measurement shown in Figure 4.2 the change in the value of charge with variation in temperature was also essentially linear with time. The Peterson distilled water's charge behavior was, however, more steady with temperature change as a function of time. The temperature controller was turned off at 298 minutes into the experiment. It seems that in this measurement, even with an essentially constant temperature, the value of charge did not remain constant; whereas, in the measurement described in Section 4.2.2 when the temperature was constant the charge remained essentially constant. We note that from about 160 minutes until about 310 minutes the temperature was essentially constant, but the charge was not constant during this time period. If the temperature, however, was allowed to remain constant for a longer period, perhaps the charge would be constant in value as well. This is due in part to the time taken by the Faraday electrode to warm up. The temperature controller was kept "on" for about 300 minutes, after which it was turned off to allow the internal temperature to reach room temperature. With a decrease in temperature, the value of charge also began to decrease to its room temperature value. The experiment was stopped at 509 minutes where the internal temperature was 32.43°C , and the value of charge as recorded from the 617 electrometer was about -1.28nC . The entire experiment was allowed to run for about 8.5 hours.

Similar to the measurement described in Section 4.2.2 and shown in Figure 4.1, this measurement showed that with an increase in temperature the value of charge of distilled water also increased and with a decrease in temperature the value of charge decreased, but unlike the measurement in Figure 4.1, this measurement in Figure 4.2 did not show a constant value of charge even with an essentially constant temperature. Perhaps, if we allowed the temperature to stay constant for a longer time period, then we would see the charge value to be approximately constant as a function of time.

4.2.4 *Second Measurement of Charge Using the MIT Distilled Water*

Another measurement of charge using the MIT distilled water with temperature change as a function of time is shown in Figure 4.3. Here, the temperature was increased in steps. The initial charge value was about -2.04nC at an internal temperature of 24.89°C . Initially, the temperature controller was set to 50°C . An increase in temperature to 50°C caused the charge value to become more negative by about 0.2nC . Rhythmic changes are electrical noise. The temperature was constant from about 62 minutes to about 137 minutes. The measured charge value at 62 minutes was about -2.21nC at an internal temperature of 49.01°C . The measured charge value at 137 minutes was about -2.24nC . After 137 minutes, the temperature controller was set to 65°C . Increasing the temperature from 50°C to 65°C caused the measured charge of distilled water contained in the Polyallomer centrifuge tube to be more negative. The temperature was constant again from about 250 minutes to about 308 minutes. At 250 minutes, the measured charge value was -2.25nC at an internal temperature of 64.0°C , and at 308 minutes the measured charge value was -2.27nC at an internal temperature of 64.11°C . So, increasing the temperature to about 65°C from 24.89°C caused the measured charge to be more negative by about 0.23nC . After 308 minutes, the temperature controller was turned off to permit the internal temperature to return to room temperature value. With decreasing temperature, the charge value also decreased in magnitude with time. The charge tended to return back to the original charge value. This measurement confirmed the dependence of the measured charge of distilled water contained in the centrifuge tube to be temperature dependent.

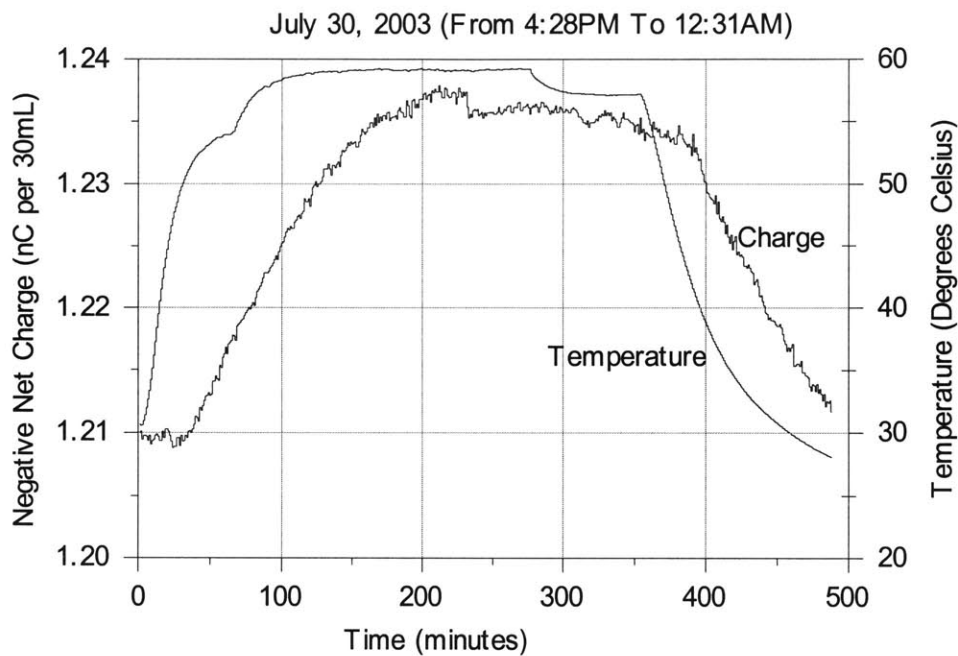


Figure 4.1: Measurement of negative charge after Peterson distilled water in a Polyallomer centrifuge tube came to rest within the upper Faraday cup electrode as temperature was being changed.

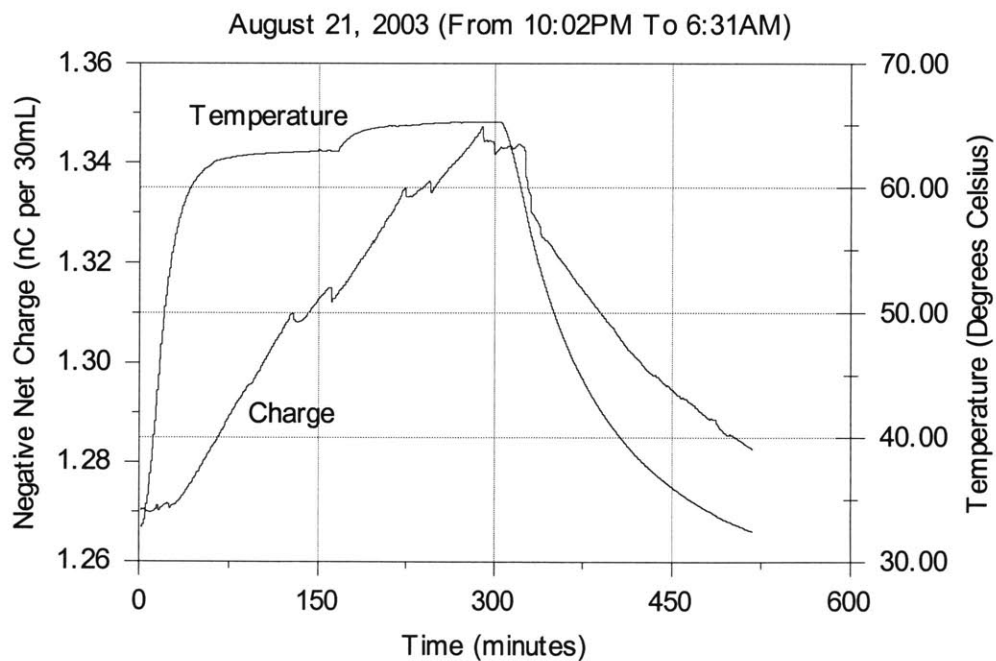


Figure 4.2: Measurement of negative charge after MIT distilled water contained in a 30mL Polyallomer centrifuge tube came to rest within the upper Faraday electrode as temperature was being changed.

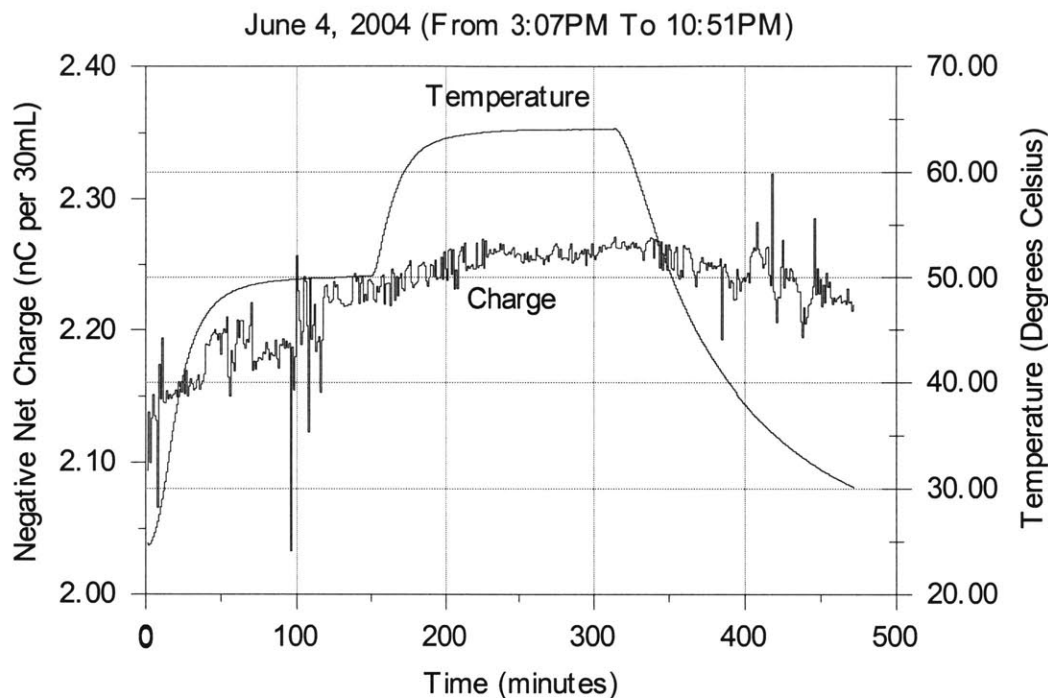


Figure 4.3: Measurement of negative charge after MIT distilled water contained in a 30mL Polyallomer centrifuge tube came to rest within the upper Faraday electrode as temperature was being changed.

4.3 Open-Circuit Voltage Measurements Using Distilled Water

The electric potential difference with an open-circuited Faraday cage electrode was measured after the distilled water came to rest within the upper Faraday electrode. The experimental method was described in Chapter 3. As the sample moved from the lower electrode to the upper electrode, the value of the voltage changed with position; when the sample reached the upper permanently grounded electrode, the voltage was recorded. The value was recorded from the Keithley 617 electrometer while operating in the Voltage mode. In the month of February, 2003, when the Peterson distilled water was initially put inside the chamber, the initial value of the voltage was about -13.57V, and the charge value was about -2.10nC. The distilled water was put inside the chamber again on July 29, 2003. This time the initial value of the voltage was a little above -8.2V at room temperature, and the charge value was about -1.21nC. Further measurements were taken on the measured voltage of distilled water with temperature change as a function of time.

A measurement of the variation of voltage with temperature change as a function of time is shown in Figure 4.4. The temperature controller was set to 60°C. The initial voltage was about -8.21V at a temperature of 26.17°C. The behavior of the voltage variation is similar to the charge variation which is shown in Figure 4.1. We note that, an increase in temperature caused the voltage to increase in magnitude; when the temperature was essentially constant the voltage was also essentially constant, and with the decrease in temperature the voltage also decreased. It took about four hours for the internal temperature to reach 60°C. The peak temperature was 60.26°C when the measured voltage was about -8.47V. The temperature was constant from about 225 minutes until about 375 minutes during which the voltage was also essentially constant. After about six hours into the experiment, the temperature controller was turned off to allow the internal temperature to reach room temperature. Here, from 380 minutes to 409 minutes, no data was acquired which is denoted as a solid line in the temperature curve. This experiment was stopped after 9 hours when the internal temperature reached a value of 28.62°C where the voltage was -8.29V which was about its original room temperature value. One major difference that can be noted between this measurement and the charge measurement shown in Figure 4.1 is that from the very beginning the voltage increased with increasing internal temperature; charge value did also increase with temperature except for the first 30 minutes. Nevertheless, this measurement demonstrates that the voltage is also a function of temperature.

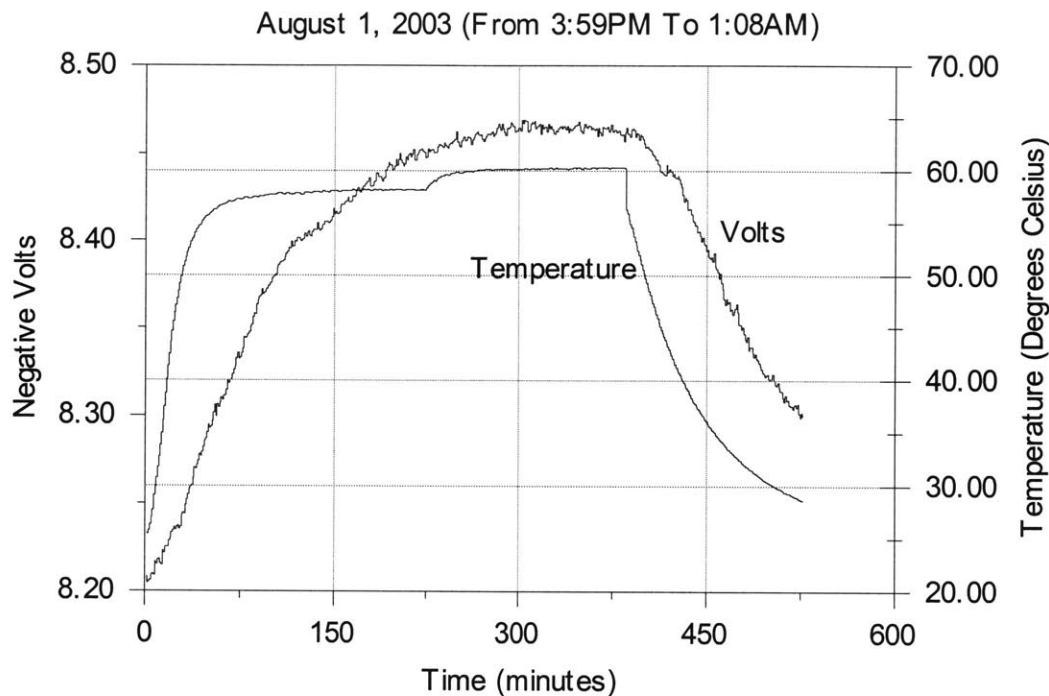


Figure 4.4: Measurement of open-circuit voltage after the negatively charged Peterson Distilled water came to rest within the upper Faraday cup electrode as temperature was being changed.

4.4 Measurements and Calculations of Capacitance Using Distilled Water

4.4.1 *Measurements of Capacitance Using Distilled Water*

Capacitance of the Faraday cage was measured with and without any sample inside using a Model Andeen-Hagerling (AH) 2500 capacitance bridge. Measurements of capacitance were measured using a stainless steel grounding screw and also without a grounding screw. Results are tabulated in Table 4.2. Capacitance of the Faraday cage alone (without any water sample) was measured to be 129.93pF. When the grounding metal screw was used to hold the sample, measured capacitance with the sample at the lower Faraday electrode was larger than the measured capacitance when at the upper Faraday electrode. Using no grounding metal screw, capacitance slightly decreased after the sample came to rest within the upper Faraday electrode.

Table 4.2. Capacitance (pF) measurements of distilled water using a metal grounding screw and using no screw

<i>Screw used</i>	<i>Position</i>	<i>Capacitance(pF)</i>
Stainless steel	Lower electrode	144.04
Stainless steel	Upper electrode	129.76
None	Lower electrode	130.54
None	Upper electrode	129.77

4.4.2 Calculations of Capacitance Using Distilled Water

Capacitance, C , is related to charge, Q , and voltage, V , as:

$$Q = CV \quad (1)$$

From Figure 4.1, the initial charge value was -1.21nC at a temperature of 31.33°C. From Figure 4.4, the voltage value was about -8.25V at around the same temperature. Using (1), we calculate the capacitance to be 146.66pF. At a temperature of about 60°C, the charge value was about -1.237nC and the voltage value was about -8.47V. Again, using (1) we calculate the capacitance to be 146.04pF. Between the peak temperature and the initial temperature, the calculated capacitance was within 1%.

4.5 Arrhenius Activation Energy

Activation energy can be calculated from the following equation:

$$q = q_0 \exp(-E / kT) \quad (2)$$

where E denotes the activation energy; k denotes the Boltzmann constant with value 1.38×10^{-23} J/k and T denotes the internal temperature in the kelvin scale. We can calculate the activation energy between the initial charge value and the highest charge value reached by increasing the internal temperature of the chamber. From the charge measurement conducted using the Peterson distilled water as a function of temperature with respect to time shown in Figure 4.1, we can calculate the activation energy. Equation (2) can be expressed as:

$$\ln(q) = \ln(q_0) - \frac{E}{kT} \quad (3)$$

The initial charge value recorded was -1.21nC at 303.82K (30.67°C); the highest charge value recorded was -1.237nC at 332.20K (59.05°C).

Substituting for the initial charge value and highest charge value with corresponding temperature value into (3) we have,

$$\ln(1.21 \times 10^{-9}) = \ln(q_o) - \frac{E}{(1.38 \times 10^{-23})(303.82)} \quad (4)$$

and

$$\ln(1.237 \times 10^{-9}) = \ln(q_o) - \frac{E}{(1.38 \times 10^{-23})(332.20)} \quad (5)$$

Now, we can solve for q_o and E . Substituting (4) into (5) for $\ln(q_o)$ we have,

$$\ln(1.21 \times 10^{-9}) + \frac{E}{(1.38 \times 10^{-23})(303.82)} = \ln(1.237 \times 10^{-9}) + \frac{E}{(1.38 \times 10^{-23})(332.20)} \quad (6)$$

From (6) we solve for E , the activation energy, to be 1.08×10^{-21} J or 0.067eV. This is the activation energy obtained between the initial charge value and the highest charge value recorded. Substituting (6) into either (4) or (5) we solve for q_o to be 1.565nC where the polarity is negative.

4.6 Charge Measurements Using MIT Tap Water

Charge was measured using tap water from MIT's HVRL. Tap water placed inside the Faraday cage chamber was contained in a 30cc Polyallomer centrifuge tube. The first measurement of tap water charge was performed on 5th August, 2003 and the initial recorded value was -5.14nC as given by the 617 electrometer while operating in the Coulomb mode. The ambient temperature was 28.49°C, as displayed by the 2001 Digital Multimeter. The sample was allowed to stay inside the chamber for about a day to let the initial charge decay to an equilibrium value of about -4.75nC to about -4.80nC. Further measurements were taken on the charge of tap water as a function of temperature.

4.6.1 First Measurement of Charge Using Tap Water

To note the effect of temperature upon the magnitude of tap water electrical charge, the same temperature controller was used as for the distilled water experiment. The temperature controller was set to 65°C. A variation of the charge with temperature change as a function of time is shown in Figure 4.5. The initial value of charge was about

-4.76nC at an internal temperature of 29.66°C. The curve is similar in shape to the curve obtained for the measurement performed using the Peterson distilled water as shown in Figure 4.1. With an increase in temperature, the charge magnitude also increased smoothly with time. It took a little more than three hours for the internal temperature to reach a peak temperature of 64.16°C where the charge value was -4.94nC. From about 100 minutes to 230 minutes, the value of temperature was constant, and with the temperature constant the charge was also essentially constant. After the internal temperature reached 64.1°C, the temperature controller was turned off to allow the internal temperature to decrease to room temperature. With a decrease in temperature the value of charge also decreased. After the temperature reached about 35°C, the value of charge was -4.81nC which was about the original room temperature value. So we conclude that the measured charge value of tap water in a Polyallomer centrifuge tube is temperature dependent.

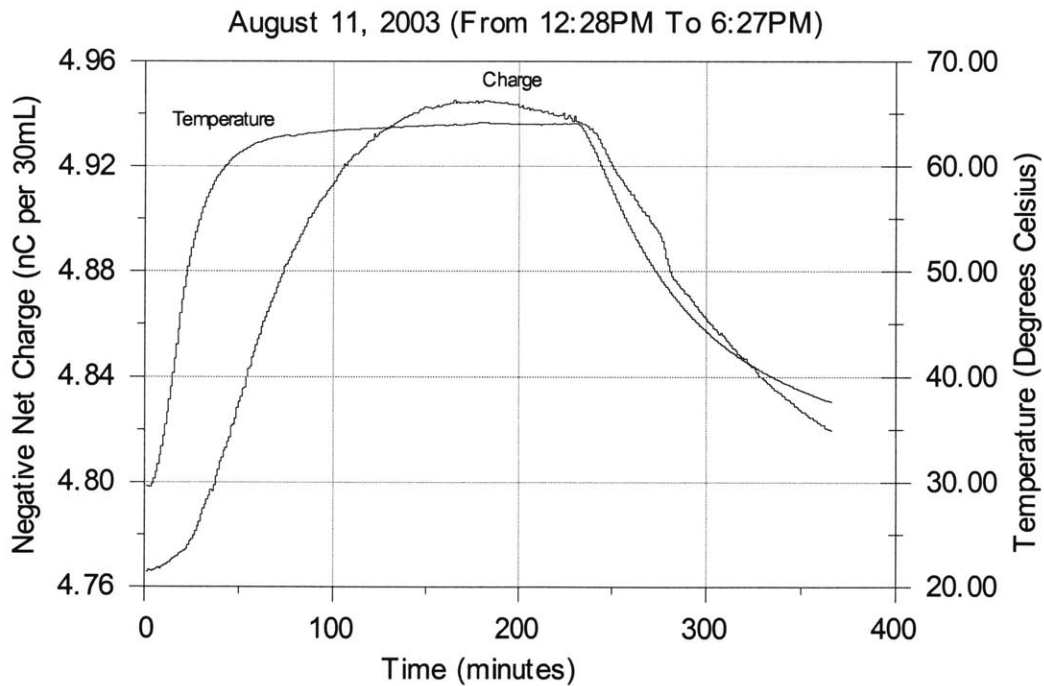


Figure 4.5: First measurement of negative charge flow after Tap water came to rest within the upper Faraday cup electrode as temperature was being changed.

4.6.2 *Second Measurement of Charge Using Tap Water*

The measurement of tap water charge shown in Figure 4.5, taken on August 21, 2003, shows that the measured charge was temperature dependent. Another measurement that was taken where the variation of the charge with temperature change as a function of time is shown in Figure 4.6. The initial charge value was -4.75nC at an internal temperature of 32.97°C , and an ambient relative humidity of 42%. In this measurement, however, the increase in charge was occurring at a slower rate than the measurement shown in Figure 4.5. It took about four hours for the internal temperature to reach the temperature controller set point at 70°C . From Figure 4.6, it is noted that the charge increased with time with an increase in temperature. From about 97 minutes to 197 minutes, the charge was essentially constant with a constant temperature. After about 210 minutes the temperature controller was turned off, with charge value of -4.79nC . In the measurement shown in Figure 4.5, around this temperature, the value of charge was a little more negative than -4.9nC . Suddenly, in this measurement shown in Figure 4.6 at 227 minutes, the charge value jumped to a value of about -4.93nC at a temperature of 60.77°C . The temperature controller was again turned on for fifteen minutes and was set at 65.0°C , but during that period the charge value did not show any noticeable increase. The value of charge then decreased smoothly with time as the internal temperature decreased. The experiment was allowed to continue until the internal temperature decreased to a temperature of 35.09°C , and the value of the charge at this temperature was -4.78nC which was about its original room temperature value. So, even though the shape of the curve here is different from the measurement shown in Figure 4.5, we note that with an increase in internal temperature of the chamber the value of measured charge became more negative and with lowering the internal temperature the value of measured charge decreased in magnitude.

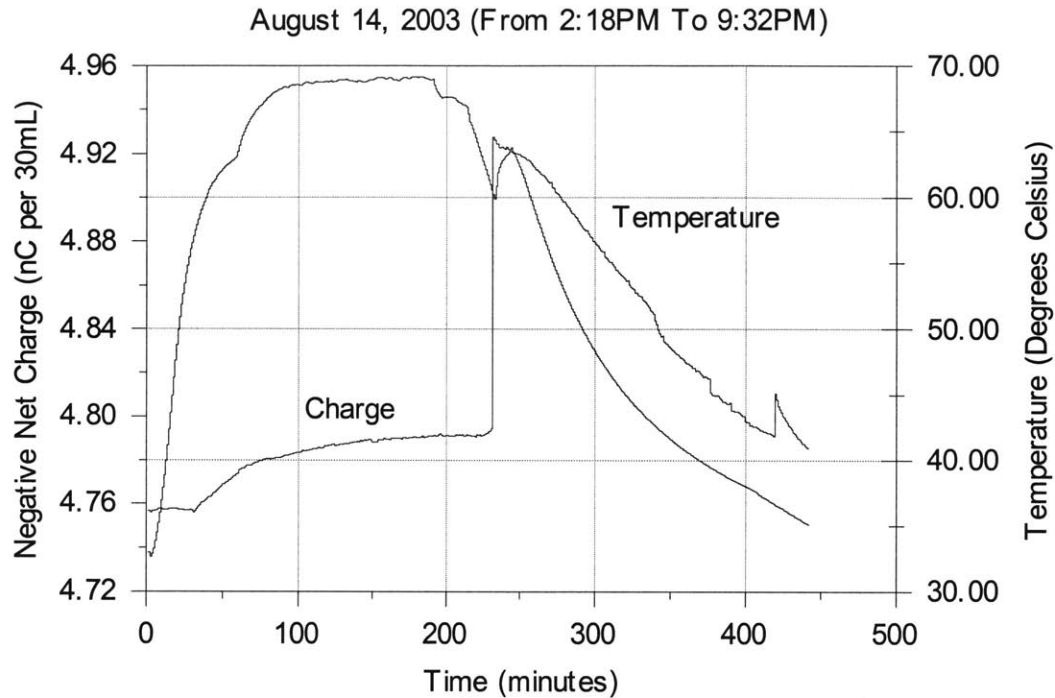


Figure 4.6: Second measurement of negative charge after the MIT Tap water came to rest within the upper Faraday cup electrode as temperature was being changed.

4.6.3 Third Measurement of Charge Using Tap Water

Measurements shown in Figure 4.5 and in Figure 4.6 demonstrate that the measured charge of tap water is temperature dependent though the first measurement shows a more smooth temperature dependence. A third measurement of charge was taken using the same tap water as shown in Figure 4.7. The initial charge value was about -4.77nC at an internal temperature of 32.80°C and at an ambient relative humidity of 57%. The temperature controller was set to 65.0°C . The smooth curve shown in Figure 4.7 is similar to the first measurement curve shown in Figure 4.5. With an increase in temperature, the value of measured charge increased in magnitude with time. It took three hours and thirty-seven minutes for the internal temperature to reach a peak temperature of 64.79°C where the measured charge value was -4.88nC . From about 100 minutes to 273 minutes, the temperature was essentially constant. It appears that the measured charge was constant from 200 minutes to 273 minutes. The highest value of charge reached was about -4.89nC when the internal temperature was 64.73°C . At 273 minutes, the temperature controller was turned off to allow the internal temperature to return back to

the room temperature value. With a decrease in temperature, the value of charge also decreased. The Testpoint program stopped acquiring data from 334 minutes until 352 minutes; thus, no data was recorded during that time period, which is marked by a solid line in the charge curve. The charge value recorded at 334 minutes was about -4.85nC at a temperature value of 44.70°C , and the charge value recorded at 352 minutes was about -4.78nC at a temperature value of 41.54°C . Between 353 minutes and 361 minutes, the temperature was decreasing, but the measured charge value was exhibiting an increase. At 353 minutes, the temperature was 41.38°C , and the charge value was about -4.79nC ; at 361 minutes, the temperature was 40.24°C , and the charge value was -4.81nC . Then, the charge value started to decrease, but again at 368 minutes the value of charge jumped to -4.83nC at a temperature of 39.32°C . After this, the value of charge began to decrease with time with a decrease in temperature. At 413 minutes of the experiment, there was a little jump which appears to be electrical noise. After that jump, the value of charge began to decrease smoothly with time as temperature was decreased. The experiment was allowed to run for 453 minutes. Because no data were recorded from 334 minutes to 352 minutes, the actual running time of the experiment was less than 453 minutes. After the temperature reached 32.61°C , the value of measured charge was -4.76nC which was about the original room temperature value. From this measurement, we conclude that the measured charge of tap water contained in a Polyallomer centrifuge tube in the Faraday cage is temperature dependent.

4.6.4 Charge Measurements Using Different Metal Grounding Screws

For tap water, using a brass grounding screw, we obtained a charge value of -3.6nC , and using a stainless steel grounding screw, we obtained a charge value of -3.9nC . The values are similar indicating that the source of the charge may not be significantly dependent upon galvanic action. Such a slight variation in the charge value could be due to handling.

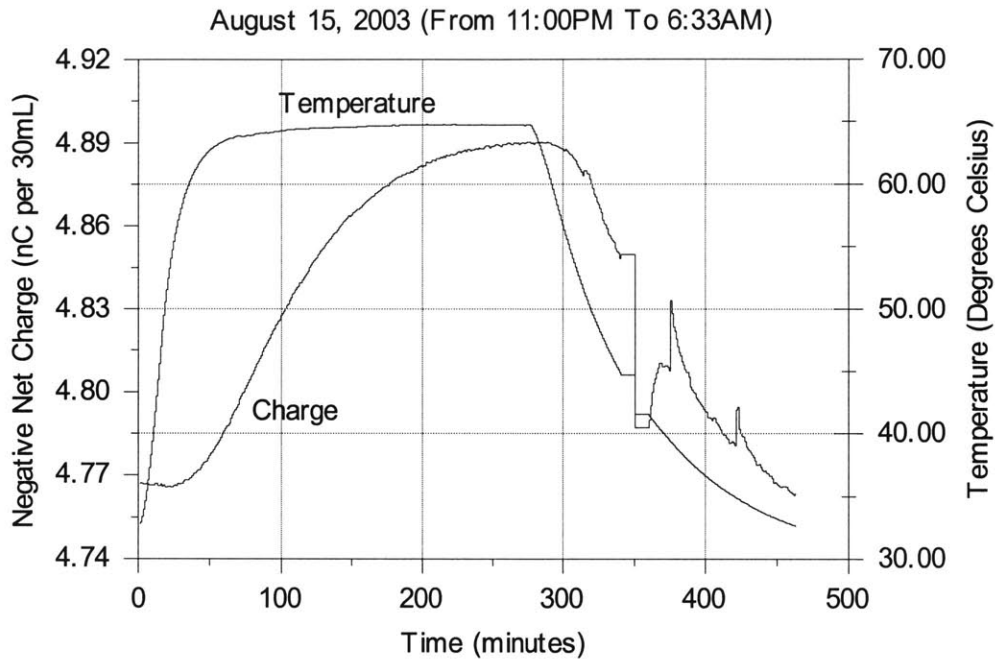


Figure 4.7: Third measurement of negative charge flow after MIT Tap water came to rest within the upper Faraday cup electrode when temperature was being changed.

4.7 Open-Circuit Voltage Measurements Using Tap Water

The electric potential difference using tap water with an open-circuited Faraday cage electrode was also measured after it came to rest within the upper Faraday cup electrode. The variation of the voltage with change in temperature was recorded and both are plotted with respect to time. The value was recorded from the 617 electrometer while operating in the Voltage mode. The tap water was put inside the chamber on 5th August, 2003 and was allowed to reach an equilibrium value of -32.50V.

4.7.1 First Measurement of Open-Circuit Voltage Using Tap Water

A measurement of the variation of voltage with temperature change as a function of time is shown in Figure 4.8. The initial voltage value was -32.70V at a temperature of 32.05°C. The ambient relative humidity was 53%. It took about four hours for the internal temperature to reach the temperature controller set point at 70°C. The value of the voltage increased negatively with an increase in temperature. From about 120 minutes until 240 minutes, with an approximately constant temperature the value of voltage was essentially constant. The temperature controller was turned off at about 249 minutes

where the value of voltage was -32.85V . For the next 24 minutes, the value of voltage did not change significantly, but then suddenly it jumped to a value of -33.69V at a temperature of 59.36°C . The erratic voltage behavior is essentially similar to the charge behavior shown in Figure 4.6. Such an anomalous large increase in the voltage value is unknown. Then again with a decrease in the temperature the value of the voltage also began to decrease smoothly. The internal temperature was allowed to reach a temperature of 38.67°C ; at this temperature the measured value of the voltage was about -32.95V which was about its original room temperature value. The experiment was allowed to run for 366 minutes. The vertical line just after 350 minutes appears to be electrical noise.

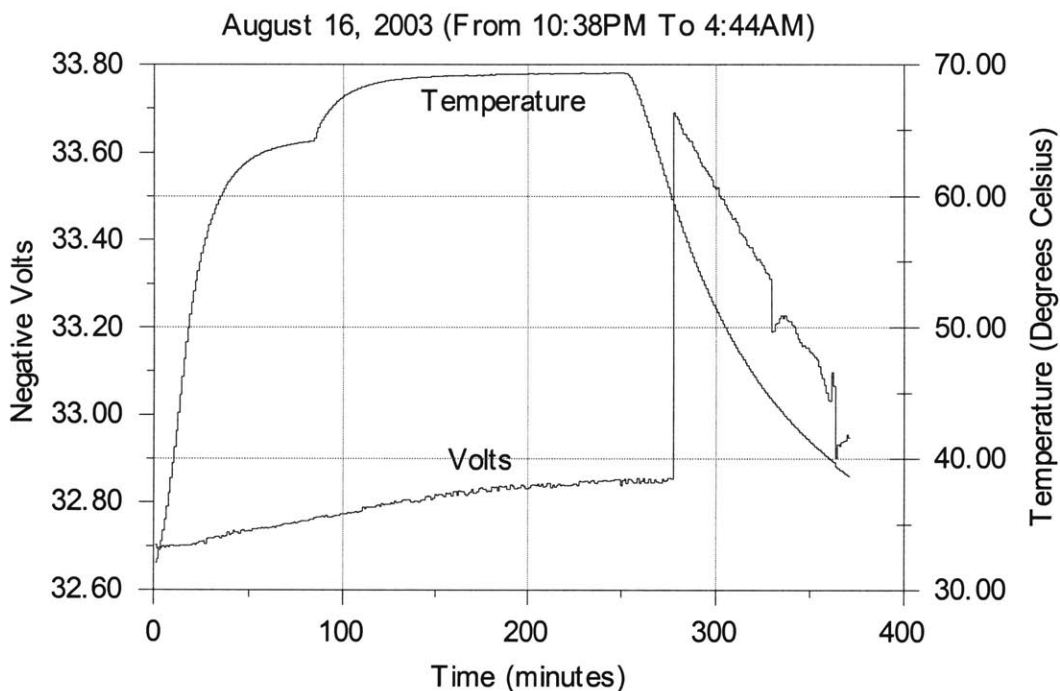


Figure 4.8: First measurement of voltage after negatively charged Tap water in a Polyallomer centrifuge tube came to rest within the upper Faraday cup electrode as temperature was being changed.

4.7.2 Second Measurement of Open-Circuit Voltage Using Tap Water

A second measurement of open-circuit voltage with temperature change as a function of time is shown in Figure 4.9. As in the previous experiments, this experiment also continuously recorded the voltage value using the Testpoint program. Here, the initial value was -49.07V at a temperature of 22.25°C . The tap water had been put in the chamber on March 23rd, 2004 to allow time for the voltage and charge to decay to their

equilibrium values. The temperature controller was set to 60°C. This time, it took less than three hours for the internal temperature to reach a peak temperature of 63.68°C where the value of voltage was -50.41V. The measured voltage values are higher than the voltage values in Figure 4.8. With an increase in temperature, the value of voltage also increased in magnitude with time. From about 150 minutes to about 240 minutes into the experiment, with an approximately constant temperature the value of voltage was also essentially constant with time. The highest value of voltage reached was -50.95V. The temperature controller was turned off at about 235 minutes to allow the internal temperature to slowly return to room temperature. With a decrease in temperature, the value of voltage also decreased in magnitude smoothly with time. Noisy data with large step changes were removed. The experiment was stopped when the internal temperature was 26.0°C and the value of measured voltage was -49.38V. The value of measured voltage almost decreased to the original room temperature value.

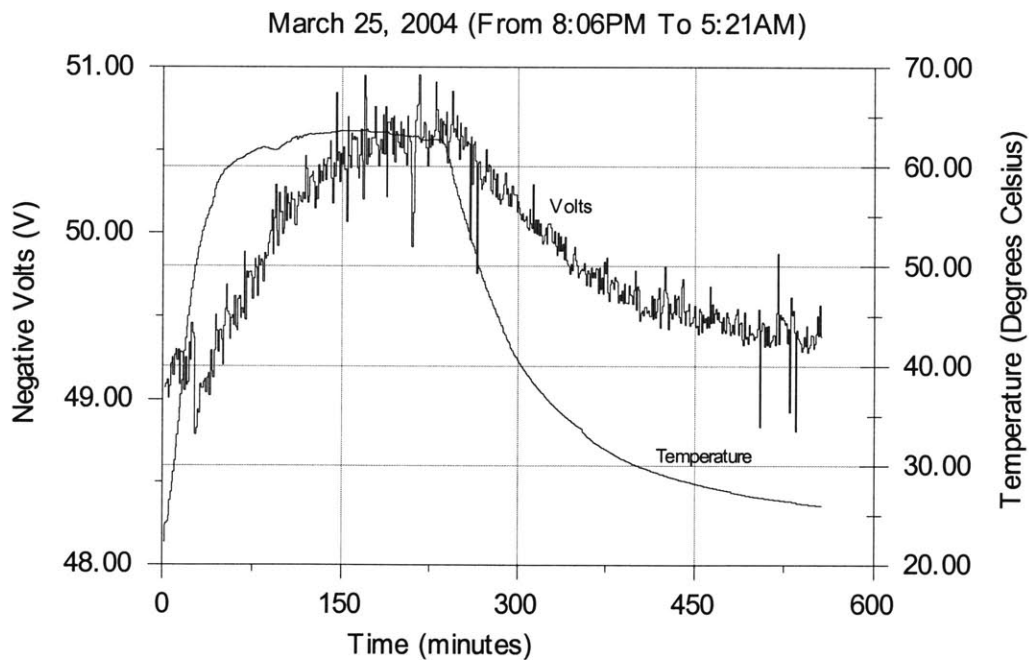


Figure 4.9: Second measurement of open-circuit voltage after the tap water in 30mL Polyallomer centrifuge tube came to rest within the upper Faraday electrode as temperature was being changed.

4.8 Measurements and Calculations of Capacitance Using the Tap Water

4.8.1 Measurements of Capacitance Using Tap Water

Capacitance of the Faraday cage with tap water in a 30mL Polyallomer centrifuge tube was measured using Model AH 2500 capacitance bridge. It was measured using both brass and stainless screws and the values are comparable. Capacitance was also measured without using any metal screw. The values are tabulated in Table 4.3. It was measured at the lower Faraday electrode and at the upper Faraday electrode. The values are similar to the capacitance values in Table 4.2 with distilled water inside the Faraday cage.

Table 4.3 Capacitance (pF) measurements of tap water using stainless steel and brass grounding screws and without using a metal grounding screw

<i>Screw</i>	<i>Position</i>	<i>Capacitance(pF)</i>
Brass	Lower electrode	144.32
Brass	Upper electrode	129.92
Stainless steel	Lower electrode	144.26
Stainless steel	Upper electrode	129.96
None	Lower electrode	130.99
None	Upper electrode	129.93

4.8.2 Calculations of Capacitance Using Tap Water

Here, we shall calculate capacitance from the charge measurement in Figure 4.5, and the voltage measurement in Figure 4.8. These two measurements were performed at the same time period. At an initial temperature of 32.05°C, the measured voltage was about -32.70V. At around this same temperature, from Figure 4.5, we find the charge value to be about -4.76nC. We calculate the capacitance to be 145.56pF using Equation (1). At the peak temperature of about 64°C, the measured value of voltage was about -32.76V, and the charge value was -4.94nC. Again, using (1) we calculate the capacitance to be 150.97pF. Between the peak temperature capacitance value and the initial temperature capacitance value, the capacitance increased by about 5.41pF.

4.9 Arrhenius Activation Energy

The initial charge value recorded was -4.76nC at 302.81K (29.66°C); the highest charge value recorded was -4.94nC at 337.12K (63.97°C).

Substituting for the initial charge value and highest charge value with corresponding temperature value into (3) we have,

$$\ln(4.76 \times 10^{-9}) = \ln(q_o) - \frac{E}{(1.38 \times 10^{-23})(302.81)} \quad (7)$$

and

$$\ln(4.94 \times 10^{-9}) = \ln(q_o) - \frac{E}{(1.38 \times 10^{-23})(337.12)} \quad (8)$$

Now, we can solve for q_o and E . Substituting (7) into (8) for $\ln(q_o)$ we have,

$$\ln(4.76 \times 10^{-9}) + \frac{E}{(1.38 \times 10^{-23})(302.81)} = \ln(4.94 \times 10^{-9}) + \frac{E}{(1.38 \times 10^{-23})(337.12)} \quad (9)$$

From (9) we solve for E , the activation energy, to be 1.516×10^{-21} J or 0.00946eV. This is the activation energy obtained between the initial charge value and the highest charge value recorded. Substituting (9) into either (7) or (8) we solve for q_o to be 6.849nC, and the polarity is negative.

4.10 Charge Measurements Using Sargasso Sea Water

Faraday cage measurements of the electrical charge of Sargasso Sea water near Bermuda were conducted at MIT's HVRL. The sea water was contained in a 30mL Polyallomer centrifuge tube. The first measurement of charge of sea water was performed on 4th April, 2003, and the initial recorded value of charge was about -2.10nC as given by the 617 electrometer while operating in the Coulomb mode. Of course, the sign shown by the 617 electrometer was positive after the sample came to rest within the upper Faraday electrode indicating the presence of negative charge. To provide a representative set of measurements, data will be presented of the measured charge of sea water with temperature change as a function of time.

4.10.1 First Measurement of Charge Using Sargasso Sea Water

The Sargasso Sea water was subjected to a high temperature of about 60°C in order to note the effects of temperature upon the value of charge of sea water. The

temperature controller was set at a value of 55°C. First measurement of charge using the sea water as a function of temperature is shown in Figure 4.10. The initial value of charge was about -2.03nC, where the internal temperature was 26.93°C. Compared to the distilled water and the tap water charge measurements as described in Sections 4.2 and 4.6 respectively, the measured charge of sea water exhibited a less significant change with temperature change. In some intervals, the charge value increased negatively with an increase in temperature, and in some intervals with an increase in temperature the charge value slightly decreased. The rate of charge increase with temperature increase was lower in the 25°C to 35°C interval. From start to the 200 minutes of the experiment, the measured charge did show a small increase with temperature increase. The time taken for the internal temperature to reach a peak temperature of 53.89°C was six hours where the measured charge value was about -2.09nC. The temperature was essentially constant from about 97 minutes where the temperature was 48.99°C and the measured charge value was -2.07nC until 302 minutes where the temperature value was 49.38°C and the measured charge value was about -2.08nC. During this constant temperature, the charge value was also essentially constant but noisy. After the internal temperature reached a temperature of 49.38°C, there was a jump in temperature. After the temperature reached 53.89°C, the temperature controller was turned off to allow the internal temperature to reduce to room temperature. With this decrease in temperature, the charge value started decreasing but not in a smooth way. The highest value of charge reached was about -2.12nC when the temperature was 49.39°C. So, the charge value increased in magnitude by 0.090nC from the initial charge value. The experiment was stopped after 771 minutes. Many data were removed since they were very noisy, and still there is significant noise. After the temperature reduced to 21.93°C, the value of measured charge was -2.01nC which was about the original room temperature value.

The measured charge value of sea water did not exhibit a smooth relationship with time and temperature change that distilled water and tap water exhibited. The change in the value of charge was small with temperature change. Even though the charge value changed with temperature change, the values of the measured charge did not change smoothly. Noise could be due to electrode chemical surface activity.

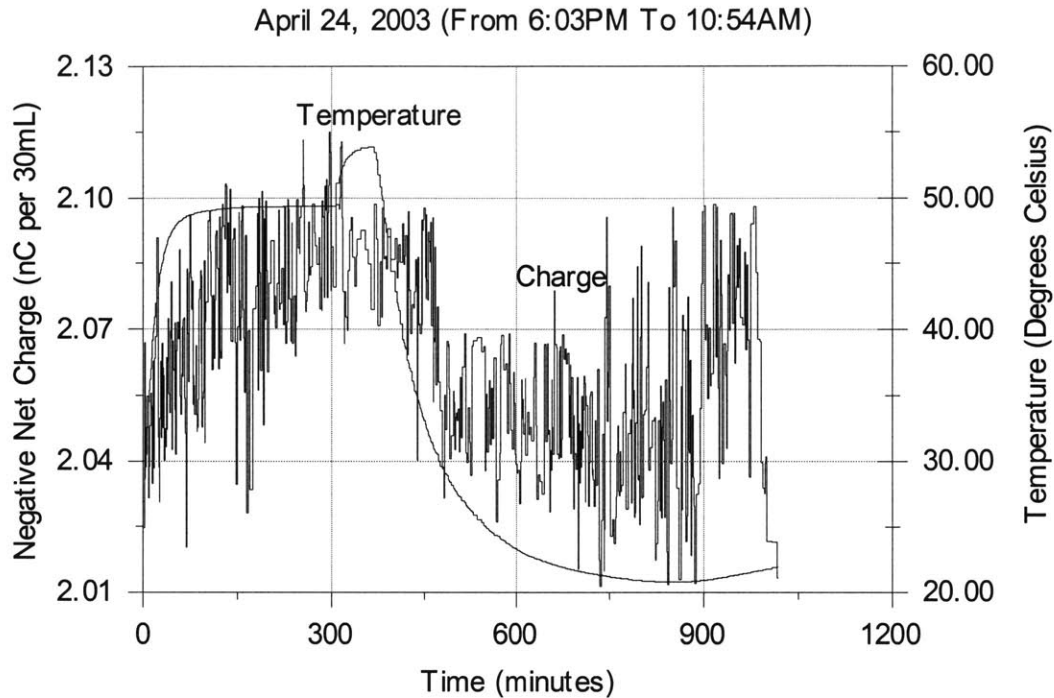


Figure 4.10: First measurement of negative charge after the Sargasso Sea water in 30mL Polyallomer centrifuge tube came to rest within the upper Faraday electrode as temperature was being changed.

4.10.2 Second Measurement of Charge Using Sargasso Sea Water

The first measurement of charge as described in Section 4.10.1 and as shown in Figure 4.10 using the Sargasso Sea water did not show a significant dependence upon temperature. On 5th May, 2003, the sea water sample was taken out of the Faraday cage chamber and was then put back into the chamber immediately. A new value of charge was measured by the 617 electrometer to be about -1.05nC. Figure 4.11 shows the second measurement of charge with temperature variation as a function of time. In this measurement, the measured charge of sea water was initially -1.05nC at a temperature of 21.17°C. The temperature controller was set to 60°C. Like the first measurement shown in Figure 4.10, this second measurement of charge in Figure 4.11 also shows small change in the charge value with temperature change. It took about five hours and forty-six minutes for the internal temperature to reach a peak temperature of 59.0°C where the measured charge value was about -1.08nC. With temperature increase, the charge also increased but not smoothly with time. The increase in the value of charge was smaller than the increase in the value of charge for distilled water or tap water. From 179 minutes

until 346 minutes, the value of temperature was essentially constant and so was the value of charge. The charge value remained constant at around -1.08nC at a temperature of about 59°C . After 346 minutes of the experiment, the temperature controller was turned off to allow the internal temperature to decrease to room temperature. With a decrease in the temperature, the value of measured charge also decreased but not in a smooth way with time. The highest value of charge reached was about -1.09nC when the temperature was 55.12°C . The experiment was allowed to run for 574 minutes. Many data points were deleted since they were noisy. The final charge value recorded was about -1.06nC at a temperature of 26.22°C . The value of charge essentially returned to the original room temperature value. The measured charge value of sea water is not significantly dependent upon the temperature.

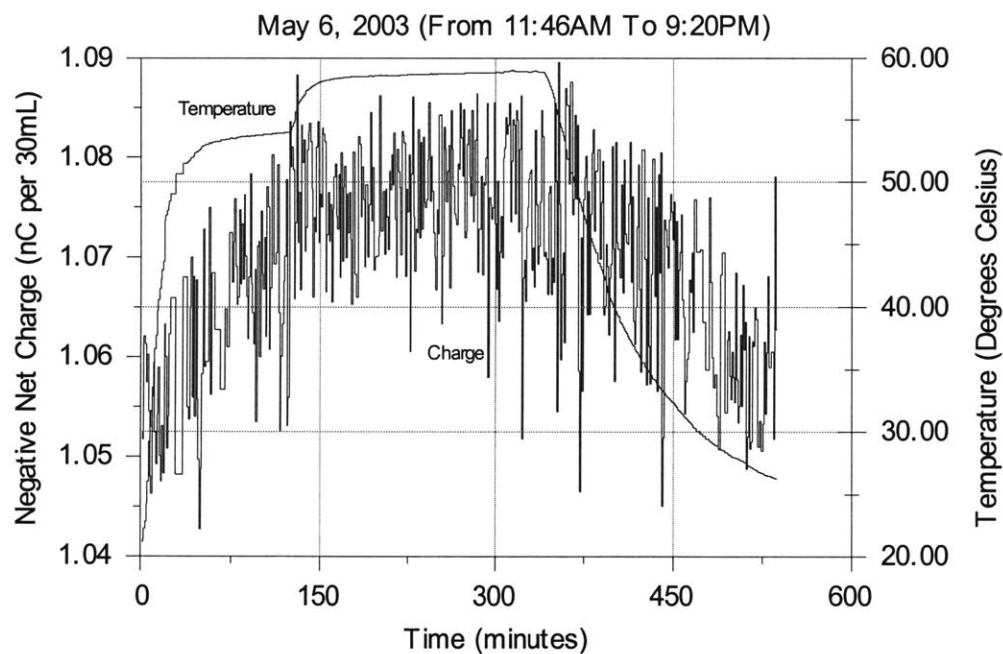


Figure 4.11: Second measurement of negative charge after the Sargasso Sea water came to rest within the upper Faraday cup electrode as temperature was being changed.

4.10.3 Charge Measurements Using Different Metal Grounding Screws

For the Sargasso Sea water, using a brass grounding screw, we obtained a charge value of -1.64nC , and using a stainless steel grounding screw, we obtained a charge value of -1.38nC . The values are similar.

4.11 Open-Circuit Voltage Measurements Using Sargasso Sea Water

The sea water was put inside the Faraday cage on 4th April, 2003. The initial measured voltage value was -14.69V after the sample reached the upper Faraday electrode, and the measured charge value was -2.09nC.

Figure 4.12 shows a plot of voltage with variation in temperature with respect to time. The initial temperature inside the Faraday cage was 27.33°C, and the measured voltage was -14.40V. Unlike the dependence of voltage of tap water or distilled water on temperature, the measured voltage of sea water did not show a significant dependence on temperature. With an increase in temperature, the voltage neither showed a linear increase nor a linear decrease with time. The data appears to be very noisy. The highest voltage value reached was -19.93V when the internal temperature was 53.71°C. The temperature was almost constant from about 100 minutes to about 240 minutes. With a constant temperature, the voltage was essentially constant. It took more than three hours for the internal temperature to reach a peak temperature of 54.88°C. The temperature controller was turned off at around 240 minutes into the experiment to allow the internal temperature to decrease to room temperature. With a decrease in temperature, the voltage value neither showed a smooth increase nor a smooth decrease with time.

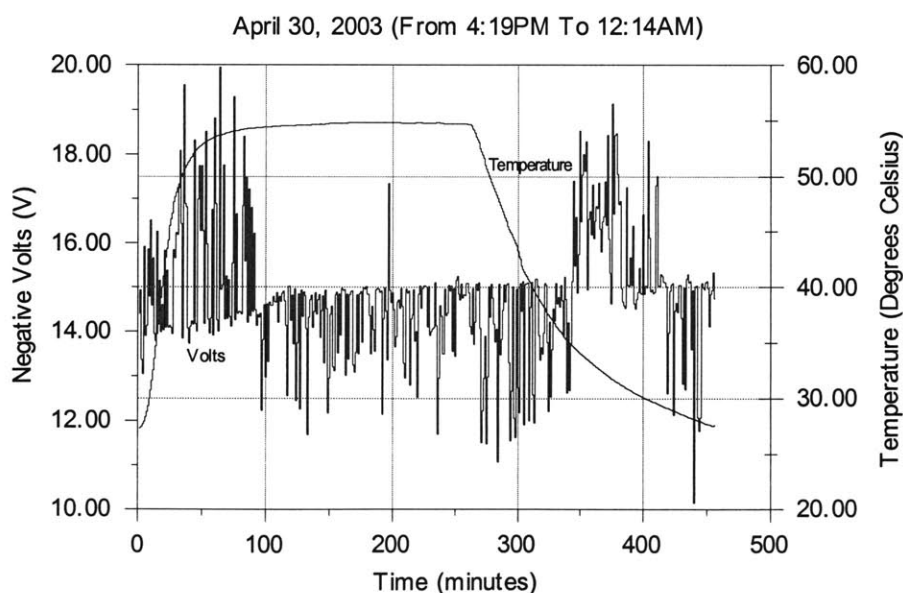


Figure 4.12: Measurement of open-circuit voltage after the negatively charged Sargasso Sea water contained in a 30mL Polyallomer centrifuge tube came to rest within the upper Faraday electrode as temperature was being changed.

4.12 Measurements and Calculations of Capacitance Using Sargasso Sea Water

4.12.1 Measurements of Capacitance Using Sargasso Sea Water

Capacitance of the Faraday cage with Sargasso Sea water contained in a 30mL Polyallomer centrifuge tube was measured using Model AH 2500 capacitance bridge. It was measured using both brass and stainless screws and the values are comparable. Capacitance was also measured without using any metal screw. The values are all tabulated in Table 4.4. It was measured at the lower Faraday electrode and at the upper Faraday electrode.

Table 4.4 Capacitance (pF) measurements of Sargasso Sea water using stainless steel and brass grounding screws and without using a metal grounding screw

<i>Screw</i>	<i>Position</i>	<i>Capacitance(pF)</i>
Brass	Lower electrode	144.44
Brass	Upper electrode	129.93
Stainless steel	Lower electrode	144.26
Stainless steel	Upper electrode	129.96
None	Lower electrode	132.81
None	Upper electrode	129.86

4.12.2 Calculations of Capacitance Using Sargasso Sea Water

Here, we shall calculate capacitance from the charge measurement in Figure 4.10, and the voltage measurement in Figure 4.12. Since the voltage value was pretty noisy and was essentially independent of temperature, we shall use the mean value of voltage to calculate the capacitance. The mean value was about -14.76V. We take the charge value to be about -2.09nC at a temperature of 53.89°C. So, using (1) we calculate the capacitance to be 141.59pF.

4.13 Measurements of Charge Using 0.9% NaCl Solution

To compare the charge values obtained using Sargasso Sea water, we also conducted charge measurements using 0.9% NaCl solution. The first value recorded was about -4nC and was allowed to remain inside the Faraday cage for about a day to reach an equilibrium value of about -1.68nC. Figure 4.13 shows variation of charge values with temperature change as a function of time. The initial measured charge value was about -1.68nC at an internal temperature of 25.53°C. The temperature was increased in steps.

After about 12 minutes, the charge value suddenly dropped from about -1.64nC to about -1.38nC which could be due to electrical noise. Similar to the Sargasso Sea water charge measurements, increasing the temperature caused the charge values to be only slightly more negative. The temperature remained constant at about 55°C from 66 minutes to 183 minutes. At 66 minutes, the measured charge value was -1.43nC , and at 183 minutes the measured charge value was -1.45nC . Then, the temperature controller was set to 65°C . Again, from about 232 minutes to about 376 minutes, the charge value was about constant at around 65°C . At 232 minutes, the temperature was 64.03°C where the measured charge value was -1.45nC . At 376 minutes, the temperature was 64.71°C , and the measured charge value was about -1.49nC . After 376 minutes, the temperature controller was set to 25°C . Decreasing the temperature, the charge value was also decreasing in magnitude. Comparing the data to the data taken using Sargasso Sea water, both sets appear to be noisy which could be due to the presence of salt or due to chemical degradation of the brass grounding screws.

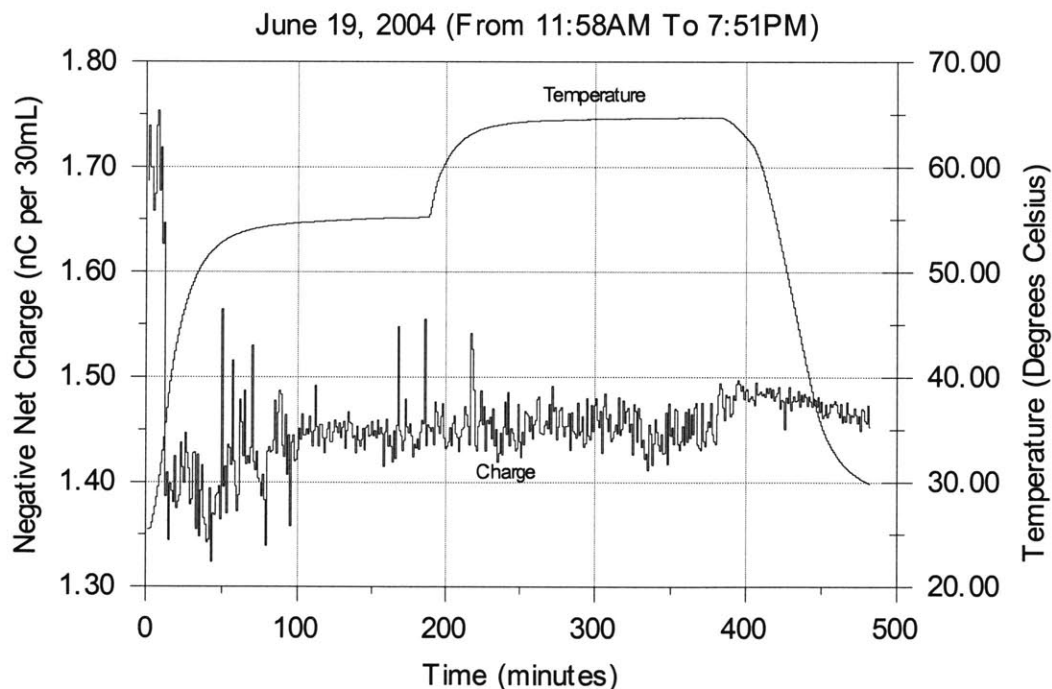


Figure 4.13: Measurement of negative charge after the 0.9% solution in 30mL Polyallomer centrifuge tube came to rest within the upper Faraday electrode as temperature was being changed.

4.14 Measurements of Capacitance Using 0.9% NaCl Solution

Capacitance of the Faraday cage with 0.9% NaCl solution contained in a 30mL Polyallomer centrifuge tube was measured. It was measured using both brass and stainless steel screws. Similar to all other water dielectrics, using 0.9% NaCl solution also yielded capacitance at the upper Faraday electrode to be lower than capacitance at the upper electrode. Values obtained using the two metal screws are similar as tabulated in Table 4.5.

Table 4.5 Capacitance (pF) measurements of 0.9% NaCl solution using brass and stainless steel screws

<i>Screw</i>	<i>Position</i>	<i>Capacitance(pF)</i>
Brass	Lower electrode	144.37
Brass	Upper electrode	129.93
Stainless steel	Lower electrode	144.39
Stainless steel	Upper electrode	129.92

4.15 Discussion

Charge and open-circuit voltage measurements with temperature change as a function of time using distilled water, tap water, Sargasso Sea water, and 0.9% NaCl were presented. Charge was also measured using both brass and stainless steel screws to determine whether the source of the net charge can be related to galvanic action. Capacitance of the Faraday cage was measured with the samples and brass or stainless steel grounding screws inside. It was also measured without any screws. Conductivity of the water samples was also measured where the values are tabulated in Table 4.1.

Measurement of charge with variation in temperature as a function of time using distilled water showed a smooth relationship as discussed in Section 4.2. Measurement of voltage with variation in temperature as a function of time also showed a smooth relationship as discussed in Section 4.3. Both charge and voltage were shown to vary with temperature. Temperature increase caused both charge and voltage to increase in magnitude, and a temperature decrease caused them to decrease. This means that an increase in temperature caused distilled water contained in Polyallomer centrifuge tube to acquire more negative charge.

Measurement of charge with variation in temperature as a function of time using tap water also showed a similar behavior as distilled water. Measurements are discussed

in detail in Section 4.6. Measurement of voltage also showed a temperature dependence as discussed in Section 4.7.

Measurements of charge with variation in temperature as a function of time using Sargasso Sea water showed a less significant change than distilled water and tap water as discussed in Section 4.10. Open-circuit voltage measurement did not show any unique dependence on temperature. Charge was also measured with temperature variation using 0.9% NaCl solution. Both Sargasso Sea water and 0.9% NaCl solution charge data were noisy and showed a small change with temperature change. Sargasso Sea water data was especially noisy which could be due to chemical reaction between the brass screw and the dissolved ions in the water.

References

- [1] Manual for the Model 142 Orion Conductivity Meter, pp 7 & 61.
- [2] Peterson, Thomas F. Jr., *Electrochemical Measurement Anomalies, and Related Geophysical Factors*, International Committee for Research and Study of Environmental Factors, Partenit, Crimea, Ukraine, October 1999.

Chapter 5

Advanced Faraday Cage Measurements of Charge and Open-Circuit Voltage Using Teflon and Acrylic

In this chapter, we shall describe measurements of charge and voltage using solid dielectrics of Teflon and Acrylic. The experimental method was described in Chapter 3.

5.1 Charge Measurements Using Teflon

The Teflon used is of a cylindrical shape with a diameter of 2.0cm and a length of 10.0cm. We found it to have a negative non-zero equilibrium charge value in the range of -4.70nC to -7.60nC. The equilibrium value tends to change with increasing age. The Teflon sample was first put inside the Faraday cage on 29th October, 2003. After the Teflon came to rest within the upper Faraday electrode, the initial charge value shown by the 617 electrometer was -6.90nC at an ambient temperature of 24.02°C. The following day, the charge value decayed to -6.85nC when the ambient temperature was 22.90°C. Charge and voltage measurements of Teflon with temperature change as a function of time were performed.

The variation of charge as a function of temperature and time is shown in Figure 5.1. The initial recorded charge value was -7.76nC at an internal temperature of 21.84°C. Next, the temperature was increased in steps. Initially, the temperature controller was set to 60.0°C, but at 81 minutes into the experiment the temperature setting was changed to 65.0°C. In this measurement, an increase in temperature caused the Teflon to discharge smoothly with time. With a constant temperature, the value of measured charge was essentially constant. The temperature was essentially constant from 100 minutes to 232 minutes. The measured charge value recorded at 100 minutes was -7.68nC at a temperature of 64.03°C, and the measured charge value recorded at 232 minutes was -7.67nC. The temperature controller was turned off after recording the data taken at 232 minutes to allow the internal temperature to decrease to room temperature. A decrease in

the temperature did not cause any significant change in the charge value. The experiment was stopped at 448 minutes when the internal temperature was 25.57°C, and the measured charge value was -7.64nC. This measurement shows that increasing the temperature causes Teflon to discharge faster and to decay to an equilibrium value that appears to be independent of temperature. Allowing the internal temperature to cool back to the original temperature did not produce any significant effect on the final charge value.

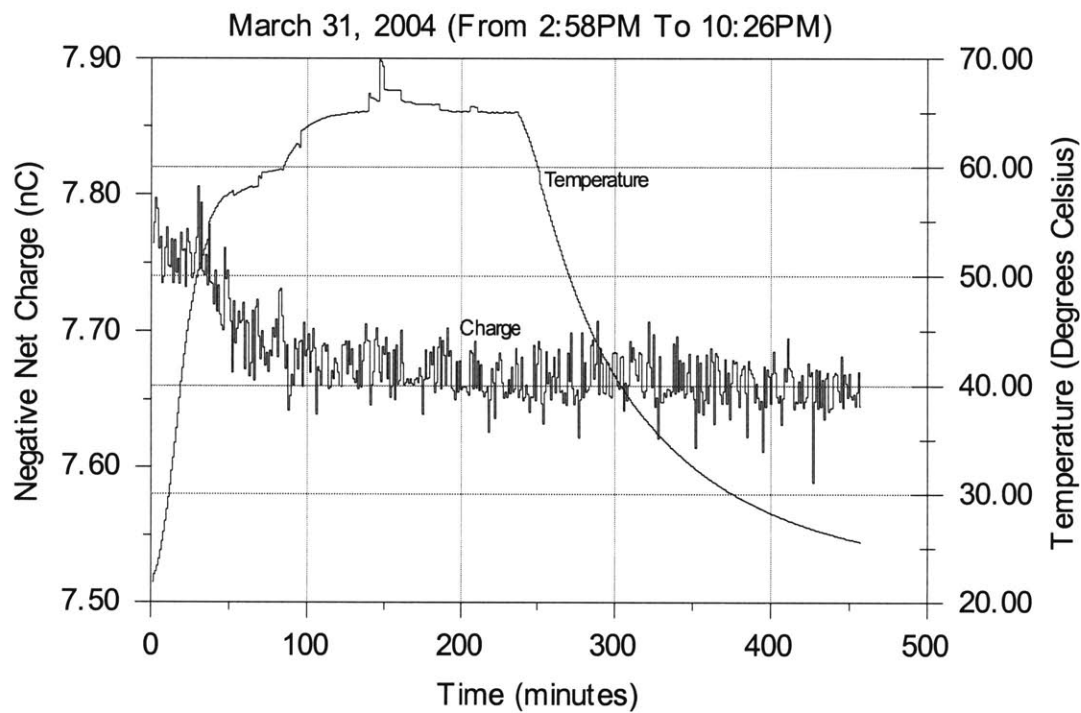


Figure 5.1: Measurement of negative charge after Teflon came to rest within the upper Faraday electrode from the lower Faraday electrode as temperature was being changed. Increasing the temperature caused the Teflon to discharge faster to an equilibrium value. Cooling did not produce any appreciable effect on the final charge values.

5.2 Triboelectric Effects

Triboelectric currents are generated when there is a charge transfer between two dissimilar materials, usually between a conductor and an insulator. When two different metals come into contact with each other, one of them acquires a positive charge and the other one acquires a negative charge due to contact potential. The metal with the lower work function becomes positively charged, and the metal with the higher work function becomes negatively charged [1]. If both materials are nonconductors, they can become

more charged by rubbing with each other than from having a single contact because of an increased contact surface area. Materials do not become charged because of friction but because of adhesive force. Adhesive force is the reason behind the transfer of electrons from one material to another when either in contact or when rubbed against each other. Some materials have a tendency of losing electrons, and some have a tendency of attracting electrons. A few materials do not have the tendency of either attracting or losing electrons; one good example is steel. Table 5.1 presents a typical triboelectric series [1,2,3,4]. Materials at the bottom of the series are negative with respect to those upper in the series. For instance, rubbing cotton with Teflon will cause cotton to be positively charged and the Teflon to be negatively charged. Rubbing wool with Teflon will make wool to be positively charged and Teflon to be negatively charged but the effect will be stronger. The Teflon will be more negatively charged by rubbing it with wool than with cotton. Position of the materials that are presented in Table 5.1 can readily change due to many factors such as surface area of contact, humidity, surface roughness, etc.

Table 5.1 A Typical Triboelectric Series

Rabbit's Fur

Lucite
Bakelite
Cellulose acetate
Glass
Quartz
Mica
Wool
Cat's fur
Silk
Cotton
Wood
Amber
Resins
Metals
Polystyrene
Polyethylene
Teflon
Cellulose nitrate
Polyvinyl chloride
Silicon rubber
Saran wrap

5.2.1 First Triboelectric Charge Measurement Using Teflon

From Table 5.1, we note that Teflon is one of the most negative insulators. An experiment was performed where Teflon was rubbed with some materials to note the change in the value of the original charge as shown by the 617 electrometer. The experiment was conducted at an ambient temperature of 24.09°C. Table 5.2 shows the triboelectric series of Teflon for the experiment conducted, and it also shows the amount of charge acquired by Teflon after rubbing with each of the tested materials. Before rubbing Teflon with the given materials, the measured charge value given by the electrometer had been -6.36nC. Rubbing with cotton increased the negativity of Teflon to -7.38nC; thus, it made Teflon a little more negative than its original charge value. Rubbing with Acrylic produced a more profound effect. This means acrylic can be placed above cotton in the triboelectric series. After rubbing with a jacket composed of 100% polyester, the charge value decreased to -6.28nC which is a little lower than the original value of Teflon, so Polyester is placed below Teflon. Finally, rubbing with polypropylene made the Teflon charge to be more negative by 2.53nC.

Table 5.2 Triboelectric series at 24.09°C for Teflon with starting value -6.36nC

<i>Materials rubbed with:</i>	<i>Teflon charge value (nC)</i>
Acrylic	-11.74
Polypropylene	-8.89
Cotton	-7.38
Teflon	-6.36
Polyester	-6.28

After triboelectrically charging the Teflon, it was subjected to a higher temperature to note the effect of temperature. Figure 5.2 shows the variation of measured charge of Teflon with temperature change as a function of time. The temperature controller was set to 70.0°C. Unlike the charge measurements conducted using distilled water, tap water, Sargasso Sea water and 0.9% NaCl solution, an increase in temperature caused the Teflon to discharge approximately linearly with time. The increase in temperature caused the Teflon to lose the charge obtained from triboelectric charging at a faster rate. The temperature was essentially constant from 120 minutes to 282 minutes. The charge value recorded at 120 minutes was about -7.006nC at a temperature of 71.34°C, and the measured charge value recorded at 282 minutes was about -6.94nC at a

temperature of 71.99°C. The computer stopped acquiring data from 226 minutes to 281 minutes. The value of charge recorded at 225 minutes was about -6.96nC when the temperature was 71.86°C. At 282 minutes, the measured charge value was about -6.94nC at a temperature of 71.99°C. The temperature was essentially constant during the time period when the data was not recorded, but the charge magnitude decreased from -6.96nC to about -6.94nC. The temperature controller was turned off at 283 minutes to allow the internal temperature to decrease to room temperature. Decreasing the temperature caused no significant change in the value of charge, similar to the charge measurement in Figure 5.1. The experiment was stopped at 480 minutes when the temperature was 21.62°C, and the measured charge value was about -6.94nC. The result of this measurement showed that a higher temperature increases the rate that the Teflon loses charge obtained from triboelectric charging.

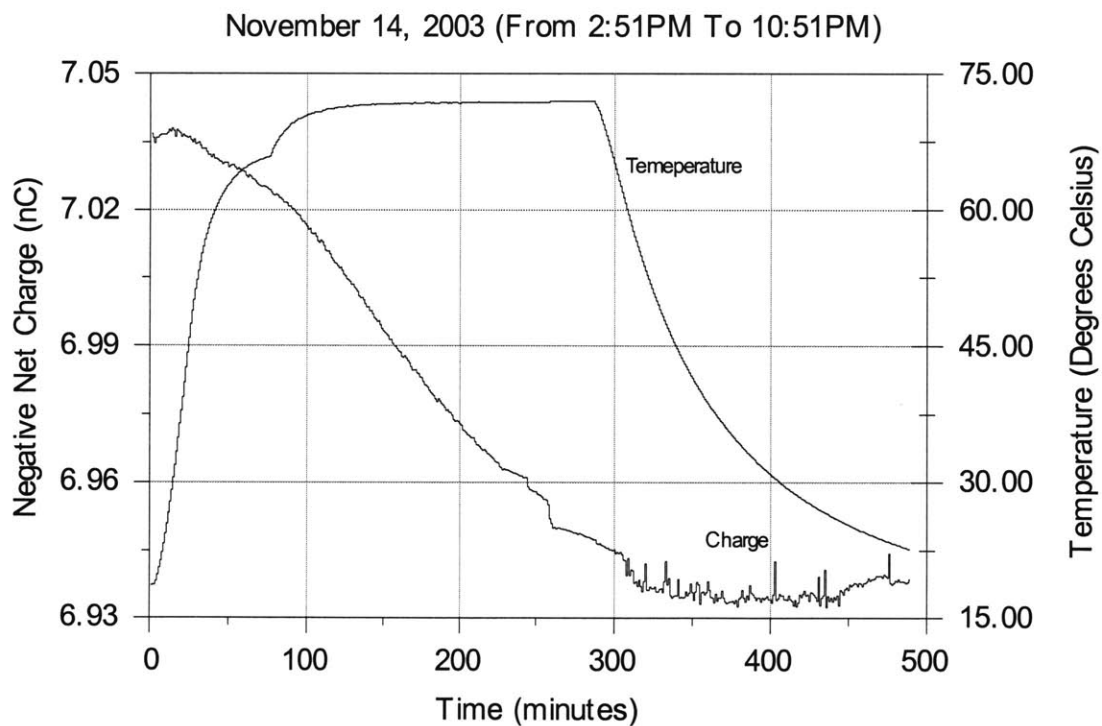


Figure 5.2: Teflon was triboelectrically charged by rubbing with some materials. Then, increasing the temperature allowed the triboelectric charge to decay faster. After the Teflon came to rest within the upper Faraday cup electrode, charge values were recorded as temperature was being changed. Data from 226 to 281 minutes is estimated with a linear fit as the computer was not acquiring any data during this interval.

5.2.2 Second Triboelectric Charge Measurement Using Teflon

Another experiment was also conducted where Teflon was triboelectrically charged. Before rubbing, the measured charge value had been -4.73nC at an ambient temperature of 32.35°C . Here, with each tested material it was rubbed fifteen times. The tested materials were cotton, Polypropylene, Acrylic, paper towel, and Aluminum foil. The charge value obtained by Teflon after each rubbing is shown in Table 5.3 where the formulation of the triboelectric series of Teflon for this experiment is also shown. Here, rubbing Teflon with cotton also caused a smaller change than expected. Teflon became only a little bit more negative. From -4.73nC , the negativity increased to -6.25nC . Since rubbing with Aluminum foil caused the largest increase in the negativity of Teflon, Aluminum foil was placed at the very top of the triboelectric series.

Table 5.3 Triboelectric series for Teflon with starting value -4.73nC at 32.35°C

<i>Materials rubbed with:</i>	<i>Teflon charge value (nC)</i>
Aluminum foil	-19.97
Paper towel	-16.31
Acrylic	-13.36
Polypropylene	-11.89
Cotton	-6.25
Teflon	-4.73

After Teflon became more negative by rubbing with other materials, we subjected it to an elevated temperature for the charge value to decay faster. Figure 5.3 shows the decrease of charge with increasing temperature change as a function of time. The temperature was increased by the temperature controller which caused the charge value obtained from triboelectric charging to decrease smoothly with time. The temperature controller was set to 65°C . From about 60 minutes to about 377 minutes, the temperature was permitted to stay approximately constant at a temperature of about 65°C during which the charge value was also decreasing smoothly with time. Because the elevated temperature was constant, the rate of decrease in the magnitude was less than when the temperature was initially rapidly increasing with time. At 60 minutes, the recorded charge value was about -16.31nC at a temperature of 64.24°C , and at 377 minutes the recorded charge value was about -14.11nC at a temperature of 65.77°C . The temperature was increased in steps. In order to further increase the dissipation rate of charge value, the temperature controller was increased to 75°C . The temperature value reached a highest

value of 74.49°C when the recorded charge value was -13.54nC . In this measurement, we only recorded the effect of increased temperature. This experiment verified that an increased temperature caused the charge acquired by Teflon from triboelectric charging to decrease at a faster rate.

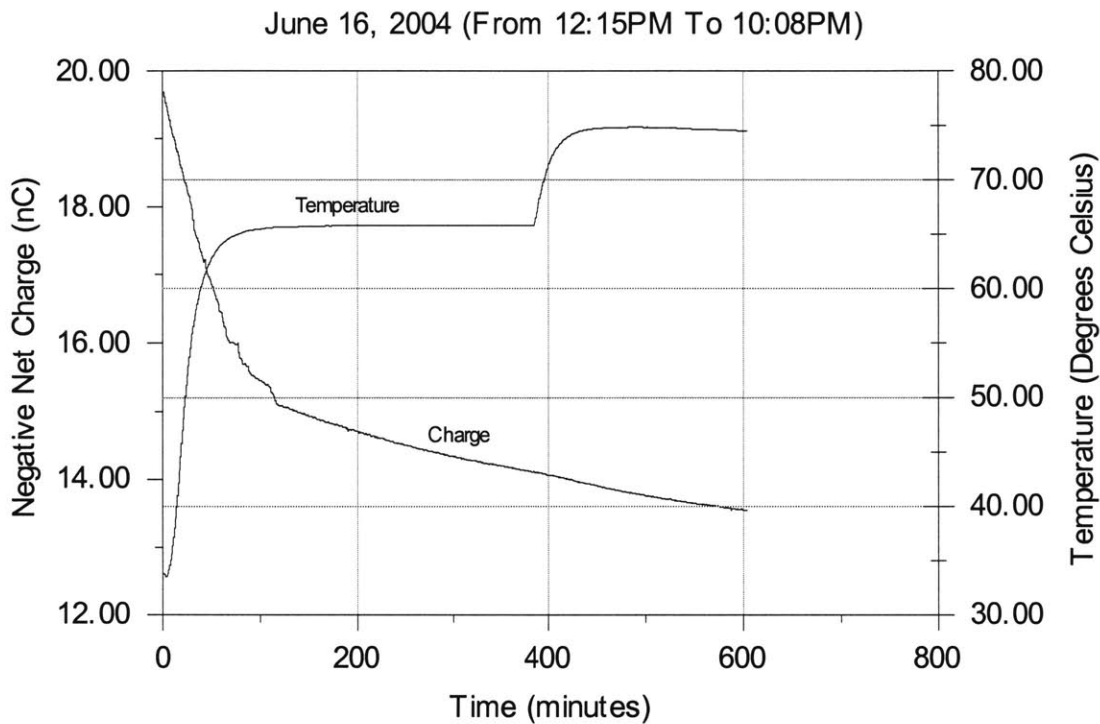


Figure 5.3: A second measurement of the triboelectric effect of Teflon was performed. To speed up the discharge rate, Teflon was subjected to an increased temperature. Such an increase caused the triboelectric charge to decrease in Teflon at a faster rate. The charge values were recorded after it came to rest within the upper Faraday cup electrode as temperature was being changed.

5.2.3 Third Triboelectric Charge Measurement Using Teflon

We performed another experiment where we rubbed Teflon with only Cotton. Before rubbing, the recorded charge value had been -3.77nC . After rubbing about fifteen times with cotton, the measured charge value of Teflon was recorded to be -6.24nC . At the time, the ambient temperature was 27.82°C and the relative humidity was 69%. Here, we also increased the temperature in steps. The temperature was increased to speed up the discharge rate. Figure 5.4 shows the variation of charge value of Teflon with temperature change as a function of time. Initially, the temperature controller was set to 65°C . An increased temperature caused the charge obtained from rubbing with Cotton to

decrease smoothly with time. The temperature was essentially constant from 88 minutes to 138 minutes. During this period, the charge value did not show any appreciable change. The temperature was then increased to 70°C. This increased temperature caused the charge value to decrease in magnitude. The charge value decreased from about -5.08nC to about -4.73nC. After this, the temperature controller was set to 25°C to note the effect of cooling. This measurement, similar to the previous measurements, also showed that cooling slowed the rate of decrease of charge value. This experiment was allowed to run for about 516 minutes. The final recorded temperature was 29.07°C, and the charge value was -4.62nC.

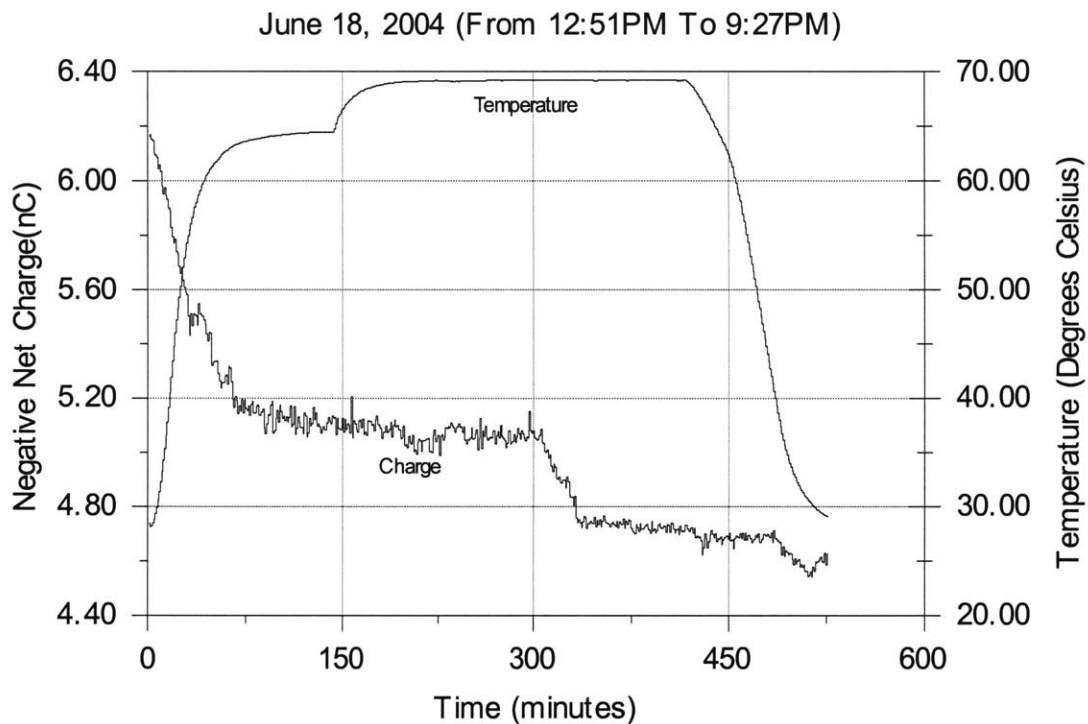


Figure 5.4: After Teflon was rubbed with only Cotton, Teflon was subjected to an increased temperature. Increasing the temperature caused the acquired charge to decrease at a faster rate. Cooling did not show any appreciable effect on the charge. Charge values were recorded after Teflon came to rest within the upper Faraday electrode as temperature was being changed.

5.3 Open-Circuit Voltage Measurements Using Teflon

In the previous chapter, in addition to describing the charge measurements we also described the open-circuit voltage measurements using distilled water, tap water, and

Sargasso Sea water. In this section, we shall describe the open-circuit voltage measurements taken using the solid dielectric, Teflon.

To determine the effect of temperature upon the voltage, a measurement was performed using Teflon after the measurement of charge described in Section 5.1 and shown in Figure 5.1. The Teflon was kept inside the Faraday cage at all times between the measurement of charge and this measurement of open-circuit voltage. Figure 5.5 shows the measurement of the variation of voltage as a function of temperature with respect to time. The initial internal temperature was 21.99°C, and the measured voltage value was -53.81V. The temperature controller was set to 65.0°C. From the measurement of charge in Figure 5.1, we found that an increase in temperature caused the charge value to decrease to an equilibrium value that appeared to be independent of temperature. As expected, there was essentially no change in the voltage value with temperature change because the Teflon was already in equilibrium. The temperature was essentially constant from 68 minutes to 231 minutes. The internal temperature at 68 minutes was 64.01°C and the voltage value was -53.20V; the internal temperature at 231 minutes was 65.18°C and the voltage value was -53.12V. Some data acquired from 232 minutes to 267 minutes was filtered since the recorded voltage values were very noisy. Then, the temperature controller was turned off to permit the internal temperature to reach room temperature. Again, some data acquired from 298 minutes to 344 minutes was also filtered because they were erroneous as the motor string got displaced. Besides deleting this erroneous data, some data was removed because they were noisy. The experiment was stopped at 469 minutes when the internal temperature was 25.47°C, and the measured voltage value was -53.77V. This voltage measurement did not show any significant change in the values possibly because from the measurement of charge shown in Figure 5.1 the value had decayed to an equilibrium state of about -6.9nC.

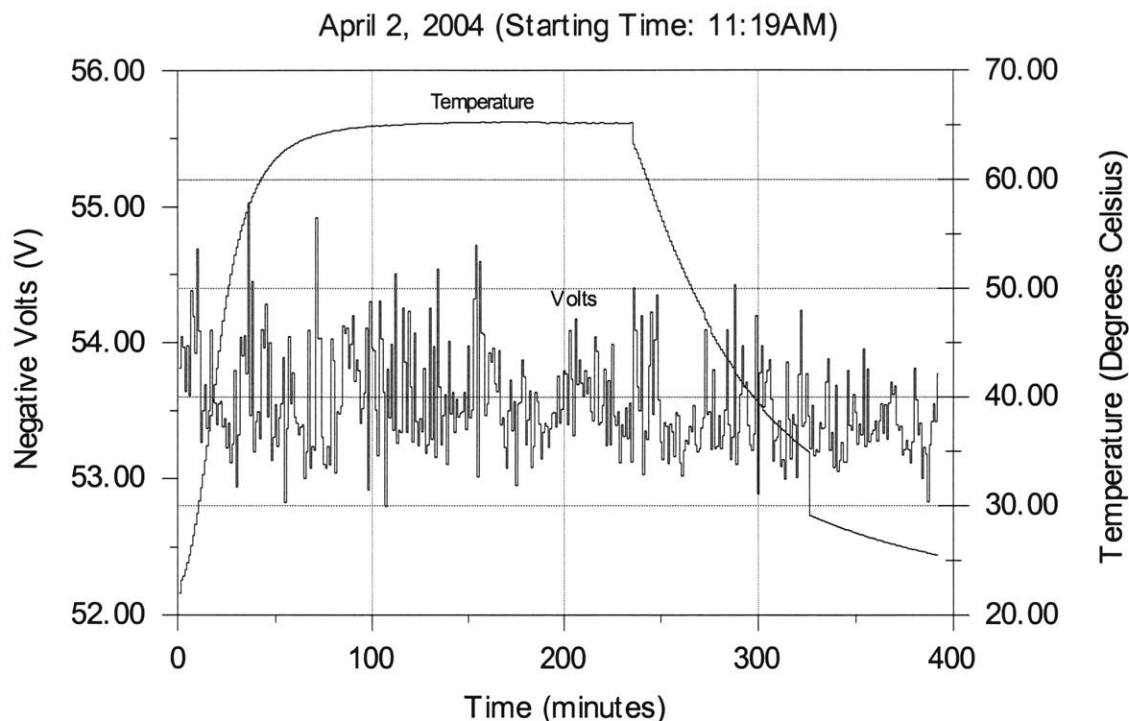


Figure 5.5: Measurement of voltage after the negatively charged Teflon came to rest within the upper Faraday electrode with temperature change as a function of time.

5.4 Charge Measurements Using Acrylic

The first charge measurement of Acrylic was conducted on 22nd May, 2003, and the initial value given by the 617 electrometer was -3.63nC. Measurements of charge were performed with temperature change as a function of time.

A variation of charge of Acrylic with temperature change as a function of time is shown in Figure 5.6. The temperature was increased in two steps. At first, the temperature controller was set to 65°C. Here, the initial measured charge value was about -7.06nC at a temperature of 25.17°C. Increasing the temperature caused the charge to decrease smoothly with time. The temperature was permitted to stay approximately constant from 71 minutes to 196 minutes. At such a constant higher temperature, the charge value of Acrylic was also decreasing with time. At 71 minutes, the temperature was 64.02°C and the recorded charge value was about -6.87nC; at 196 minutes, the temperature was 65.14°C and the recorded charge value was about -6.09nC. Then, the temperature controller's setting was changed to 70°C. Such an increase in temperature

increased the discharge rate. At about 458 minutes the temperature was 69.75°C and the measured charge value was -5.29nC. The temperature controller was then set to 25°C to cool the internal temperature of the Faraday cage. Cooling greatly decreased the rate of discharge. The sample was then kept inside the grounded Faraday cage until July 19, 2004, where the charge value was essentially unchanged from the final charge value recorded as shown in Figure 5.6. The charge value recorded on July 19, 2004, was -4.83nC.

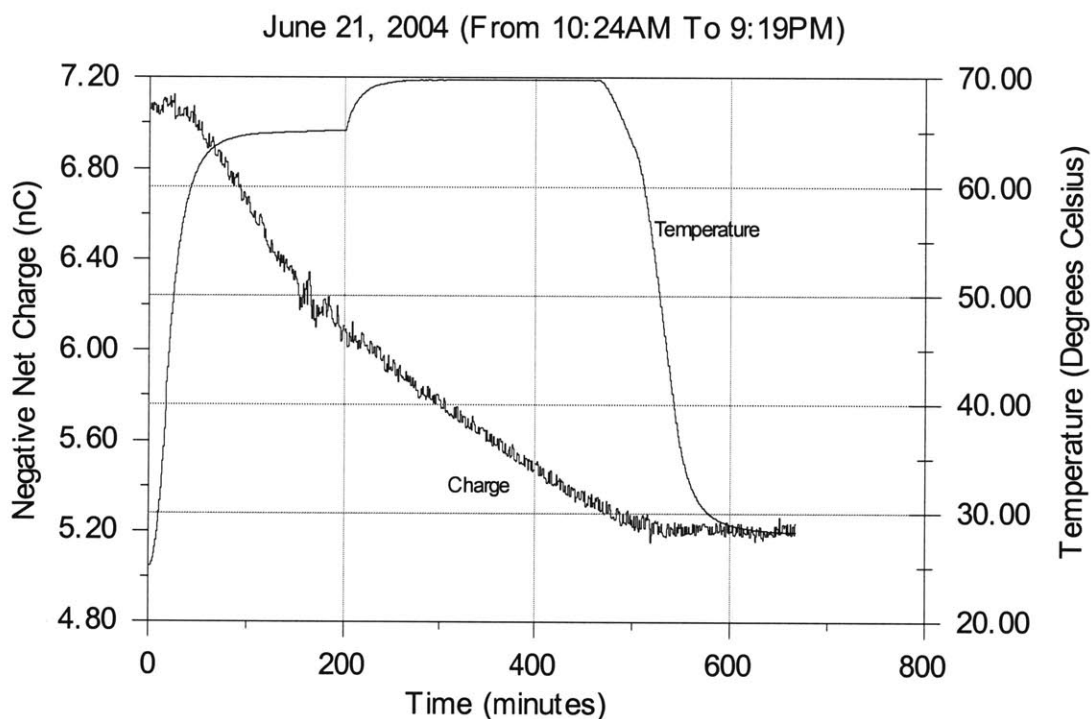


Figure 5.6: Measurement of negative charge after Acrylic came to rest within the upper Faraday electrode as temperature was being changed within the Faraday cage by using the temperature controller.

5.5 Triboelectric Charge Measurements Using Acrylic

The triboelectric effect, in general, was described in Section 5.2. Acrylic was rubbed with some materials to note the variation in the value of charge. Before rubbing, the charge magnitude of Acrylic had been about -2.35nC at an ambient temperature of 24.15°C. Table 5.1 shows a typical triboelectric series, but Acrylic is not listed there, so measurements were performed to determine the triboelectric series position for Acrylic. Acrylic was rubbed with several materials to note the variation in the charge value. Table

5.4 shows the results of triboelectric charging of Acrylic in the triboelectric series for Acrylic. At first, Acrylic was rubbed with cotton. Then, Acrylic became more negative and increased from -2.35nC to -8.80nC. So, Acrylic can be placed below cotton in the triboelectric series. Then, Acrylic was rubbed with Polypropylene. The polarity was still negative indicating the affinity of Acrylic to gain electrons. The magnitude was lower than the original value of charge by 1.43nC. This means that the affinity of gaining electrons of Acrylic is less than that of polypropylene signifying Acrylic to be more positive than Polypropylene. Therefore, Acrylic can be placed above Polypropylene in the triboelectric series. Since Teflon is one of the most negative insulators according to Table 5.1, and correspondingly from the experiment we found that rubbing Acrylic with Teflon caused Acrylic to acquire positive charge by losing electrons. After rubbing Acrylic with paper towel, the magnitude of charge given by the electrometer was -6.44nC. The polarity shown by the electrometer was positive after it moved to the upper Faraday electrode indicating the Acrylic to be negatively charged. So, Acrylic can be placed below a paper towel. The value was less negative than rubbing with cotton which means that the paper towel should be placed below cotton in the triboelectric series. Finally, Acrylic was rubbed with Aluminum foil. Rubbing Acrylic with Aluminum foil caused the largest change in the magnitude of measured charge value, and it caused Acrylic to be more negative than rubbing it with the previous materials. Rubbing Aluminum foil with Acrylic caused more transfer of electrons to the Acrylic which means Aluminum foil should be placed first in the triboelectric series for this experiment.

Table 5.4 Triboelectric series for Acrylic with initial value -2.35nC at 24.15°C

<i>Materials rubbed with:</i>	<i>Acrylic charge value(nC)</i>
Aluminum foil	-16.86
Cotton	-8.80
Paper towel	-6.44
Acrylic	-2.35 (initial value)
Polypropylene	-0.92
Teflon	+2.02

To determine the temperature dependence of Acrylic's charge value acquired after rubbing, the temperature controller was used to control the temperature. The Testpoint program was used for automatic and continuous recording. The temperature controller was set to 65°C. Figure 5.7 shows a plot of the variation of charge with temperature

change as a function of time. The initial charge value was high due to frictional charging with other materials. Increasing the temperature caused the charge to discharge faster. The value of measured charge decreased approximately exponentially with time. The temperature was essentially constant from 73 minutes to 258 minutes. The temperature at 73 minutes was 63.03°C, and the measured charge value was -10.04nC. The temperature at 258 minutes was 63.81°C, and the measured charge value was -2.14nC. With a constant high temperature, the charge was still decreasing exponentially with time. The temperature controller was turned off after recording the data at 258 minutes to permit the internal temperature to decrease to room temperature. Decreasing the temperature caused a small change in the value of charge, but the charge value was still decreasing. The value of charge was essentially constant from 345 minutes to 440 minutes. The charge value recorded at 345 minutes was about -1.59nC at a temperature of 37.1°C, and the charge value recorded at 440 minutes was about -1.53nC at a temperature of 28.49°C. The experiment was stopped after recording the data at 440 minutes. A higher temperature caused Acrylic to discharge faster. Without increasing the temperature, the value of charge would also have decreased, but a high temperature caused the charge value to reach an equilibrium value sooner. Cooling greatly reduced the charge discharge rate.

5.6 Open-Circuit Voltage Measurements Using Acrylic

To observe the effect of temperature variation on the measured value of voltage with Acrylic inside the Faraday cage, an experiment was performed following the measurement of charge shown in Figure 5.7. Figure 5.8 shows the plot of voltage variation as a function of temperature with respect to time. The initial temperature was 24.60°C, and the recorded voltage value was -8.60V. The temperature controller was set to 65.0°C. The Testpoint program was used to record the data automatically. During the period of temperature increase, the voltage value was essentially constant. The temperature was essentially constant from 81 minutes to 289 minutes during which the charge was not constant but was decreasing approximately linearly with time. The temperature at 81 minutes was 63.03°C, and the charge value was -8.62V; the temperature at 289 minutes was 63.71°C, and the charge value was -6.28V. So, the voltage decreased by 2.34V during this constant temperature interval. The charge value at 81 minutes was approximately the same as the initial charge value. After the temperature

reached the peak value, the measured voltage value started to decrease smoothly with time. The temperature controller was turned off after recording the data at 289 minutes to permit the internal temperature to return to room temperature. During the period of temperature decrease, the voltage value was essentially constant. The experiment was stopped after recording the data at 402 minutes and the internal temperature was 30.74°C. After the temperature decrease, the voltage value was approximately steady. No data was filtered.

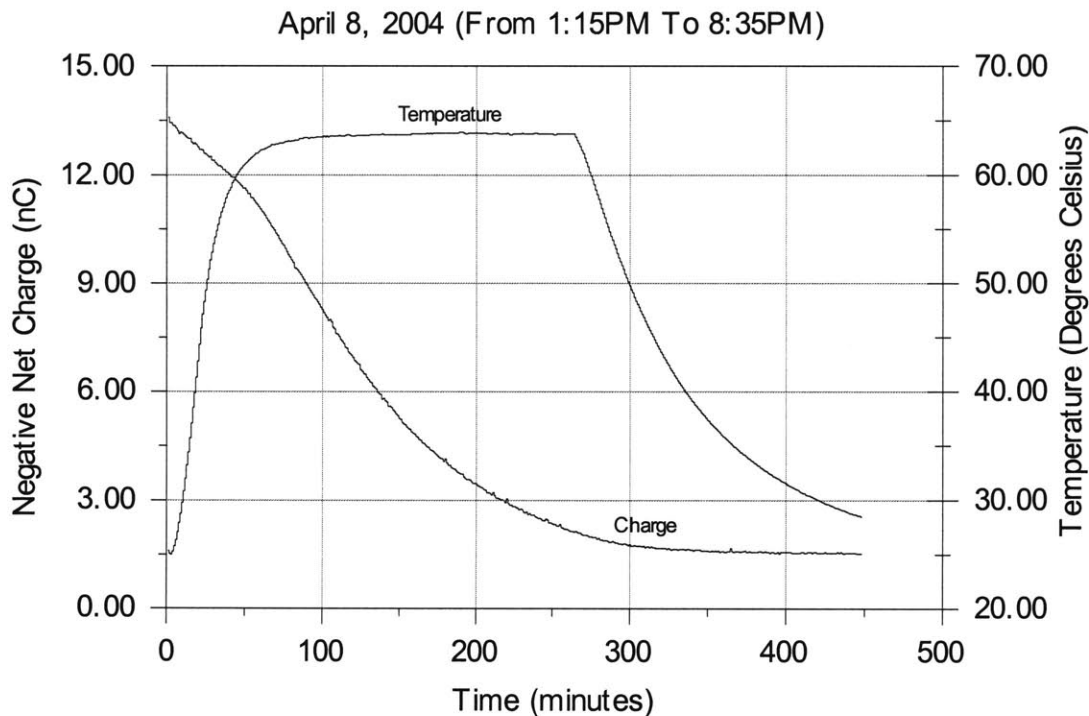


Figure 5.7: After rubbing Acrylic with a few solid materials, it was subjected to an increased temperature. Increasing the temperature caused the charge to be driven away exponentially with time. Cooling greatly slowed the discharge rate. The charge values were recorded after Acrylic came to rest within the upper Faraday electrode as temperature was being changed.

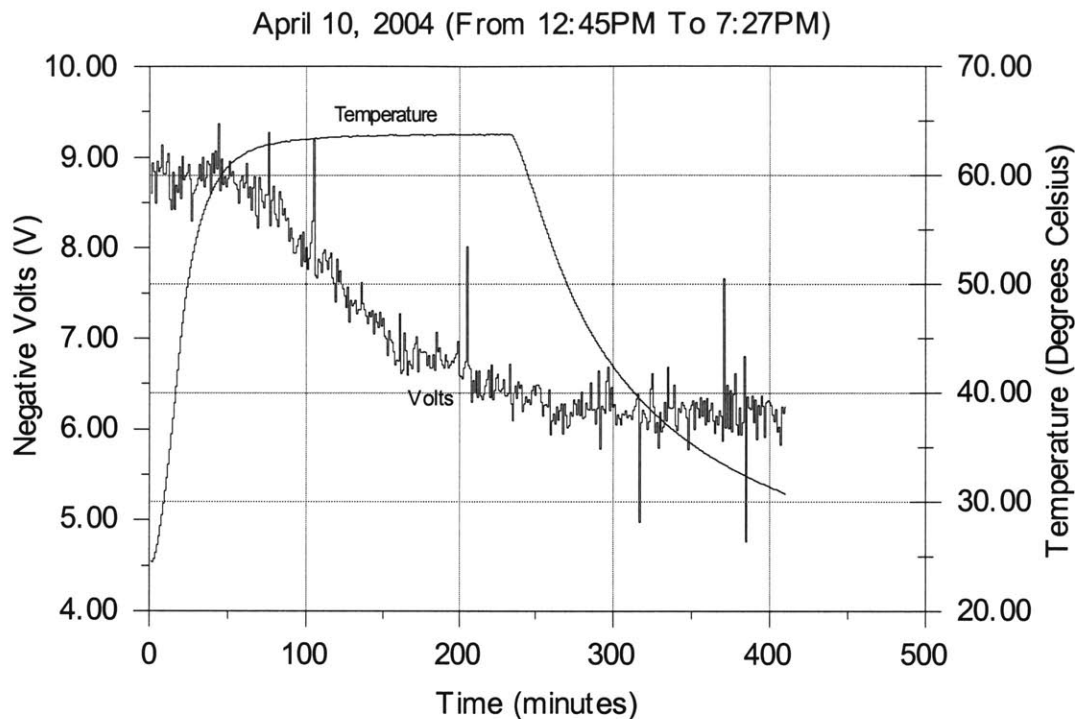


Figure 5.8: Open-circuit voltage was measured after Acrylic came to rest within the upper Faraday electrode as temperature was being changed. The voltage started decreasing with time after the temperature reaching the higher temperature set by the temperature controller.

5.7 Measurements of Capacitance

Capacitance of the Faraday cage was measured using a Model Andeen Hagerling (AH) 2500 capacitance bridge after putting Teflon and Acrylic in the Faraday cage chamber. When Teflon was in the lower Faraday cup electrode, the capacitance was measured to be about -130.16pF. After it came to rest within the upper Faraday electrode, the capacitance slightly reduced to a value of about -129.90pF. When Acrylic was in the lower Faraday electrode, the capacitance was measured to be about -130.32pF. After it came to rest within the upper Faraday electrode, the measured capacitance was -129.95pF. So, in the presence of Acrylic, the capacitance was also slightly reduced after it reached the upper Faraday electrode.

5.8 Discussion

Charge and open-circuit voltage measurements were conducted with temperature change as a function of time using Teflon and Acrylic. Both Teflon and Acrylic were rubbed with several materials and with each other to note the variation in the charge value. From these measurements, a triboelectric series was formulated for both Teflon and Acrylic after becoming triboelectrically charged by rubbing. Capacitance of the Faraday cage containing Teflon and Acrylic was measured when at the lower Faraday electrode and when at the upper Faraday electrode.

Measurement of the change in the charge of Teflon with temperature change as a function of time after no triboelectrification is discussed in Section 5.1. Initially, the measured charge value was -7.76nC when the temperature was 21.84°C . This measurement showed that an increase in temperature caused the Teflon to discharge approximately linearly with time. The final recorded charge value was -7.64nC after cooling to a temperature of 25.57°C . Section 5.2 discusses the triboelectric effect. Subsections 5.2.1, 5.2.2, and 5.2.3 discuss the effect of temperature on the charge obtained by Teflon after rubbing with some materials. After becoming triboelectrically charged, when we subject Teflon to an increased temperature, we found the charge value to discharge at a faster rate than when the temperature was not increased. Additionally, cooling greatly slowed the discharge rate.

An open-circuit voltage measurement was also performed using Teflon after conducting the measurement of charge discussed in Section 5.1. The measurement result is discussed in Section 5.3, and the plot is shown in Figure 5.5. Increasing the temperature did not cause any significant change in the voltage value which could be because the equilibrium value was already reached.

Measurement of charge of Acrylic without any triboelectrification is discussed in Section 5.4. An increased temperature caused the charge value to decrease smoothly with time as shown in Figure 5.6. Again, cooling greatly hindered the rate of decrease of charge value with time. The triboelectric effect of Acrylic is explained in Section 5.5. Then, the temperature was increased which caused the charge obtained from such

triboelectrification to decrease smoothly with time. Increasing the temperature caused the charge value to decay faster.

Open-circuit voltage measurements using Acrylic is described in Section 5.6. After the charge measurements discussed in Section 5.5, this voltage measurement was performed. Unlike the measurement of voltage conducted using Teflon shown in Figure 5.5, Figure 5.8 shows the voltage to vary as a function of temperature when Acrylic was inside the Faraday cage. The initial recorded voltage value was -8.60V at a temperature of 24.60°C. While the temperature was increasing, the voltage value was essentially constant with time. While the temperature was approximately constant at the peak value, the voltage started to decrease linearly with time. The voltage reduced by 2.34V in magnitude during this constant temperature interval.

These experiments have shown that if a solid sample is triboelectrically charged by rubbing, an increased temperature increases the rate of discharge rate, and cooling significantly slows the discharge rate. Additionally, these experiments show the value of this measurement method in quantifying a triboelectric series, rather than relying upon individual differences in relative charge as it has been in previously used method to construct a triboelectric series. All samples eventually tend to reach non-zero negative equilibrium charge values.

References

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Chapter 6

Concluding Remarks

This thesis focuses on Faraday Cage measurements of air, liquid, and solid dielectrics. Experiments use pressurized air with fixed Faraday cage electrodes, and a moving sample method between two Faraday cup electrodes for liquid and solid dielectrics.

For the air experiment, we have identified the source behind the flow of electrode current after ruling out many other possibilities that could cause charge generation, and also any experimental artifacts. In the air experiment, the primary objective was to find the source of the flow of electrode current in the electrode chamber during transient air pressure change. We have shown that the flow of electrode current cannot be due to changes in measured capacitance and input offset voltage. We have considered cases when the air is dry and when the air is moist. In both cases, the calculated values due to capacitance and input offset voltage changes are much less than the measured current. An experiment was conducted where we were able to control the internal humidity of the electrode chamber. At first, we increased the internal humidity by passing air through a closed beaker containing water, and then we decreased the internal humidity by passing air through a cylindrical tube containing desiccant Drierite (anhydrous CaSO_4). From this experiment, we have shown that the primary cause of the flow of electrode current is related to atmospheric humidity. As the humidity was reduced, amplitude of the electrode current was also reduced. We were able to decrease the internal humidity to about 2.52% where the amplitude of current was negligibly small. For further prove, we substituted dry nitrogen for air where no significant flow of current was observed as well with transient pressure change. This proves that the primary cause of current flow in the electrode chamber is related to atmospheric humidity.

Initial measurements showed consistently the polarity of the measured current to reverse when the ambient or internal temperature was below 20°C . Numerous measurements were taken to understand the reason behind the polarity reversal. At a low temperature with a small pressure increase a negative flow of current was only observed; however, with a pressure increase of about more than 10psi above atmospheric pressure

two simultaneous pulses of current were observed where the amplitude of the negative pulse was greater than the amplitude of the positive pulse. Similarly, at a low temperature with a small pressure decrease only a positive flow of current was observed; however, a pressure decrease of more than 10psi below atmospheric pressure generated two simultaneous pulses of current with the positive pulse being dominant over the negative pulse. We were able to control the temperature using a portable room heater, heat gun, or heating tape. Using heating tape was much more time effective than using either a portable room heater or a heat gun, since using heating tape only took 2 to 3 minutes to increase the internal temperature of the electrode chamber by 1°C. As the internal temperature was increased, amplitude of the electrode current reduced and at 20°C the polarity of the electrode current reversed to match the sign of the variation of pressure. At a very low temperature, a small pressure change caused higher amplitude of current. Further measurements verified that the negative current at a low temperature was due to condensation of water on the insulation of the triaxial connector that connects the electrode chamber to the electrometer. As water condensed upon the connector, a strong negative galvanic current was generated which concealed the positive pulse. So, it is possible that the positive electrode current is due to evaporation from the center electrode of the electrode chamber, and the negative current is produced from the galvanic action between the two dissimilar metals in the triaxial connector.

Using dew point analysis, we also showed that for water to condense on metallic surfaces, it is not necessary to reach the dew point.

In the water dielectrics experiment, we are still investigating the source behind the net measured current when the water dielectrics are kept in a Polyallomer centrifuge tube in a grounded Faraday cage. Many experiments were conducted to prove that the charge is not due to any experimental artifacts or any false instrument readings. Recent measurements have shown that the source behind the net measured current could be either due to the surface interactions between the water and the plastic or could be a volume effect or could be a combination of both. Future work will be conducted in depth using plastics with different surface characteristics.

We found that the measured current for distilled water and tap water is temperature dependent. With a temperature increase, the charge becomes more negative,

and after the temperature returns to the original room temperature, the charge also returns to the original room temperature value. Open-circuit voltage using distilled water and tap water also showed the voltage value to be temperature dependent similar to the dependence of measured charge on the temperature. For the Sargasso Sea water and 0.9% NaCl solution, the data is very noisy which could be due to chemical degradation of the metal grounding screw. Here, the measured charge changed only slightly due to temperature change. A temperature increase caused the charge to be only slightly more negative, and a temperature decrease caused the charge to decrease in magnitude as well. It was shown that the water was contributing an effect to the net measured current since an empty Polyallomer centrifuge tube showed only charge decay with temperature increase.

In the solid dielectrics experiments, we used Teflon and Acrylic. We measured charge and voltage as a function of temperature. We also triboelectrically charged them by rubbing with other solid materials. Increasing the temperature caused the charge obtained by rubbing to discharge faster. Cooling the temperature greatly slowed the process. A triboelectric series was also formulated for each of the triboelectric experiments. Using the given Faraday cage and the electrometer, we can precisely measure the triboelectric charge values with good numerical precision.

Several future experiments are suggested by the current research. In attempting to discharge Teflon surface charge more rapidly by dipping it in distilled water, it was found that this procedure caused a distinct triboelectric charge value on the Teflon. It will be necessary in future experiments to allow sufficient time for equilibrium states to be reached before this effect can be confirmed. It would appear that dipping of Teflon into non-wetting liquids might produce useful numeric triboelectric values.

In order to change samples, it was difficult, if not impossible, to disassemble and reassemble the Faraday cage apparatus without introducing unwanted charge to the samples. Therefore, some of the data, such as for the comparison of different metal grounding screws, may show small differences because equilibrium non-zero values had not yet been reached. Ideally, newly introduced samples require several days to lose unwanted charge.

As for the values of non-zero net charge, only a few samples were left in the grounded Faraday cage and observed over extended periods of up to four weeks without showing any change in value. Some of the data plots [Figure 5.5 and 5.7] show a clear tendency to reach a flat equilibrium charge value after 500 minutes. Most of the liquid dielectric experiments were not run long enough to show such a flat equilibrium value in their plot. Future experiments should include some with very long time periods to confirm these equilibrium states.

The cause of noise in the seawater data needs to be investigated. If the liquid sample is not connected to ground during the entire experiment, the liquid's charge will not change. This can be confirmed by running experiments that do not use a metal grounding screw. Plots that do not match the majority should be repeated with attention given to liquid levels and proper grounding. These include Figures 4.10, 4.12, and 4.13. The metal rod that connects samples to ground moves in a bearing that can collect dirt or oil that interferes with a good ground connection. The metal screws may also develop surface double layers that interfere with the passage of the low currents involved. Other metals should be tried in the future.

Finally, time only allowed for a casual experiment using several concentrations of surfactant wetting agent. The charge of distilled water in a Polyallomer tube appeared to be a function of that concentration. This has created sufficient interest to plan further experiments for confirmation. If confirmed, it would suggest that the charge source of liquid dielectrics in Polyallomer tubes is related to the liquid/plastic interface. Several other plastic tubes have been obtained that have different surface properties and they appear to produce different values of charge using the same source of distilled water.

Appendix A

A.1 Data Acquisition from the Tektronix TDS 1012 Oscilloscope

To acquire the waveforms from the oscilloscope to the computer terminal, first press the “run/stop” button on the oscilloscope. This will freeze the waveforms and allow them to be copied to the computer terminal.

In order to acquire the data from the oscilloscope, open the “wavestar” program and use “Notesheet,” or the “YT sheet” from the New DataSheet that is under the File menu. Then, use “Screen copy” if you use the “Notesheet” or use “Waveform” icon if you use the YT sheet to drag the waveforms from the oscilloscope.

When using the “Waveform” icon, there are some steps that need to be followed and they are as follows:

- The “math” waveform, the “Ref 1” and the “Ref 2” waveforms must be disabled.
- In order to disable the math waveform, press the math menu on the oscilloscope, and then disable it from there by pressing the button that is adjacent to the On/Off display on the oscilloscope. If it shows “on,” then pressing the button next to it will put it in the “off” mode, and if it is already in the “off” mode nothing needs to be done.
- Next, to disable the “Ref 1” and “Ref 2” waveforms, press the save/recall button on the oscilloscope. Then at the bottom of the oscilloscope screen, “Ref 1” and “Ref 2” will appear. If they are in the “on” mode, disable them by pressing the button next to the “on” display.
- If these waveforms are not disabled before copying them to the computer, then on the oscilloscope screen all these redundant waveforms will be copied to the computer. If this procedure is not performed properly, then after copying waveforms and pressing the “run/stop” button on the oscilloscope, continued scanning will disable the system. The very top of the oscilloscope screen will show “Armed”, and then to start new waveforms all the channels must be disabled and it is necessary to reset the divisions. That is why, it is better to disable all the waveforms before pressing the “run/stop” on the oscilloscope.
- Finally, after disabling the waveforms from the oscilloscope, you can employ the “Waveform” icon to drag the waveforms from the oscilloscope. Clicking on the “Waveform” icon from the computer will show five items, “Ch1, Ch2, Math, Ref1, and Ref2”. Since only Ch 1 and Ch 2 are wanted, left click on Ch 1 and hold it and then release it upon bringing it into the YT sheet. That will display Ch 1, and following the same procedure for Ch 2 will show the Ch 2 waveform on the computer screen. If there is no printer connected to the computer, copy those waveforms into the “paint” icon that is under “Accessories” from the “Program” menu in the computer. Then, the waveforms can be saved on a disk, and can be printed from any computer where a printer is connected. The reason that waveforms must be copied into the “paint” icon is so that the computer does not need “Wavestar” installed to print.

A.2 Steps of Storing and Recalling Temperature Data from the 2001 Digital Multimeter

The steps which were taken to store and recall the internal temperature of the chamber using the 2001 are as follows:

- At first, the 2001 needs to be programmed to display the internal temperature either in centigrade scale or in Fahrenheit scale.
- To store the data, press on the “store” button. Then, select an adequate number of data points to serve the purpose of analyzing the data. For our measurements, we chose 100 data points.
- After choosing the number of data points, the next step is to press the “enter” button. Once the “enter” button is pressed, it starts recording data.
- After it records the desired number of data points, press the “recall” button. Immediately after pressing the recall button, the first data point will be displayed, and then using the right arrow in the multimeter the following data can also be recorded.
- After recording all the data points from the multimeter, plot them in any desired spreadsheet.

Appendix B

B.1 Permittivity of Saturated Water Vapor

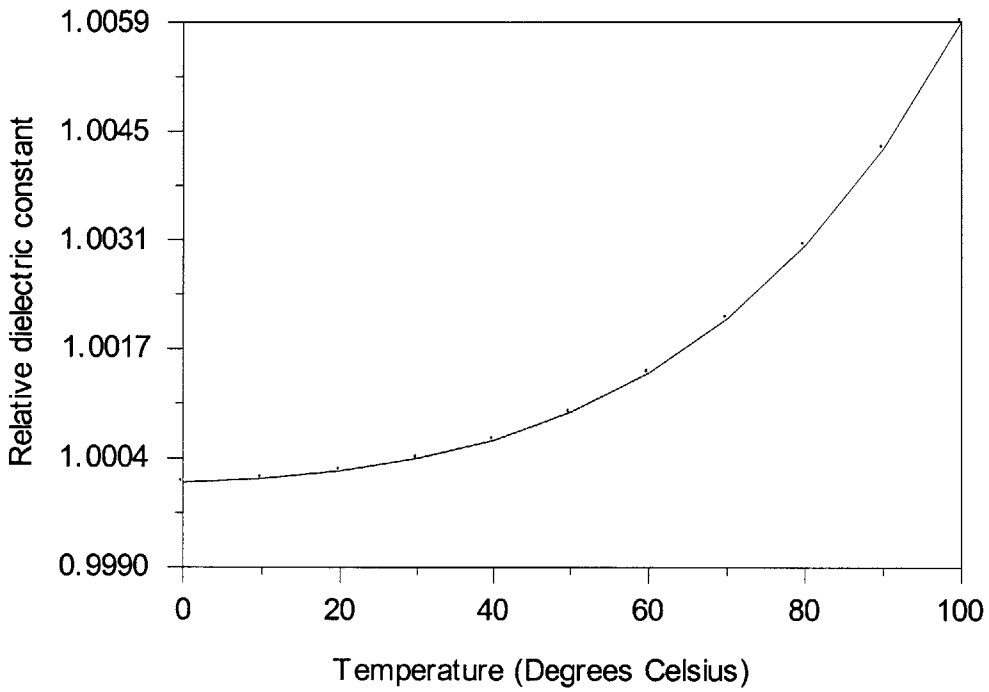


Figure B.1: Permittivity of saturated water vapor as a function of temperature. The data for the relative dielectric constant and temperature are adapted from [1]. With an increase in temperature, the permittivity of saturated water vapor increases in an exponential way.

B.2 Saturated Vapor Pressure of Air as a Function of Temperature

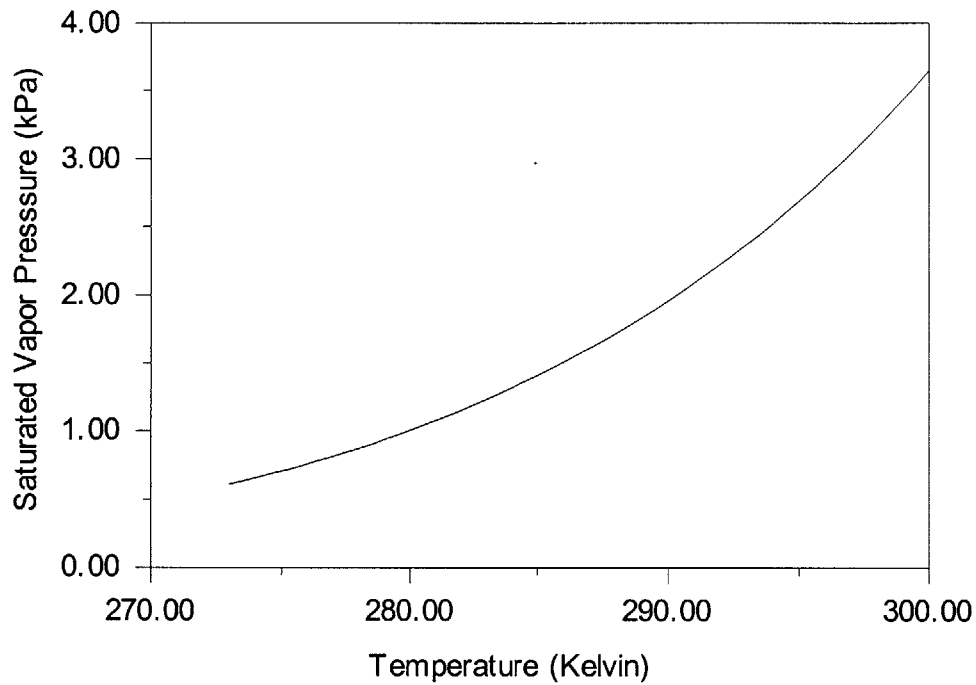


Figure B.2: Variation of saturated vapor pressure of air denoted as E_s with temperature. The relationship between E_s and T is given in Eq. (6) in Chapter 2. With an increase in temperature, the saturated vapor pressure increases essentially in an exponential way.

B.3 Variation of Relative Dielectric Constant with Temperature and Pressure of Dry Air

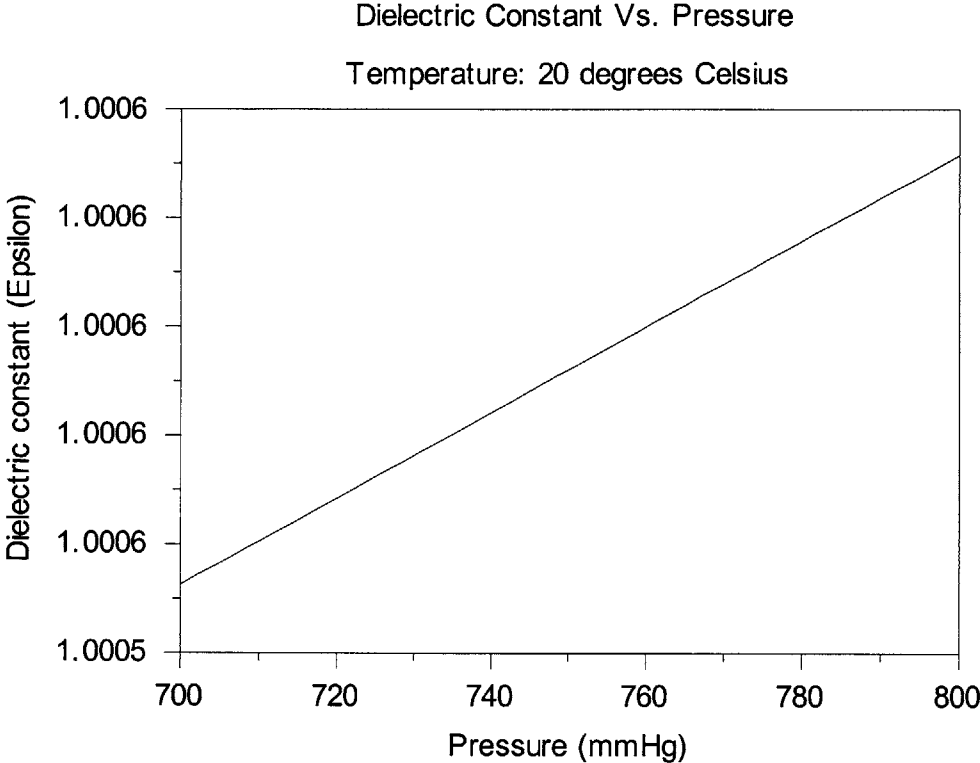


Figure B.3: Variation of relative dielectric constant with pressure at 20°C. The relationship between relative dielectric constant, pressure, and temperature of dry air is given in Eq. (15) in Chapter 2. With an increase in pressure, the relative dielectric constant increases linearly with pressure at a constant temperature.

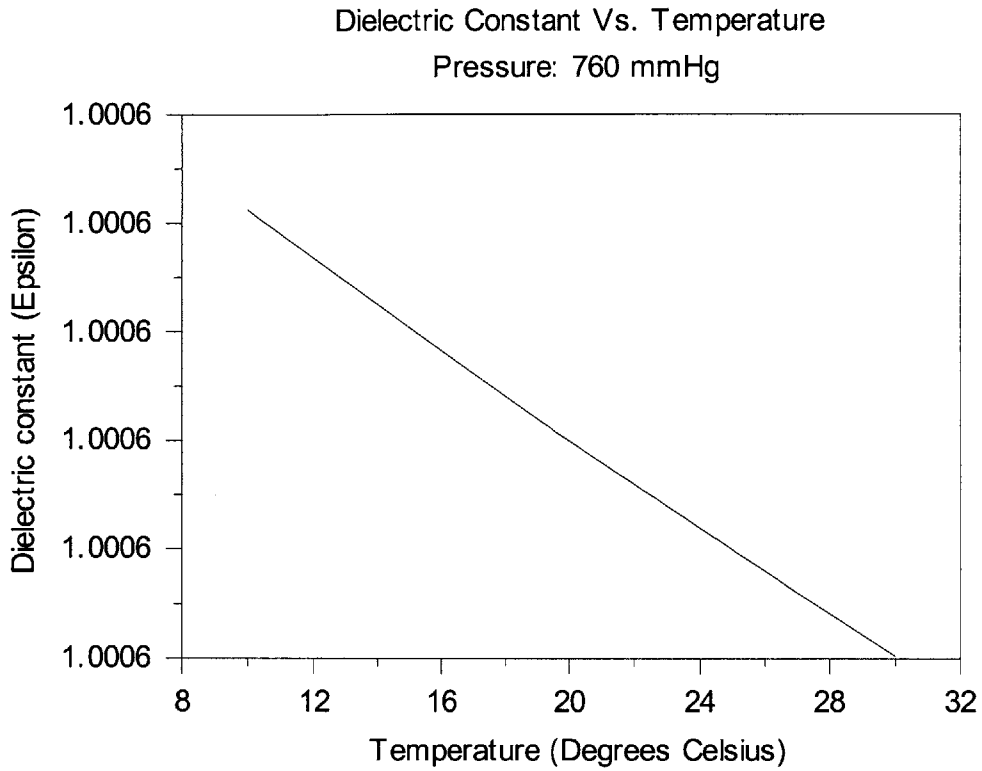


Figure B.4: Variation of relative dielectric constant with temperature at a pressure of 760mmHg. The relationship between relative dielectric constant, pressure, and temperature of dry air is given in Eq. (15) in Chapter 2. With an increase in temperature, the relative dielectric constant decreases linearly with temperature at a constant pressure.

B.4 Variation of Relative Dielectric Constant with Humidity at a Constant Temperature and Pressure of Moist Air

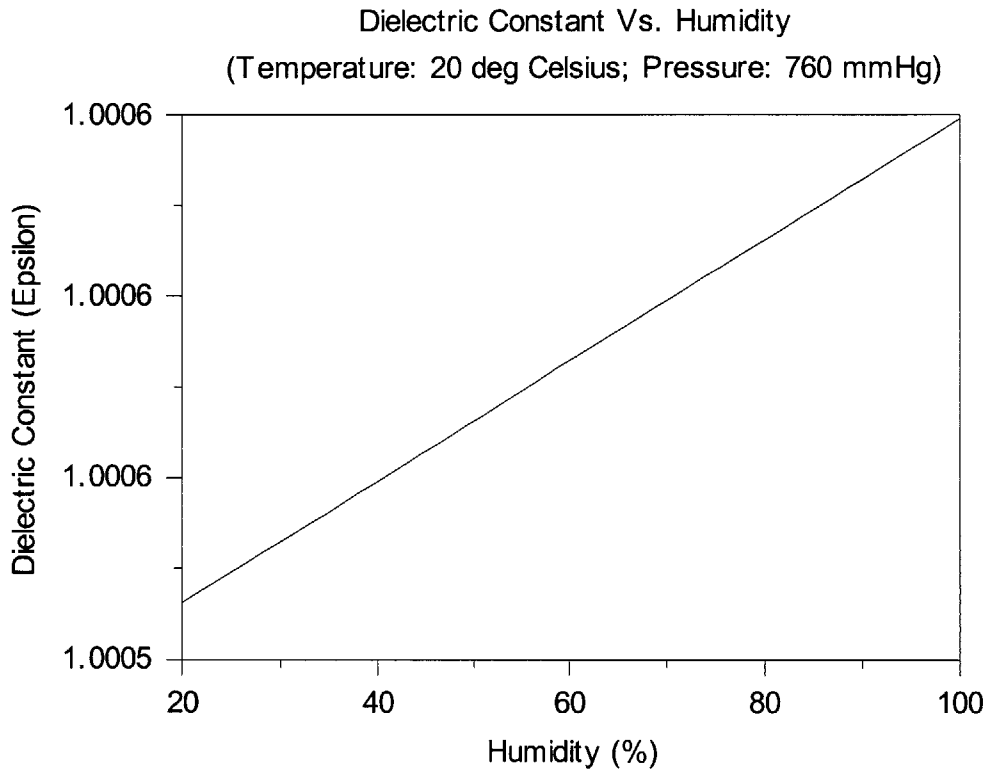


Figure C.5: Variation of relative dielectric constant with humidity at a pressure of 760mmHg and at a temperature of 20°C. The relationship between relative dielectric constant, pressure, temperature, and humidity of moist air is given in Eqs. 22 & 26 in Chapter 2. With an increase in humidity, the relative dielectric constant increases linearly with humidity at an invariant temperature and pressure.

References

- [1] Lide, David R., *Handbook of Chemistry and Physics*, 76th Edition, CRC press, Chapter 6, pp. 210.

Appendix C

C.1 Programming the 2001 Digital Multimeter to Control the Motion of the Sample inside the Faraday Cage [1]

The Digital I/O port located at the back of the 2001 must be connected to the black box containing 4 AA batteries. The box has two wires which act as a switch which goes to the 8 pin relay socket. Next, to control the motion of the sample using the multimeter, the following steps need to be followed.

- On the 2001, press on Main Menu.
- Then using the right arrow button find “General Menu,” and then press Enter.
- Select Digital I/O from the General Menu and then press Enter.
- Select Output State and then press Enter.
- Then select “ON” or “OFF” using “up” and “down” button.
- Selecting “ON” makes the sample move from the lower Faraday electrode to the upper Faraday electrode and selecting “OFF” makes the sample move from the Faraday upper electrode to the Faraday lower electrode.
- To exit from the program, press Exit.

C.2 Programming the 2001 Digital Multimeter to Configure Channels to Record the Temperature [2]

- Push the Input button that is located on the front panel of the 2001.
- Press on Configure.
- Select channel and then select internal channels.
- Then a list of functions will be displayed as: 1 = DCV 2 = DCV.....
- Set the first three channels to measure temperature, TMP. Select the first channel and then press on TMP button, and use the right arrow button to move to the second channel and then press on TMP button again. Channel 1 is used to measure the ambient temperature, and Channel 2 is used to measure the internal temperature of the Faraday cage. Channel 3 is used for accuracy purposes. So, also select the third channel, and press on TMP button.

C.3 Steps of recording the temperature [3]

- Connect the RTD appropriately to the 2001.
- Press on TMP button; if the “Overflow” message is shown, it means the RTD might not be connected properly.
- If the “Overflow” message does not appear, then select “type” = PT 100.
- For Units, select Degrees Celsius.
- For Speed, select Normal.
- For Filter, select Auto.
- For Resolution, select 0.01 degrees, and then press on the Exit button.

C.4 Steps of Using the Channels to record the Room Temperature and the Internal Temperature of the Faraday Cage [4]

- Select Channel from the front panel of the 2001.
- Select Close-Channels.
- Because the first three channels are used, the first three channels must be closed.
- After selecting Close-Channels, at first select Channel #1, and then press Enter.
- The process needs to be performed two more times to close Channel #2 and Channel #3.

References

- [1] Keithley Instrument Co. *Operator's Manual for the 2001 Digital Multimeter*, Chapter 3, pp.139 to pp 140, 1992.
- [2] Keithley Instrument Co. *Operator's Manual for the 2001 Digital Multimeter*, Chapter 3, pp.111, 1992.
- [3] Keithley Instrument Co. *Operator's Manual for the 2001 Digital Multimeter*, Chapter 3, pp.56, 1992.
- [4] Keithley Instrument Co. *Operator's Manual for the 2001 Digital Multimeter*, Chapter 3, pp.110, 1992.