4-1980

# Variables Influencing the Filtration of Water through Paper

Daniel J. Geddes
*Western Michigan University*

# VARIABLES INFLUENCING THE FILTRATION OF WATER THROUGH PAPER

by

Daniel J. Geddes

A Thesis submitted
in partial fulfillment of
the course requirements for
The Bachelor of Science Degree

Western Michigan University
Kalamazoo, Michigan
April, 1980

## ABSTRACT

When water is filtered through paper under constant pressure, the flow rate decreases with time, even if distilled water is used as the permeating fluid. On the basis of previous literature, possible causes of this effect were thought to be fiber swelling, the presence of microscopic bubbles in the water, electrical forces, or structures formed by water molecules and ionic impurities.

Experimentation showed that there is a blocking agent present in the distilled water which causes the decrease in flow rate. These particulate agents are denser than water, and have a greater affinity for cellulose than for glass. The particulates have a positive charge associated with them, and it is possible that some amount of electrolyte may be physically or chemically bound to them.

It was observed that filtration of water through ordinary laboratory filter paper can result in decreasing the conductivity of the water. Three possible mechanisms were proposed, although on the basis of this study alone the exact nature of the conductivity reducing effect can not be determined.

The electrical potential difference that may easily measured between the two side of a filter paper as water flows through it is actually a complex combination of the affects of several sources. The most important of these sources are the streaming potential and the accumulation of charged particulates.

# TABLE OF CONTENTS

# INTRODUCTION

When water, even distilled water, is filtered through a paper filter at a constant pressure drop across the filter, the flow decreases with time. The objective of this thesis investigation is to determine the cause of the flow blocking effect and to gain a better understanding of the mechanisms involved.

The cause of the filter permeability reduction has practical implications, even aside from the many interesting theoretical questions it raises. A suitable explaination will lead to a better understanding of filtration processes which involve water and perhaps will allow improvements to be made in such operations. The blocking phenomenon may play a role in slowing industrial filtration processes, for example.

## THEORETICAL DISCUSSION

Initial Observations:

Although the cause of the flow rate blocking phenomenon remains unknown, several observations have been made concerning it (1). If a paper filter is subjected to the flow of water and the flow rate through the paper is monitored over a period of time, the flow rate will be found to decrease with time. If the filter paper is removed and dried once the decrease in flow rate has occurred and is then resubjected to the flow of water, the subsequent flow rate obtained is in the range of that of the initial flow rate before the paper was dried. Similarly, if the filter is removed and inverted once flow has decreased and the flow rate of water through it is measured immediately, without drying the filter, the flow rate is again restored to its initial level. In addition, a positive correlation between the magnitude of the decrease in flow rate and the conductivity of the distilled water used to permeate the filters was observed.

These observations are somewhat puzzling, taken as a group. The experiment in which the filter paper is inverted suggests that solid particulates in the water could be causing the blockage, but it is hard to explain the effect drying the filter had in these terms. On the basis of these initial observations, however, the literature was searched and several, somewhat interrelated, possible explainations were found. These will be discussed in the balance of the theoretical dis-

cussion section of this paper.

Bubble Nuclei:

Since the reduction in permeability to the flow of water dissappears when the filters are removed and dried, the presence of some sort of a volatile blocking agent is suggested. Roland Gertjejansen and Ralph Hossfield of the University of Minnesota published a report on work they had undertaken in the investigation of variables affecting the permeability of wood pulp pads to water (2). Their work dealt primarily with the flow of water through pads of pulp that were pre-saturated with water. Somewhat suprisingly, the study indicated that the age of the distilled water used in determining pad permeability had a major influence on the magnitude of the permeability that was observed. The term 'age' was used to denote the length of time that elapsed between the time the water was distilled and the time it was used in a permeability experiment. Their eventual conclusion was that microscopic bubbles, which form the nuclei for the formation of larger bubbles, are present in distilled water, at levels that somehow depend on the age of the water.

A summary of their results is as follows:

1. When freshly distilled water was ised to permeate a pulp pad, the permeability of the pad remained fairly constant with respect to the elapsed time of flow.
2. When aged distilled water was used, on the other hand, the pad underwent a substantial permeability decrease

over a period of time, until an equilibrium flow rate was reached at a reduced permeability several hours later.

3. The affect of the aged water was independent of its dissolved air content.
4. When aged water was filtered using a 0.22 micron Millipore filter prior to being used in a permeability experiment, the permeability obtained remained constant with respect to time.

In a follow-up study, Gertjejansen (3) was able to show that the size range of the blocking agents in the water was 1.2 to 5.0 microns. This range is in good agreement with the size ranges obtained for bubble nuclei by other workers, notably Fox and Herzfield (4). Freshly distilled water that was purposely contaminated with bentonite clay particles 1.0 to 9.0 microns in diameter by Gertjejansen behaved similarly to the aged water, while the addition of polystyrene latex particles 0.365 microns in diameter introduced no such behavior. This was further proof that the blocking agents in the water were of the size range determined.

In the same follow-up study, Gertjejansen showed in another experiment that boiling the aged water minimized the decrease in permeability, but vacuum induced vaporization of the water had little effect.

Pioneering work in the area of bubble formation by E.N. Harvey and others (5) showed that bubble nuclei do exist, at least in irregularities of the surfaces of glass containers.

Gertjejansen's explaination of the pulp pad permeability drop is reasonable only if free bubble nuclei can exist dispersed in large quantities in distilled water. Because of surface tension factors, however, small bubbles would be expected to dissolve in a very short time. The work of Fox and Herzfield (op. cit.) does provide the needed justification. Their work with the ultrasonic cavitation of water led them to propose a mechanism by which bubble nuclei can be both free and stable in water. Basically, their hypothesis is that tiny bubbles may be stabilized by a thin organic film, similar to the film that forms rapidly on any water surface exposed to the atmosphere. The organic sheath acts as a barrier to prevent diffusion of gases from within the bubble and so protects the bubble from dissolution. Liebermann (6), in fact, has shown that there are hydrophobic organic residues associated with bubbles forced into solution under high pressure.

It seems possible that the blocking effect of interest in the current investigation of the flow of water through paper could be caused by agents similar to those that were responsible for the permeability decrease that was seen by Gertjejansen and his co-workers.

## Electrical Forces:

Since some correlation between the extent of flow rate decrease during the filtration of water through paper and the conductivity of the water which is filtered has been observed, the possibility exists that the effect is at least partially

electrical in nature. The electrokinetic effects of electo-osmosis and streaming potential are factors which may play a role. If a potential difference is applied between the ends of a plug of finely divided material which contains an electrolyte solution, a movement of the liquid can be observed (7,8). This phenomenon is electro-osmosis. Conversely, when water or other liquid is forced through a porous medium, an electrical potential difference between the two sides of the porous medium is generated. This induced potential is called the streaming potential.

A thesis investigation by Morcos (9) examined the magnitude of the streaming potential under various conditions of flow through a pad of fifty cellulose filter papers. By analyzing the problem mathematically from an engineering standpoint, Morcos concluded that a reasonable source of the electrical energy generated by the streaming potential would be the mechanical energy that is dissapated in flow through the pad, provided that the dissapated energy was not entirely consumed in the generation of frictional heat. Morcos' work denies the relationship between streaming potential and zeta potential that earlier workers, such as Mason (10,11), had proposed. Morcos concluded instead that the source of the electrical energy is not an "intrinsic constant quantity" of the substances involved, but is generated by the dynamics of fluid flow.

When Morcos started experiments with dry pads, he noticed that when water was introduced to the pad and began to flow through it, the initial potential was positive (i.e. the

upstream electrode was positive). The positive potential decayed and reached an equilibrium negative value several hours later. The equilibrium streaming potential was also found to be negative when glass paper was used instead of cellulose paper.

When dilute electrolyte solutions were used in place of distilled water in the experiments, the magnitude of the equilibrium streaming potential decreased drastically. This was attributed to the higher conductivities of the solutions as opposed to the conductivity of pure water. This caused the solutions to act as conductors between the two sides of the pad, allowing accumulated charges to move across the pad and neutralize the opposite charges.

## Structure of Liquid Water:

Although the structure of liquid water is not fully understood, it seems possible that structural considerations could come into play in the filtration blocking phenomenon. It could be that structures big enough to plug filter pores are formed with time, from water and ionic impurities alone, for example.

Some researchers hold that water in its liquid state can be regarded as a mixture of "bound" and "free" molecules (12, 13). The bound molecules constitute the bulk of the liquid and are hydrogen bonded together into a lattice structure similar to that of ice. This "vacant-lattice-point" model holds that the free, single water molecules are dispersed in defects of

the ice-like structure. An important implication of the theory is that the ice-like regions become more and more dis-organized as the temperature of the water is increased.

The "flickering cluster" theory of water structure holds that liquid water is composed of clusters of associated molecules and highly reactive monomeric $H_2O$ units in dynamic equilibrium (13,14). Although this theory has some resemblence to the previously mentioned one, it has different experimental implications with regard to the present study. Under this theory, the introduction of ionic species into an aqueous system inevitably changes the number and sizes of the organized cluster regions. Small or highly charged ions, such as $Na^+$ or $Li^+$, will act as nuclei for cluster formation by immobilizing the surrounding water molecules with an ion-dipole attraction. Similar ions of lesser charge or larger ionic radii, such as $K^+$ or $NH_4^+$, have the opposite effect of acting as centers around which monomeric $H_2O$ units exist. Thus, the nature of ionic impurities in distilled water can have an effect on the overall structure of the water, and so affect flow properties. This provides another possible explaination of why flow blocking might be related to the conductivity of the water.

Clusters of water molecules surrounding an ion may form structures which are large enough to plug filter pores. It is unlikely, however, that simple hydrated ions can act as blocking agents. The largest ion sizes are on the order of tens of

Angstrom units, probably too small to affect ordinary filtration.

## EXPERIMENTAL PROCEDURE

The relationship between flow rate trough a filter and elapsed time of flow was measured by means of the filtration chamber, shown in figure 1. The device consisted of a porcelain laboratory Buchner funnel, designed for 11.0 cm filter paper, with a plastic extension attached to it. The inlet and outlet tubes were made of ¼-inch I.D. glass tubing connected to ¼-inch I.D. tygon tubing. The outlet tube served to control the head level of water above the filter pad and was connected to a vacuum aspirator to provide quick response to remove excess water and keep the head level to within ± 0.1 cm of its desired value. The flow rate measurements were made by collecting the filtrate that flowed through the filter paper for a known amount of time, measuring the amount volumetrically, and calculating the flow rate in ml/minute.

In every case where cellulose filter paper was used, it was four sheets (used as a pad) of Fisher Qualitative Filter Paper. When glass paper was used, it was three sheets of Whatman GF/A Glass Fiber Paper. The number of sheets used was determined by observing that three sheets of the glass paper gave approximately the same flow rate as four sheets of the cellulose paper. Unless otherwise noted, all experiments were conducted with the paper wire-side up (i.e. the wire-side was the upstream side of the filter pad).

The electrodes were formed from thin copper plates, about

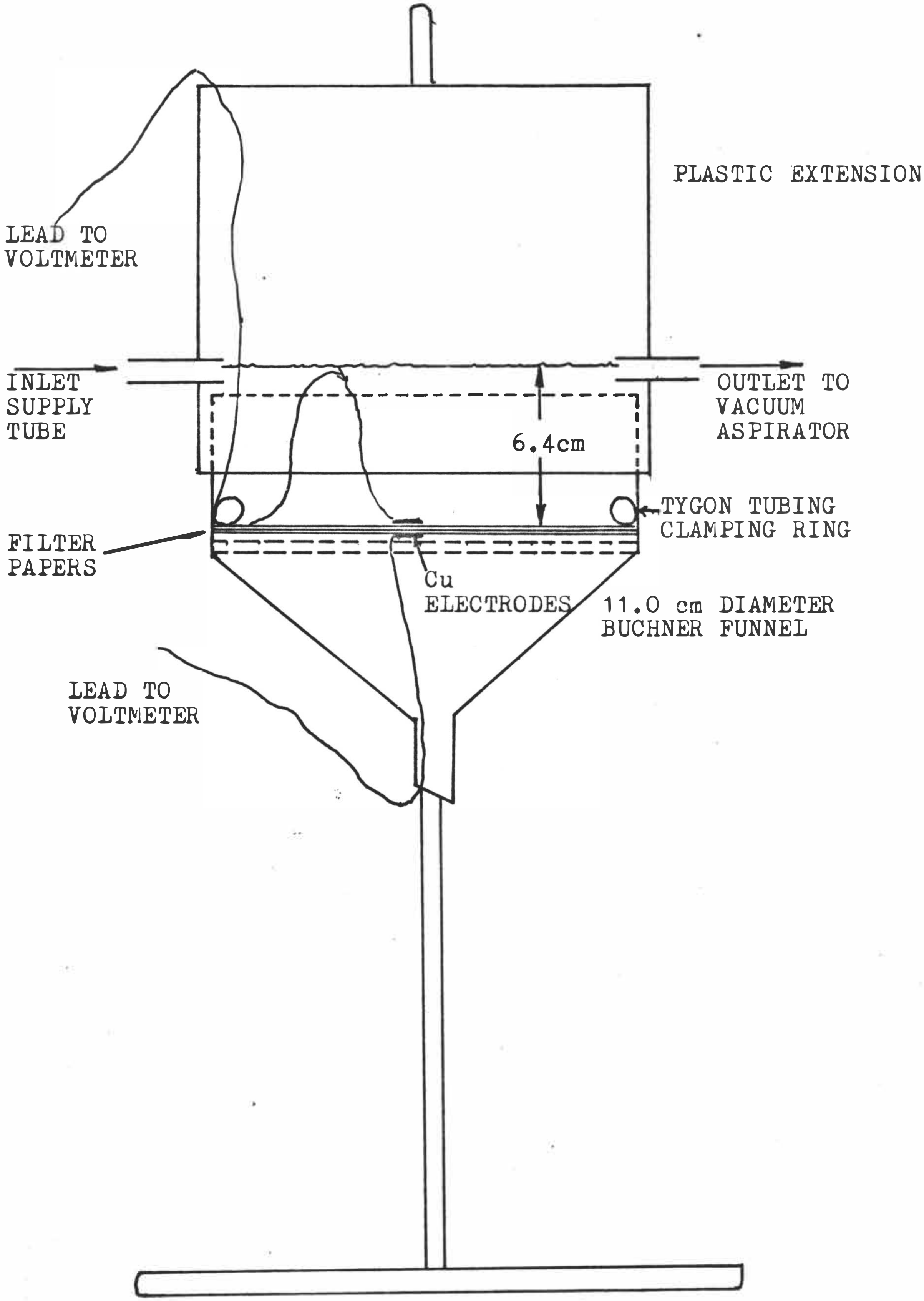


Figure 1-- Filtration Chamber

1 cm x 1 cm in size. The bottom electrode laid flat on the porcelain plate of the funnel, its lead wire (insulated copper) extending down through one of the holes in the porcelain plate. The paper to be used in the experiment was placed on top of the lower electrode, then the upper electrode on top of the paper. The paper and the electrode were then clamped into place with a ring of tygon tubing that was big enough to fit snugly against the walls of the funnel.

The potential difference between the two electrodes was measured with a Keithley 610B Electrometer (as shown in figure 2), a high impedence ($10^{14}$ohm) voltmeter. Each time a filtrate sample was collected for flow rate determination, a voltage reading was recorded. In all instances, the sign of the observed potential refers to the sign of the upstream electrode.

Conductivities were monitored during each experimental run, both of the inlet water and of each filtrate sample collected. Measurements were made using a Beckman conductance bridge and conductivity cell.

The water used in all experiments was supplied by the McKracken building distilled water system. Because minor variations in the quality of the water produced by this system were expected, it was decided to do a seperate control run for each experiment to be conducted. All water and solutions were handled in 6½ gallon Nalgene polyethylene storage bottles with spigots.

All flow rates were determined by collecting filtrate in

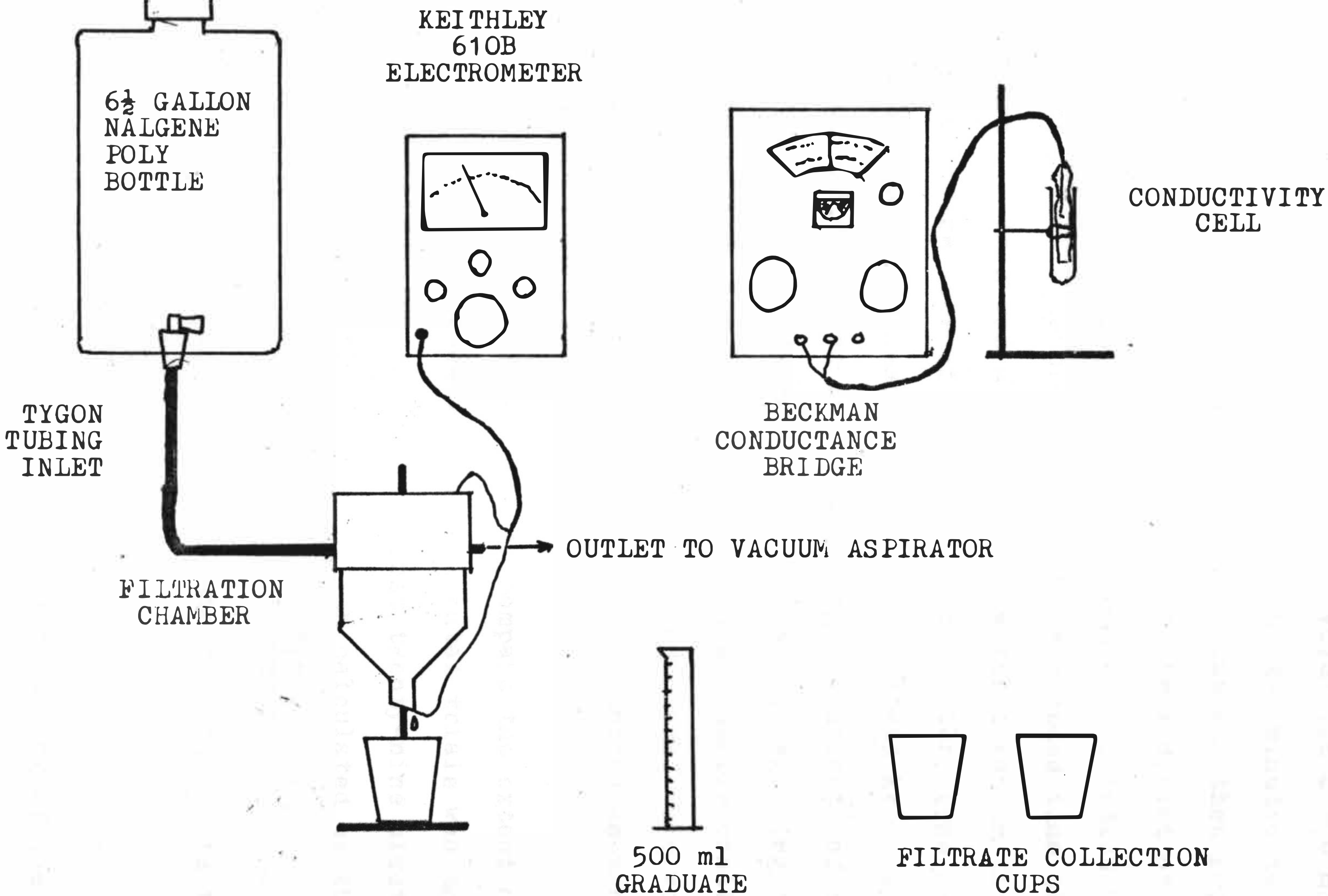


Figure 2-- Experimental Apparatus

two minute samples, measuring the volume in a 500 ml graduated cylinder, and dividing the volume by two minutes to give the flow rate in ml/minute. This value was then reported as the flow rate through the filter at the midpoint of the two minute collection period. For example, collection of the first filtrate sample began when the elapsed time clock was started. This was at the instant water began to flow through the overflow tube of the filtration chamber. (The amount of time required to reach this water level was kept as constant as possible between runs by opening the spigots of the supply bottles to their maximum openings in the beginning of each run.) Collection of the first filtrate sample continued until 120 seconds elapsed on the time clock. The volume of this sample, divided by two would be reported as the flow rate at minute one.

The index that was used to compare the extent of the drop in flow rate between experimental trials was the per cent drop in flow rate during the first twenty-nine minutes of flow through the filter. This value was calculated by the formula

$$\% \text{ DROP IN FLOW} = \frac{F_1 - F_{29}}{F_1} \times 100,$$

where $F_1$ is the flow rate at minute one and $F_{29}$ is the flow rate at minute twenty-nine.

In order to gain a better understanding of the flow rate blocking phenomenon, a series of nine experiments was proposed and conducted. In addition, two experiments were conducted at a later date to help explain the results of the first nine.

The objective of the experiments was to distinguish between the possible explainations of the decrease in flow rate with time. The possible explainations were:

1. Fiber swelling- Flow rate decrease could be caused by water swelling the fibers, thus closing off pores.
2. Bubble nuclei- Microscopic bubbles stabilized by a thin organic film may be present in the water and act as particulates to plug pores.
3. Electrical forces- Electrical forces, such as streaming potential could exert an electrostatic repulsion on the water, thus slowing flow.
4. Water structure- Structures composed of water molecules and ion impurities could form or exist in the water and act as particulates to block flow.

The nine experiments initially proposed and performed were as follows:

1. Inverting Filter: To verify previous observations, an experiment was conducted to determine the affect of inverting the filter once the flow rate had decreased because of the blocking effect. This experiment was used to determine if fiber swelling plays a role in decreasing flow rate.
2. Drying Filter: This experiment, too, was performed to verify previous observations, and allow determination of the effect solid particles have on the decrease of flow rate.
3. Age of Water: A series of experimental runs was carried out using distilled water that had been aged 0,1,2, and

3 weeks to determine if there was a relationship between the age of the water and the blocking effect, as Gertjejansen had noticed in his pulp pad permeability experiments.

4. Conductivity: A series of experimental runs was performed with water of several different conductivities. The conductivity was controlled by adding a one percent sodium chloride solution to obtain the desired conductivities. This experiment attempted to determine if conductivity itself or conductivity in combination with streaming potential affected filter blockage.
5. Cations: A series of experimental trials was conducted with water that contained different cationic impurities. All cations were added as one percent solutions of their respective chloride salts. Evaluated were $Na^+$, $Li^+$, $K^+$, and $NH_4^+$ (to see if the structural affects predicted by the flickering cluster theory of water structure play a role) and $Ca^{++}$ (to determine if water hardness has an affect). All ions were added to an approximately equivalent conductivity to seperate conductivity effects from ionic effects.
6. Boiling: The effect of using boiled water versus non-boiled water was determined. This was to check for comparison to Gertjejansen's study and to try and break up any bubble nuclei that might be present in the water.
7. Temperature: One experiment was done with water of two different temperatures to determine if structures are formed in the water which are easily affected by changes

in temperature (such as those predicted by the vacant-lattice-point model of water structure).

8. Head Level: Because the streaming potential is expected to increase with increased pressure drop across the filter pad, one experiment determined the role streaming potential might play in the decrease in flow rate by controlling the head level of water above the filter, and thus varying the pressure drop across the pad.
9. Glass versus Cellulose: A series of runs was undertaken with both fresh and aged water using both glass and cellulose filter papers. This was to determine if the blockage was governed by some property of cellulose, or by agents within the water. In addition, the behavior of glass paper when a pH 3.0 HCl solution was used as the permeating fluid was evaluated. The surface of glass fibers gels slightly at about this pH level, and it was desired to know whether the gelling of the surface would make glass perform more like cellulose.

The final two experiments which were undertaken are discussed in the results section of this paper.

# RESULTS

## General Observations:

Table 1 and figure 3 show the results from a typical experimental trial (the control run for the boiling experiment). This example will be used to point out some of the more general observations that were made.

It is quite evident that the flow rate decreased with time in this trial. The graph of flow rate versus time shows that the decay in flow rate is a first order response, as would be expected if particles or particle-like structures were responsible for the flow rate decrease. Using the data from this example, a linear regression analysis was carried out for the variables flow rate versus log(time), and the results showed that the linear fit was very good. However, similar analyses performed on data from other runs did not show such a high correlation in every instance. This was one of the reasons that the per cent drop in flow factor was used as an index of flow rate decrease instead of regression data.

The voltage decreased with time in the example run. This in fact, was the most common observation when cellulose paper was used in the experiments. When cellulose paper was used, the trend was for the voltage to start at a maximum positive potential or rise to a maximum potential, and then decrease. When glass paper was used, on the other hand, the voltage tended to start at a minimum (a maximum negative reading) and increase. It is important to note that these observations were

| TIME (min.) | FLOW RATE (ml/min.) | VOLTAGE (mV) | CONDUCTIVITY (micromhos) |
|---|---|---|---|
| 1 | 303 | 23.0 | 4.7 |
| 3 | 295 | 21.0 | 4.6 |
| 5 | 289 | 20.3 | 4.3 |
| 7 | 283 | 20.2 | 4.4 |
| 9 | --- | 19.4 | 4.4 |
| 13 | 273 | 19.0 | 4.5 |
| 17 | 268 | 18.8 | 4.5 |
| 21 | 265 | 18.7 | 4.5 |
| 25 | 265 | 18.8 | 4.6 |
| 29 | 260 | 19.5 | 4.6 |
| 35 | 258 | 17.0 | 4.5 |
| 41 | 253 | 15.8 | 4.4 |
| 47 | 248 | 15.0 | 4.5 |
| 53 | 248 | 15.0 | 4.4 |
| 59 | 245 | 15.5 | 4.5 |

Table 1-- Results of a Typical Experimental Trial (Boiling Control)

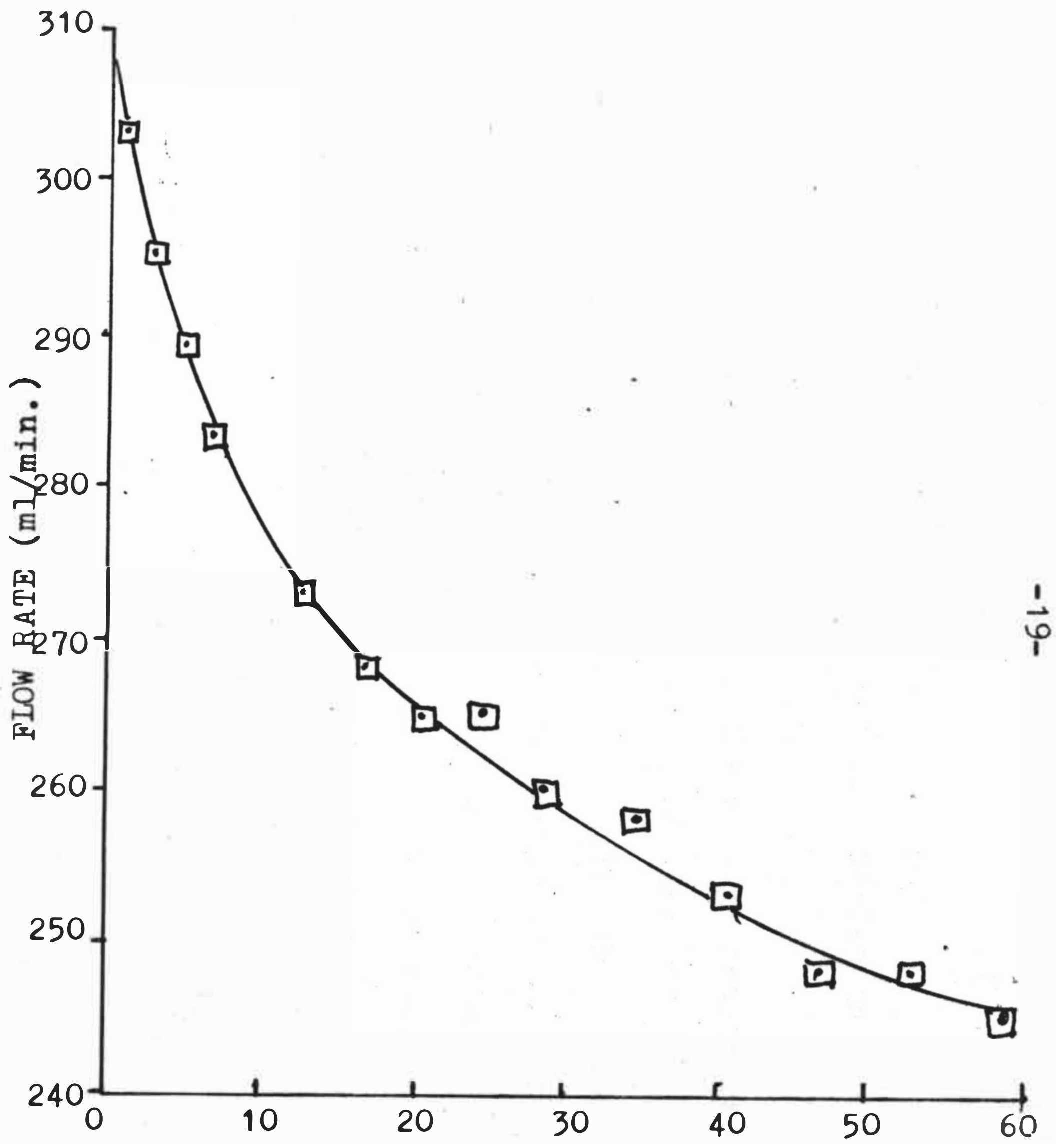


Figure 3-- Graph Showing Flow Rate Versus Time For Typical Trial

not universal, and inspection of the data tables in the appendix will uncover several exceptions.

Another observation regarding the voltage measurements was that in early experiments it was noted that if the inlet flow rate was adjusted too quickly by opening the supply valve too wide, the turbulence created around the upstream electrode caused the voltmeter reading to drop momentarily toward the negative. For this reason, in later runs the overflow rate to the outlet tube of the filtration chamber was always adjusted gradually to give just a trickle of water flowing through the outlet tube to the aspirator.

In almost every experimental run, the conductivity of the first filtrate sample was greater than the conductivity of the inlet water. It was also observed that the conductivity of the final filtrate sample was less than the conductivity of the inlet water, in almost every instance. A notable exception was that when boiled water was used as the fluid flowing through the filter, the filtrate conductivity did not drop below the inlet conductivity.

The flow rate results, as well as other pertnent observations, will be presented experiment by experiment in the balance of this section.

<u>Affect of Inverting Filter:</u>

Table 2 shows the results of three experimental runs where the filters were inverted after the flow rate was allowed to decrease after a period of time. Trial 1 was performed

| TRIAL | 1 | 2 | 3* |
|---|---|---|---|
| CONDUCTIVITY ($\mu$mhos) | 225 | 6.0 | 35 |
| INIT. FLOW W.S. UP (ml/min.) | 143 | 148 | 163 |
| FINAL FLOW W.S. UP (ml/min.) | 45 | 138 | 159 |
| INIT. FLOW F.S. UP (ml/min.) | 106 | 170 | 165 |
| TEMPERATURE ( C) | 18 | 22 | 22 |

*pH 3 HCl through glass paper

Table 2-- Affect of Inverting Filter

| TRIAL | 1 | 2 |
|---|---|---|
| CONDUCTIVITY ($\mu$mhos) | 260 | 3.3 |
| INIT. FLOW (ml/min.) | 138 | 220 |
| FINAL FLOW (ml/min.) | 123 | 172 |
| INIT. FLOW AFTER DRYING (ml/min.) | 180 | 258 |
| TEMPERATURE ( C) | 22 | 23 |

Table 3-- Results of Drying Experiment

with water that was accidently high in conductivity. Trial 2 used water of acceptable conductivity, while trial 3 was an attempt to make glass paper perform more like cellulose paper by using a pH 3.0 HCl solution in place of distilled water. In trial 1 the wire side was subjected to flow for one hour before the filter was inverted, and in the other two trials the wire side was the upstream side for thirty minutes before the filter was inverted. In all cases there was a substantial regain of flow rate when the filters were inverted. The differences between the wire side up flow rate at minute one and the felt side up flow rate at minute one can be accounted for by the normal variation between the two sides of the filters. Although experiments showed that on the average the wire side permeability to water and the felt side permeability to water were equal, in individual cases certain samples of four sheets of filter paper varied by as much as 30 ml/minute from side to side.

<u>Affect of Drying Filter:</u>

Once again, the first trial was accidently run with water high in conductivity. Both runs show that if filters are allowed to be reduced in permeability by flow, then dried in place and subjected to flow once again, the flow rates obtained actually surpass the initial flow rate before the filter was dried. These results are presented in table 3. It should be noted that the final flow rate in trial one was after one hour had elapsed, while in trial two the final flow rate was the flow after thirty minutes had elapsed. In tables 2 and 3, the initial flow rates refer to the flow rates at minute one.

Affect of Aging the Water:

Results that present the relationship between the per cent drop in flow factor and the age of the distilled water appear in table 4 and figure 4. The drop in flow increased substantially as the water was aged for greater periods of time.

Affect of Conductivity:

The addition of small amounts of electrolyte to the water decreased the drop in flow, while adding greater amounts increased the drop in flow. These data are presented in table 5 and figure 5. Note that as the conductivity was increased, the voltage decreased.

Affect of Cations:

This experiment showed that the addition of any of the cationic species that were evaluated, except for $Li^+$, caused a decrease in the per cent drop in flow. Addition of $Ca^{++}$ to the water had an intermediate affect; the drop in flow when this ion was added was less than that of the control and $Li^+$ but greater than the drop in flow obtained by the addition of the other ions. The results of this experiment appear in table 6.

Affect of Boiling the Water:

Table 8 shows that boiling the water had no affect on the percent drop in flow. One of the few cases where the conductivity of the filtrate samples did not drop below the conductivity of the inlet water was the run which used boiled water as the permeating fluid, as previously mentioned.

| AGE (weeks) | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| INLET COND. (μmhos) | 6.2 | 5.2 | 4.7 | 5.7 |
| FINAL FILTRATE COND. (μmhos) | 5.9 | 4.3 | 4.4 | 5.0 |
| FLOW @ MINUTE 1 (ml/min.) | 170 | 183 | 228 | 174 |
| FLOW @ MINUTE 29 (ml/min.) | 149 | 146 | 155 | 110 |
| % DROP IN FLOW | 12.4 | 20.2 | 32.0 | 36.8 |
| TEMPERATURE (°C) | 28 | 22 | 24 | 23 |

Table 4-- Results of Aging Experiment

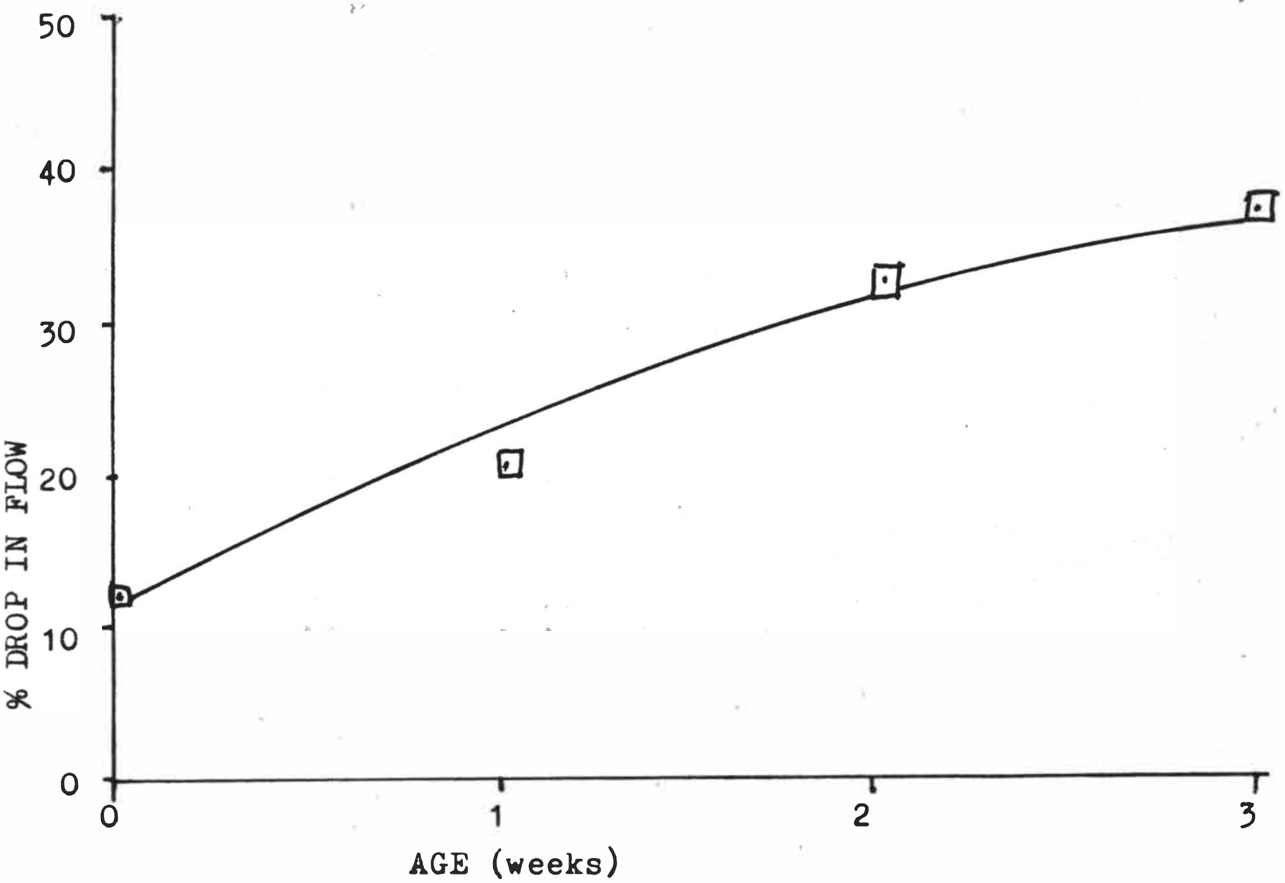


Figure 4-- Graph Showing % Drop in Flow Versus Age of Water

| INLET COND. (μmhos) | 3.9 | 11.8 | 23.0 | 46.0 | 84.0 |
|---|---|---|---|---|---|
| FINAL FILTRATE COND. (μmhos) | 3.5 | 11.9 | 22.5 | 44.0 | 82.0 |
| FLOW @ MINUTE 1 (ml/min.) | 170 | 135 | 155 | 155 | 160 |
| FLOW @ MINUTE 29 (ml/min.) | 150 | 128 | 148 | 140 | 133 |
| % DROP IN FLOW | 11.8 | 5.2 | 4.5 | 9.7 | 16.9 |
| VOLTS @ MINUTE 1 (mV) | +23.2 | +17.2 | +7.5 | +6.5 | +1.0 |
| VOLTS @ MINUTE 29 (mV) | +19.0 | +13.9 | +15.4 | +8.5 | +3.3 |
| TEMPERATURE (°C) | 20 | 19 | 22 | 20 | 19 |

Table 5-- Affect of Conductivity

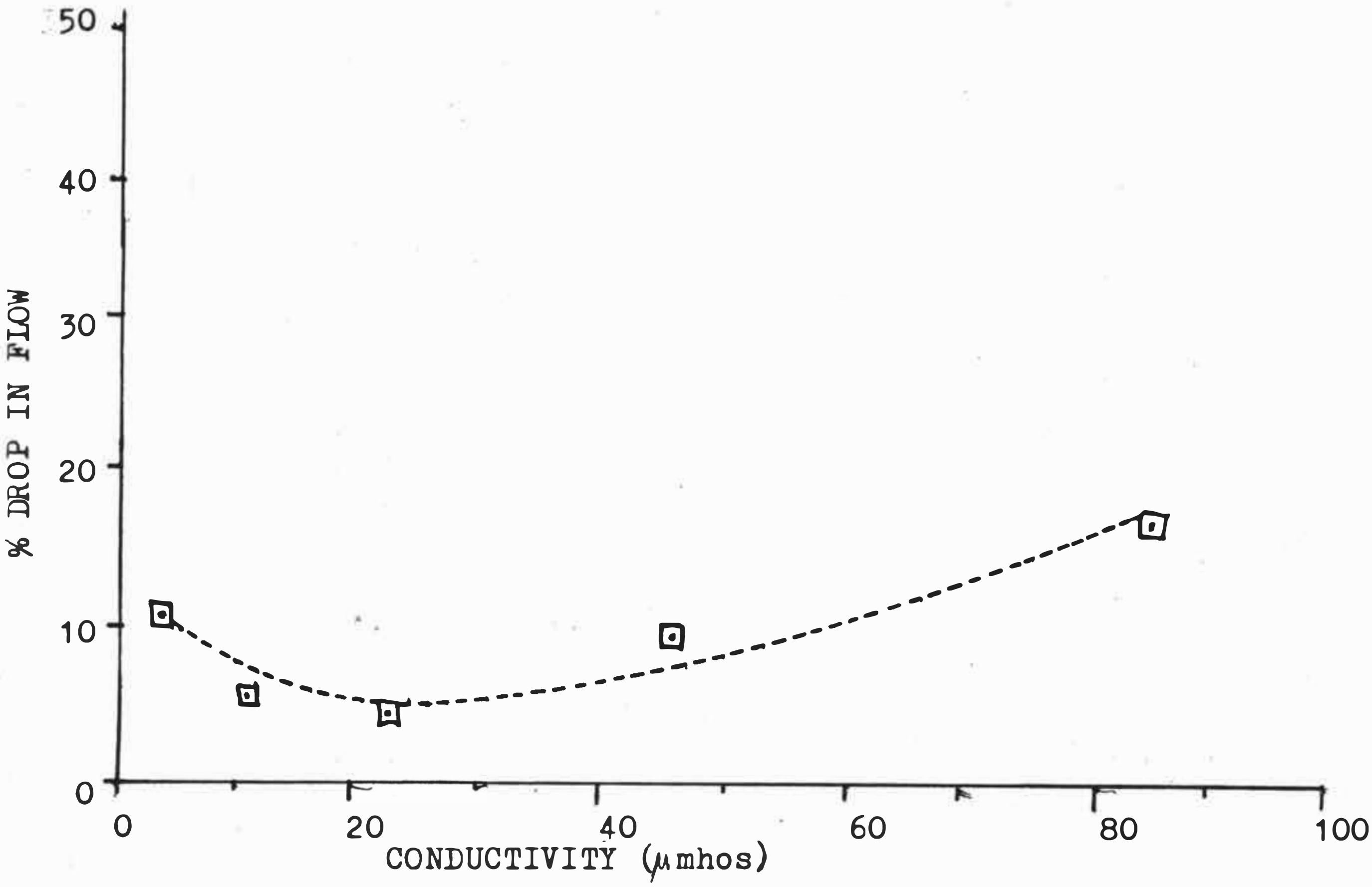


Figure 5-- Graph Showing % Drop in Flow
Versus Conductivity

| ION | NONE | $Li^+$ | $NH_4^+$ | $Ca^{++}$ | $Na^+$ | $K^+$ |
|---|---|---|---|---|---|---|
| INLET COND. ($\mu$mhos) | 3.9 | 13.7 | 13.0 | 12.8 | 12.6 | 13.0 |
| FINAL FILTRATE COND. ($\mu$mhos) | 4.5 | 12.8 | 12.7 | 11.4 | 12.6 | 12.5 |
| FLOW @ MINUTE 1 (ml/min.) | 170 | 175 | 187 | 178 | 128 | 150 |
| FLOW @ MINUTE 29 (ml/min.) | 150 | 158 | 180 | 164 | 126 | 145 |
| % DROP IN FLOW | 11.8 | 9.7 | 3.7 | 7.9 | 1.6 | 3.3 |
| TEMPERATURE (°C) | 20 | 20 | 22 | 23 | 18 | 21 |

Table 6-- Influence of Various Cations on % Drop in Flow

| TEMPERATURE (°C) | 23 | 29 |
|---|---|---|
| INLET CONDUCTIVITY (μmhos) | 6.0 | 6.0 |
| FINAL FILTRATE COND. (μmhos) | 5.3 | 5.0 |
| FLOW @ MINUTE 1 (ml/min.) | 140 | 144 |
| FLOW @ MINUTE 29 (ml/min.) | 130 | 133 |
| % DROP IN FLOW | 7.1 | 7.6 |

Table 7-- Results of Temperature Experiment

| | CONTROL | BOILED |
|---|---|---|
| INLET CONDUCTIVITY (μmhos) | 4.6 | 2.4 |
| FINAL FILTRATE COND. (μmhos) | 4.5 | 2.6 |
| FLOW @ MINUTE 1 (ml/min.) | 303 | 210 |
| FLOW @ MINUTE 29 (ml/min.) | 260 | 179 |
| % DROP IN FLOW | 14.2 | 14.8 |
| TEMPERATURE (°C) | 22 | 23 |

Table 8-- Results of Boiling Experiment

Affect of Temperature:

A moderate change in the temperature of the water had no affect on the decrease in flow rate, as shown in table 7.

Affect of Head Level:

Figure 6 and table 9 show that as the pressure drop across the filter was increased, the drop in flow increased dramatically when cellulose paper was used and increased slightly when glass paper was used. There is no apparent relationship between the pressure drop across the pad and the voltage potential that was observed. When glass and paper are compared at similar head levels, it can be seen in both cases that glass is less susceptable to the blocking effect than is cellulose.

Glass versus Cellulose:

When either aged or fresh distilled water was used as the permeating fluid, glass showed less of a drop in flow than did paper (see table 10). The use of a pH 3.0 HCl solution to permeate glass did not impart cellulose-like behavior to the glass filter. The fact that in this experiment aging the water resulted in a lower decrease in flow rate seems to directly contradict the observations made in the aging experiment. It was realized that the aged water in this experiment could have been shaken up a little bit more than in the prior experiment, since it was stored on the floor and was lifted and dropped onto a lab bench and then lifted onto a shelf just before it was used in the experiment. Because this extra

| HEAD (cm $H_2O$) | CELLULOSE 6.4 | CELLULOSE 11.0 | CELLULOSE 15.0 | GLASS 6.5 | GLASS 15.4 |
|---|---|---|---|---|---|
| INLET COND. (μmhos) | 5.2 | 5.3 | 5.0 | 6.3 | 6.3 |
| FINAL FILTRATE COND. (μmhos) | 4.4 | 4.7 | 4.8 | 5.3 | 5.3 |
| FLOW @ MINUTE 1 (ml/min.) | 125 | 207 | 278 | 160 | 280 |
| FLOW @ MINUTE 29 (ml/min.) | 99 | 148 | 99 | 155 | 253 |
| % DROP IN FLOW | 20.8 | 28.5 | 64.4 | 2.5 | 9.6 |
| VOLTS @ MINUTE 1 (mV) | +20.8 | +18.5 | +12.5 | -10.2 | -31.0 |
| VOLTS @ MINUTE 29 (mV) | +16.4 | +23.2 | +22.5 | +5.7 | +1.0 |
| TEMPERATURE (°C) | 23 | 23 | 23 | 22 | 23 |

Table 9-- Affect of Head Level on % Drop in Flow

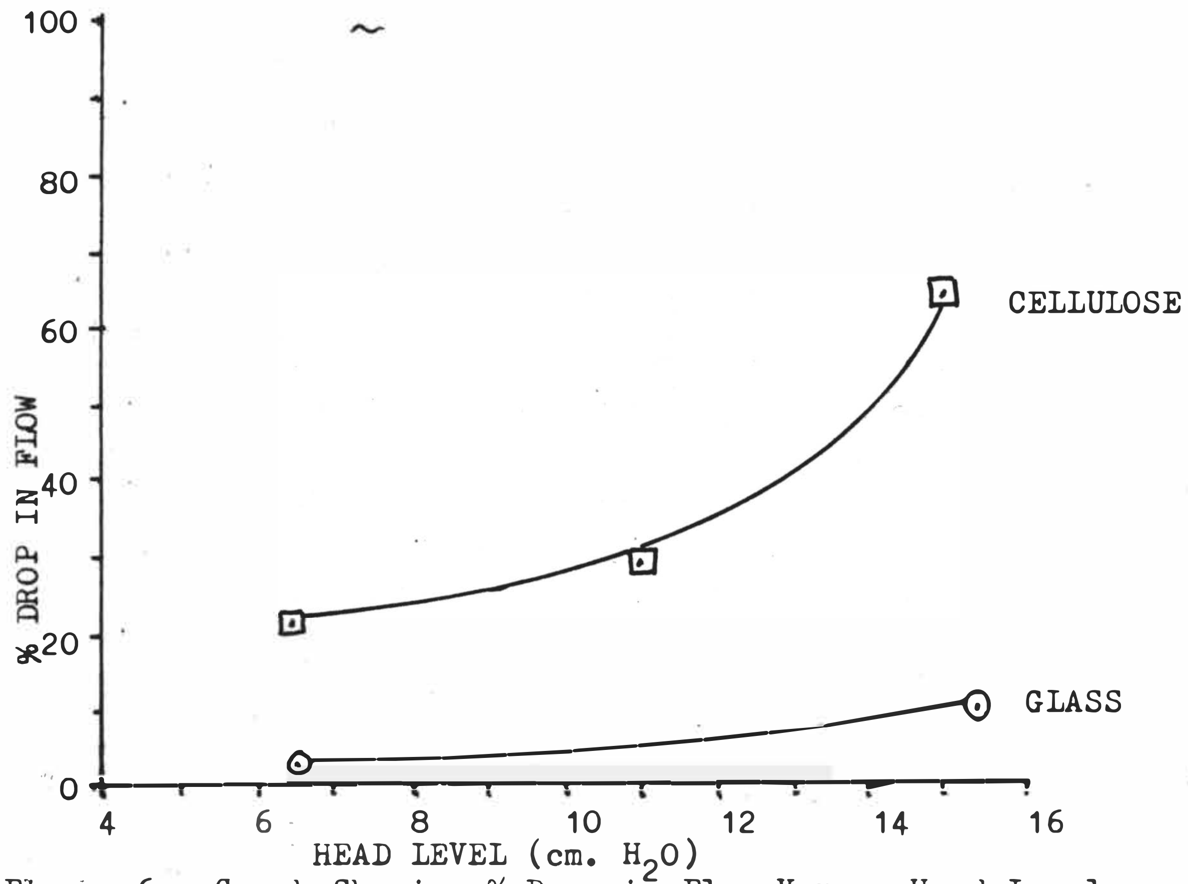


Figure 6-- Graph Showing % Drop in Flow Versus Head Level

| | PAPER | GLASS | PAPER | GLASS | AGITATED THRU PAPER | pH 3 HCl THRU GLASS |
|---|---|---|---|---|---|---|
| INLET COND. ($\mu$mhos) | 4.5 | 3.6 | 3.9 | 3.9 | 4.4 | 35 |
| FINAL FILTRATE COND. ($\mu$mhos) | 3.4 | 4.1 | 3.2 | 3.6 | 3.6 | 32 |
| FLOW @ MINUTE 1 (ml/min.) | 133 | 158 | 159 | 163 | 138 | 163 |
| FLOW @ MINUTE 29 (ml/min.) | 115 | 148 | 147 | 157 | 133 | 159 |
| % DROP IN FLOW | 13.5 | 6.3 | 7.5 | 3.7 | 3.3 | 2.5 |
| TEMPERATURE (°C) | 23 | 23 | 22 | 23 | 23 | 22 |

Table 10-- Cellulose Paper Versus Glass

might help to explain the anomaly in the results, an additional trial was carried out with aged water that was agitated with a propeller mixer prior to being used in the experiment. Water treated in this way gave an even lower per cent drop in flow.

Affect of Agitation:

Because of the observation in the previous experiment, an experiment was added to determine the affeect of agitating freshly distilled water. In table 11, the results of three trials are reported. The three trials were: (1.) a control run, where the water was allowed to stand in the storage bottle undisturbed for four hours before being used in an experiment, (2.) a trial was done to simulate the agitation which was given to the water when electrolytes were added to it in the coductivity and cation experiments, and (3.) to provide a trial with even more rigorous agitation a propeller mixer was attached to a bottle of freshly distilled water and left running throughout the run. As can be seen from the data, even the mild agitation generated by swirling the water in its storage bottle drasically reduced the drop in flow. Continuous agitation had an even greater affect.

Settling Experiment:

To gain a better understanding of why agitation should have such an influence on the decrease in flow rate, an experiment was carried out to determine if there were agents in the water

| | CONTROL | SWIRLING | MIXER |
|---|---|---|---|
| INLET COND. (μmhos) | 3.3 | 4.6 | 3.5 |
| FINAL FILTRATE COND. (μmhos) | 2.1 | 3.5 | 3.0 |
| FLOW @ MINUTE 1.(ml/min.) | 110 | 163 | 127 |
| FLOW @ MINUTE 29 (ml/min.) | 86 | 154 | 123 |
| % DROP IN FLOW | 21.8 | 5.5 | 3.1 |
| TEMPERATURE (°C) | 23 | 23 | 23 |

Table 11-- Affect of Agitation

| | SIPHONED OFF TOP | BOTTOM SPIGOT |
|---|---|---|
| INLET COND. (μmhos) | 4.2 | 4.2 |
| FINAL FILTRATE COND. (μmhos) | 3.8 | 4.0 |
| FLOW @ MINUTE 1 (ml/min.) | 113 | 110 |
| FLOW @ MINUTE 29 (ml/min.) | 93 | 63 |
| % DROP IN FLOW | 17.7 | 42.7 |
| TEMPERATURE (°C) | 23 | 23 |

Table 12-- Results of Settling Experiment

that could settle to the bottom of the storage containers with time. This was important because all of the experiments that had been conducted up to this point used water that was drawn out of the bottom of the 6½ gallon storage bottles through the spigots attached to the bottles, and if whatever caused the decrease in flow rate settled to the bottom and concentrated there, the blocking effect would be increased. Table 12 shows that water drawn from the upper layers of water stored in a bottle through a siphon gave less of a decrease in flow rate than did water drawn from the bottom of the same bottle through the spigot.

Normal Scatter of Data:

Table 13 is a summary of the per cent drop in flow data for all of the control runs which were performed. There is a moderate amount of scatter, with the standard deviation of the sample of per cent drop in flow factors being equal to 4.9. The expected scatter within individual experiments is smaller than that between control runs, because the same water was used throughout each experiment. Within an experiment a change of four in the per cent drop in flow was considered significant.

| EXPERIMENT | % DROP IN FLOW |
|---|---|
| BOILING | 14.2 |
| TEMPERATURE | 7.1 |
| AGITATION | 21.8 |
| HEAD | 20.8 |
| DRYING | 10.9 |
| GLASS VERSUS PAPER | 13.5 |
| CONDUCTIVITY & CATION | 11.8 |
| AGING | 12.4 |

Table 13-- Summary of Control Runs

## DISCUSSION OF RESULTS

Since the potential measured across the filter pads had no apparent relationship with the magnitude of the decrease in flow rate, it seems unlikely that generated electrical forces play the major role on blocking flow. Moreover, since there was no relationship between the pressure drop across the filter and the measured potential in the head level experiment, the potential that was measured could not have been simply the streaming potential. What is more likely is that the measured potential was a combination of the streaming potential (tending to be more negative at higher flow rates) and other influences, such as the decrease in conductivity with time (tending to increase the magnitude of the potential, regardless of its sign) and/or the accumulation of charged particulates on the upstream side of the filter. If particulates are partially responsible they would most likely have a positive charge associated with them, since early observations showed that when turbulence was induced around the upstream electrode (which would tend to draw accumulated particulates away from the electrode) the voltage dropped momentarily toward the negative. The hypothesis that the observed potential is a complicated combination of several factors also helps account for the observation that the potential-elapsed time relationship was different from run to run.

The fact that inverting a filter that has been blocked restores the flow rate suggests the presence of particulates or

particulate-like structures in the water. The tendency for the initial flow rate after the paper was dried to be greater than the initial flow rate before the paper was dried in the drying experiment can be explained by hornification of the fibrous structure. It is well known that drying a wetted cellulose fiber structure causes the individual fiber structures to draw together into more compact configurations, thus increaseing the area of open pores in a system such as a filter paper. Since the tendency for the fibers to draw inward could more than compensate for plugging of pores by solid particulates, solid particulates cannot be ruled out as the cause of the blocking effect on the basis of the drying experiment alone. Of course, microscopic bubbles and water molecule-ion structures remain as possibilities, as far as the results of the drying experiment are concerned.

The reason agitation affected the drop in flow rate could have been explained in two ways. First of all, structures easily broken up by even mild agitation could form uniformly throughout the water within a few hours if the water was allowed to stand undisturbed. The second possible explaination was that solid particulates or particulate-like structures formed in the water were higher in density and tended to settle to the bottom of the storage container with time. Since the water used in the experiments was drawn off the bottom of the containers, any concentration of the particles in the bottom layers would result in an observed increase in flow rate

blockage.

The settling experiment ruled out the first possibility, since the agents responsible for causing the decrease in flow rate were found to concentrate at the bottom of the storage bottles.

The reason that aging the water increased the amount that flow rate decreased is simply that greater amounts of the particulates or particulate-like structures had time to settle when the water was left undisturbed for greater periods of time.

Because agitation was not carefully controlled in adding the electrolytes to the water during the conductivity and cation experiments, the per cent drop in flow results of these experiments are not valid. The fact that agitation reduces the blocking effect helps to explain why adding any type of electrolyte to the water reduced the drop in flow, since the electrolytes were dispersed with agitation.

In the cation experiment, the ions $Na^+$ and $Li^+$ should have had the affect of creating oganized clusters in the water, according to the flickering cluster theory of water structure. The ions $K^+$ and $NH_4^+$, on the other hand, should have had the effect of reducing the number of organized structures. The observation that $Li^+$ and $Na^+$ imparted different values to the per cent decrease in flow to the water, while $Na^+$, $K^+$, and $NH_4^+$ gave similar drops in flow suggests that if the structures predicted by the flickering cluster theory play a role in decreasing the flow rate through ordinary filter paper, their affect is completely overshadowed by the affect of agitating the water.

The reason that the potential difference between the two sides of the filter pad decreased with increasing conductivity of the water in the conductivity experiment was because the decrease in the insulating ability of the water led to increased mobility of the charges from one side of the filter to the other.

Since raising the temperature of the water in the temperature experiment had no effect, there were no structures in the water large enough to plug filter pores that could easily be broken up by moderate changes in temperature. Hence, the organized ice-like structures predicted to exist in the water by the vacant-lattice-point model of water structure do not play a role in causing the flow rate decrease.

The boiling experiment showed that boiling the water had no effect on the decrease in flow rate. This was contrary to what Gertjejansen and his co-workers had observed in their pulp pad permeability studies. Since boiling the water has been predicted to provide enough heat and turbulence to destroy microscopic bubbles in the water, these agents are probably not those responsible for causing the decrease in flow rate.

In all experiments where both cellulose and glass papers were evaluated, the glass showed less of a decrease in flow rate than did paper. This suggests that cellulose has more of an affinity for the particulates or particulate-like structures which cause the flow rate decrease than does glass. This difference in affinities also explains why cellulose was more affected by increasing the head level of water above the

filter (and thus increasing the flow rate through the pad) in the head level experiment.

Another factor responsible for the wide scatter of the per cent drop in flow between the control runs is that agitation wasn't equal from run to run. The disturbances caused in preparing the water in the storage bottles for each run could not have been exactly the same in every case.

The observation that the conductivity of the initial filtrate sample was often higher than the conductivity of the inlet water is easily explained. In preparing the filters for use in an experiment they were manipulated by hand. The tygon tubing clamping ring was also pushed into place by hand. These contacts with the experimenter's hand inevitably introduced a minute quantity of conducting substances into the filtration system, resulting in an increase in the conductivity of the first few filtrate samples collected. Conductivity of the later filtrate samples decreased as the contaminants were gradually flushed from the system.

The conductivity of the final filtrate sample was often much lower than that of the inlet water. It could be that not only do the agents responsible for blocking flow have a charge associated with them, but they also have a certain amount of electrolyte chemically or physically bound to them which is removed from the filtrate water when the particles are held back by the filter. Alternatively, the lower conductivities could be caused by an ion exchange reaction with the cellulose or by the pressure drop across the pad being great enough

to cause a fraction of the dissolved gases to come out of solution. If removal of dissolved gases is responsible, this would explain why the trial done with the boiled water was one of the few cases where the filtrate conductivity did not drop below the conductivity of the inlet water. Boiling the water would have the effect of eliminating dissolved gases before filtration was carried out.

## CONCLUSIONS

The decrease in flow rate that is observed over a period of time when distilled water is filtered through paper is caused by solid particulates in the water. These particulates are denser than water, and settle to the bottom of any container that is left standing undisturbed for any length of time. It is likely that the particulates have a positive charge associated with them and possible that they have a small amount of electrolyte associated with them. Another characteristic of these particulates is that they have more of an affinity for cellulose than for glass.

Filtration through cellulose filter papers can lower the conductivity of distilled water. The mechanism by which this occurs may be (1.) the filter stops particulates with their associated electrolyte from passing through to the downstream side of the filter, (2.) the cellulose acts as an ion exchanger with ionic impurities in the water, or (3.) the pressure drop across the filter pad is great enough to force a fraction of the dissolved gases in the water out of solution.

The potential that can be measured across a filter paper as water flows through it is generated by a complex combination of several mechanisms. Among these mechanisms are streaming potential, accumulation of charged particulates, and the decrease in filtrate conductivity with time.

It should be noted at this point that the initial correlation between flow rate decrease and the conductivity of the water used made by Dr. R.B. Valley can be explained by

considering that in these early experiments the conductivity of the permeating water was controlled by passing distilled water of high conductivity through a deionizing column. This not only had the affect of removing ionic impurities from the water, but the deionizing column would also have some capability to act as a filter to remove solid particulates. The previously observed correlation, then, actually provides some verification that solid particulates are responsible for flow blockage.

# RECOMMENDATIONS

On the basis of the work conducted in the course of this investigation, the following recomendations are made for further study:

1. A comparison study using distilled water from several different sources could be used to show whether the nature of the distilling apparatus or the location of the still has an affect on the concentration of the blocking agents in the water.
2. Further work may be done to classify the sizes of the particulates in the water by using Millipore filters of different pore sizes.
3. The nature of the blocking agent could be determined by using a fine Millipore filter to seperate them from quantities of water and examing the particulates with an electron microscope under high magnification.

# REFERENCES


1. Personal communication with Dr. R.B. Valley, Western Michigan University, Department of Paper Science and Engineering

2. Gertjejansen, R. and Hossfield, R., Tappi 50(4):204

3. Gertjejansen, R., Wood Fiber 1(2): 134

4. Fox, F. and Herzfield, K., J. Accoustical Society of America 26(6): 984 (1954)

5. Harvey, E.N., et. al., J. Cellular and Comparitive Physiology 24(1): 1 (1944)

6. Liebermann, L., J. Applied Physics 28(2): 205 (1957)

7. Davies, C.W. and James, A.M., "A Dictionary of Electrochemistry" (New York: J. Wiley and Sons)

8. Hampel, C.A. (ed.), "The Encyclopedia of Electrochemistry" (New York: Reinhold)

9. Morcos, M.A., "Relationship Between Fluid Flow in Cellulose and the Generated Electric Energy with Application to Water Movement in Plants" Ph.D. Thesis, Michigan State University 1969

10. Mason, S.G., Tappi 33(8): 413 (1950)

11. Mason, S.G., Pulp Paper Mag. Can. 48(10): 76 (1947)

12. Frank, H.S., Science 169(3946): 635 (1970)

13. Kavanau, J.L., "Water and Solute-Water Interactions" (San Francisco: Holden-Day, Inc.) 1964

# APPENDIX OF
# COMPLETE DATA TABLES

SEE TABLE ON PAGE 47 FOR UNITS FOR ALL TABLES IN THE APPENDIX

| TIME (min.) | 0-wks. T=28°C INLET COND.=6.2 FLOW (ml/min.) | VOLTS (mV) | COND. (μmhos) | 1-wk. T=22°C IN. COND.=5.2 FLOW | VOLTS | COND. | 2-wk. T=24°C IN. COND.=4.7 FLOW | VOLTS | COND. | 3-wk. T=23°C IN. COND.=5.7 FLOW | VOLTS | COND. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 170 | 8.5 | 13.0 | 183 | 3.8 | 5.1 | 228 | 8.0 | 4.9 | 174 | 3.8 | 5.4 |
| 3 | 175 | 9.0 | 7.8 | 190 | 3.3 | 5.4 | 213 | 3.2 | 4.7 | 148 | 10.5 | 7.1 |
| 5 | 162 | 9.4 | 6.7 | 160 | 4.7 | 5.6 | 203 | 3.5 | 5.3 | 138 | 16.8 | 5.4 |
| 7 | 162 | 9.6 | 6.2 | 159 | 4.7 | 5.6 | 197 | 3.8 | 4.8 | 135 | 19.0 | 5.4 |
| 9 | 160 | 9.5 | 6.4 | 160 | 3.6 | 5.8 | 193 | 4.2 | 4.4 | 133 | 19.7 | 5.3 |
| 13 | 162 | 8.3 | 6.3 | 158 | 3.4 | 5.4 | 179 | 4.8 | 5.3 | 125 | 20.2 | 5.3 |
| 17 | 178 | 7.5 | 6.6 | 155 | 3.1 | 5.4 | 173 | 5.6 | 4.2 | 123 | 19.2 | 4.9 |
| 21 | 155 | 6.5 | 6.3 | 150 | 2.7 | 5.4 | 164 | 6.4 | 4.5 | 118 | 18.3 | 4.9 |
| 25 | 155 | 5.5 | 7.6 | 148 | 2.6 | 5.4 | 160 | 7.2 | 5.0 | 113 | 18.0 | 4.8 |
| 29 | 149 | 5.0 | 6.4 | 146 | 2.8 | 5.4 | 155 | 7.7 | 4.9 | 110 | 17.6 | 4.8 |
| 35 | 150 | 4.2 | 6.1 | 140 | 3.2 | 5.2 | 148 | 8.6 | 4.4 | 105 | 16.8 | 4.8 |
| 41 | 148 | 4.0 | 6.1 | 145 | 2.9 | 5.8 | 138 | 8.9 | 4.4 | 100 | 16.3 | 4.9 |
| 47 | 145 | 3.7 | 6.0 | 143 | 3.0 | 5.8 | 135 | 10.3 | 4.4 | 95 | 15.7 | 5.0 |
| 53 | 143 | 3.8 | 6.0 | 140 | 3.5 | 5.3 | 133 | 12.0 | 4.3 | 93 | 15.5 | 5.0 |
| 59 | 143 | 4.1 | 6.0 | 135 | 3.5 | 5.4 | 128 | 11.4 | 4.4 | 90 | 15.6 | 5.0 |
| 67 | 143 | 4.5 | 6.0 | 135 | 4.1 | 5.1 | | | | | | |
| 75 | 137 | 4.1 | 6.0 | 133 | 5.2 | 5.2 | | | | | | |
| 83 | 138 | 4.5 | 5.9 | 133 | 3.0 | 5.2 | | | | | | |
| 91 | | | | | 3.4 | 5.0 | | | | | | |

| TIME | IN. COND.=3.9 T=20°C | | | IN. COND.=11.8 T=19°C | | | IN. COND.=15.4 T=22°C | | | IN. COND.=46 T=20°C | | | IN. COND.=84 T=19°C | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | FLOW | VOLTS | COND | FLOW | VOLTS | COND. | FLOW | VOLTS | COND. | FLOW | VOLTS | COND. | FLOW | VOLTS | COND. |
| 1 | 170 | 23.2 | 5.8 | 135 | 17.2 | 13.0 | 155 | 7.5 | 23.5 | 155 | 6.5 | 52 | 160 | 1.0 | 84 |
| 3 | 166 | 23.7 | 6.6 | 131 | 15.7 | 13.3 | 152 | 12.0 | 24.0 | 149 | 5.0 | 50 | 150 | 9.5 | 85 |
| 5 | 165 | 22.2 | 4.5 | 130 | 15.3 | 13.8 | 150 | 13.7 | 24.0 | 150 | 6.1 | 48 | 155 | 13.5 | 86 |
| 7 | 163 | 22.2 | 5.2 | 132 | 14.6 | 11.4 | 150 | 15.3 | 23.5 | 148 | 6.8 | 46 | 155 | 14.2 | 84 |
| 9 | 162 | 22.4 | 4.2 | 132 | 14.3 | 12.2 | 150 | 15.6 | 22.5 | 148 | 7.4 | 46 | 152 | 14.2 | 86 |
| 13 | 158 | 23.5 | 4.2 | 133 | 13.7 | 12.6 | 150 | 15.6 | 23.5 | 147 | 7.8 | 45 | 150 | 14.0 | 85 |
| 17 | 156 | 23.0 | 4.2 | 132 | 13.9 | 12.3 | 148 | 15.3 | 23.0 | 143 | 8.6 | 44 | 152 | 14.3 | 84 |
| 21 | 158 | 16.5 | 3.7 | 132 | 13.8 | 13.5 | 148 | 15.0 | 22.5 | 143 | 8.5 | 44 | 149 | 13.5 | 84 |
| 25 | 155 | 18.0 | 3.7 | 130 | 13.9 | 12.0 | 148 | 15.1 | 22.5 | 143 | 8.5 | 44 | 137 | 12.5 | 84 |
| 29 | 150 | 19.0 | 3.3 | 128 | 13.9 | 12.0 | 148 | 15.4 | 22.0 | 140 | 8.5 | 43 | 133 | 13.3 | 84 |
| 35 | 148 | 19.2 | 3.7 | 125 | 14.0 | 11.8 | 148 | 13.3 | 22.5 | 140 | 8.7 | 44 | 130 | 11.0 | 83 |
| 41 | 145 | 19.5 | 3.8 | 126 | 14.3 | 11.8 | 148 | 12.0 | 23.5 | 138 | 8.5 | 44 | 134 | 10.2 | 84 |
| 47 | 141 | 20.7 | 3.9 | 125 | 14.6 | 11.8 | 143 | 11.5 | 23.0 | 138 | 8.3 | 44 | 130 | 10.2 | 84 |
| 53 | 138 | 24.7 | 3.5 | 125 | 15.5 | 11.9 | 140 | 11.2 | 22.5 | 138 | 8.2 | 44 | 132 | 10.2 | 82 |
| 59 | 138 | 24.2 | 4.5 | | | | | | | | | | | | |
| 67 | 131 | 25.0 | 3.6 | | | | | | | | | | | | |
| 75 | 133 | 18.3 | 3.7 | | | | | | | | | | | | |
| 83 | 130 | 21.0 | 3.5 | | | | | | | | | | | | |
| 91 | 130 | 23.0 | 3.5 | | | | | | | | | | | | |
| 99 | 125 | 24.0 | 3.5 | | | | | | | | | | | | |
| 107 | 128 | 17.0 | 3.5 | | | | | | | | | | | | |
| 115 | 123 | 21.5 | 3.5 | | | | | | | | | | | | |

CONDUCTIVITY EXPERIMENT

| | CONTROL T=20°C IN. CON.=3.9 | | | $Na^+$ T=18°C IN. CON.=12.6 | | | $Ca^{++}$ T=23°C IN. CON.=12.8 | | |
|---|---|---|---|---|---|---|---|---|---|
| TIME | FLOW | VOLTS | COND. | FLOW | VOLTS | COND. | FLOW | VOLTS | COND. |
| 1 | 170 | 23.2 | 5.8 | 128 | 20.2 | 12.0 | 178 | 13.8 | 12.3 |
| 3 | 166 | 23.7 | 6.6 | 130 | 19.2 | 12.4 | 172 | 14.5 | 12.8 |
| 5 | 165 | 22.2 | 4.5 | 129 | 19.6 | 11.6 | 171 | 15.3 | 12.4 |
| 7 | 163 | 22.4 | 5.2 | 126 | 20.5 | 12.0 | 171 | 16.3 | 12.2 |
| 9 | 162 | 23.5 | 4.2 | 126 | 21.5 | 12.2 | 171 | 17.3 | 11.8 |
| 13 | 158 | 23.0 | 4.2 | 126 | 22.2 | 12.0 | 170 | 18.8 | 11.7 |
| 17 | 156 | 16.5 | 4.2 | 125 | 23.0 | 11.5 | 168 | 20.0 | 11.5 |
| 21 | 158 | 18.0 | 3.7 | 128 | 23.7 | 12.0 | 167 | 20.6 | 11.2 |
| 25 | 155 | 19.0 | 3.7 | 127 | 24,3 | 11.8 | 164 | 21.7 | 11.3 |
| 29 | 150 | 19,2 | 3.3 | 126 | 24.7 | 11.6 | 164 | 22.1 | 11.5 |
| 35 | 148 | 19.5 | 3.7 | 125 | 25.4 | 11.8 | 163 | 23.0 | 11.4 |
| 41 | 145 | 20.7 | 3.8 | 125 | 25.6 | 11.5 | 160 | 24.0 | 11.6 |
| 47 | 141 | 24.7 | 3.9 | 125 | 26.0 | 12.4 | 155 | 26.7 | 11.8 |
| 53 | 138 | 24.2 | 3.5 | 126 | 26.0 | 11.6 | 167 | 25.5 | 11.7 |
| 59 | 138 | 25.0 | 4.5 | 125 | 26.0 | 12.6 | 163 | 26.0 | 11.4 |

| | $K^+$ T=21°C IN. COND.=13.0 | | | $Li^+$ T=20°C IN. COND.=13.7 | | | $NH_4^+$ T=22°C IN. COND.=13.0 | | |
|---|---|---|---|---|---|---|---|---|---|
| TIME | FLOW | VOLTS | COND. | FLOW | VOLTS | COND. | FLOW | VOLTS | COND. |
| 1 | 150 | 15.4 | 13.0 | 175 | 9.0 | 14.0 | 187 | 25.0 | 13.0 |
| 3 | 145 | 18.0 | 13.0 | 173 | 9.3 | 13.4 | 183 | 25.7 | 12.8 |
| 5 | 145 | 19.8 | 12.6 | 173 | 11.3 | 13.5 | 182 | 24.2 | 13.0 |
| 7 | 150 | 21.6 | 12.4 | 170 | 12.7 | 14.4 | 181 | 24.2 | 12.9 |
| 9 | 150 | 22.0 | 12.4 | 169 | 13.8 | 13.6 | 182 | 26.6 | 12.8 |
| 13 | 149 | 23.4 | 12.5 | 168 | 15.0 | 14.2 | 184 | 27.5 | 12.6 |
| 17 | 147 | 22.7 | 12.2 | 165 | 16.4 | 13.0 | 184 | 28.0 | 12.5 |
| 21 | 145 | 22.0 | 12.3 | 165 | 17.3 | 14.5 | 184 | 28.4 | 12.2 |
| 25 | 145 | 22.2 | 12.1 | 160 | 17.7 | 14.0 | 180 | 27.8 | 12.7 |
| 29 | 145 | 22.4 | 12.3 | 158 | 18.0 | 13.5 | 180 | 27.5 | 12.8 |
| 35 | 144 | 23.2 | 12.1 | 155 | 18.2 | 13.8 | 179 | 16.6 | 12.9 |
| 41 | 141 | 23.3 | 12.0 | 154 | 19.4 | 14.0 | 178 | 25.5 | 13.0 |
| 47 | 139 | 24.8 | 12.4 | 153 | 19.2 | 12.8 | 180 | 26.5 | 13.0 |
| 53 | 143 | 25.2 | 12.2 | 150 | 19.3 | 12.7 | 176 | 27.2 | 12.7 |
| 59 | 141 | 24.2 | 12.5 | 149 | 19.6 | 12.8 | 176 | 28.0 | 12.7 |

CATION EXPERIRIMENT

| TIME | CONTROL T=22°C IN. CON. =4.6 | | | BOILED T=23°C IN. CON.=2.4 | | | T=23°C IN. CON.=6.0 | | | T=29°C IN. CON.=6.0 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | FLOW | VOLTS | COND. | FLOW | VOLTS | COND. | FLOW | VOLTS | COND. | FLOW | VOLTS | COND. |
| 1 | 303 | 23.0 | 4.7 | 210 | 17.5 | 2.7 | 140 | 6.5 | 6.3 | 144 | 13.4 | 6.5 |
| 3 | 295 | 21.0 | 4.6 | 193 | 14.8 | 2.9 | 140 | 22.4 | 5.6 | 143 | 15.0 | 5.4 |
| 5 | 289 | 20.3 | 4.3 | 190 | 12.5 | 2.5 | 143 | 25.0 | 5.7 | 143 | 16.0 | 5.7 |
| 7 | 283 | 20.2 | 4.4 | 188 | 10.8 | 2.6 | 143 | 25.0 | 5.8 | 143 | 16.4 | 5.0 |
| 9 | --- | 19.4 | 4.4 | 188 | 9.4 | 2.5 | 140 | 24.0 | 5.0 | 141 | 16.9 | 4.8 |
| 13 | 273 | 19.0 | 4.5 | 183 | 7.0 | 2.5 | 133 | 23.8 | 5.0 | 139 | 17.9 | 4.8 |
| 17 | 268 | 18.8 | 4.5 | 183 | 5.5 | 2.5 | 132 | 23.7 | 4.8 | 138 | 18.9 | 5.2 |
| 21 | 265 | 18.7 | 4.5 | 183 | 4.5 | 2.4 | 130 | 23.6 | 5.0 | 137 | 20.0 | 4.6 |
| 25 | 265 | 18.8 | 4.6 | 180 | 3.4 | 2.4 | 130 | 23.6 | 5.0 | 135 | 20.3 | 5.0 |
| 29 | 260 | 19.5 | 4.6 | 179 | 2.6 | 2.6 | 130 | 23.8 | 4.9 | 133 | 20.7 | 5.2 |
| 35 | 258 | 17.0 | 4.5 | 175 | 2.0 | 2.4 | 128 | 23.4 | 4.6 | 131 | 21.2 | 5.0 |
| 41 | 253 | 15.8 | 4.4 | 175 | 1.0 | 2.5 | 122 | 23.2 | 4.8 | 133 | 20.0 | 5.2 |
| 47 | 248 | 15.0 | 4.5 | 180 | 0.3 | 2.6 | 128 | 22.7 | 4.7 | 132 | 19.8 | 5.0 |
| 53 | 248 | 15.0 | 4.4 | 178 | 0.0 | 3.2 | 126 | 22.0 | 4.9 | 130 | 19.7 | 5.0 |
| 59 | 245 | 15.5 | 4.5 | 175 | -0.5 | 2.6 | 125 | 22.0 | 5.3 | 128 | 20.2 | 5.0 |

BOILING EXPERIMENT

TEMPERATURE EXPERIMENT

| | CELLULOSE PAPER | | | | | | | | | GLASS PAPER | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | HEAD=6.4cm T=23° IN. CON.=5.2 | | | HEAD=11.0cm T=23° IN. CON.=5.3 | | | HEAD=15.0cm T=23° IN. CON.=5.0 | | | HEAD=6.5cm T=22° IN. CON.=6.3 | | | HEAD=15.4cm T=23° IN. COND.=6.3 | | |
| TIME | FLOW | VOLTS | COND. | FLOW | VOLTS | COND. | FLOW | VOLTS | COND. | FLOW | VOLTS | COND. | FLOW | VOLTS | COND. |
| 1 | 125 | 20.8 | 5.8 | 207 | 18.5 | 5.3 | 278 | 12.5 | 6.0 | 160 | -10.2 | 8.0 | 280 | -31.0 | 6.8 |
| 3 | 118 | 23.7 | 4.4 | 194 | 19.5 | 5.0 | 190 | 13.0 | 4.9 | 160 | -2.5 | 6.0 | 273 | -12.8 | 6.2 |
| 5 | 115 | 27.5 | 4.2 | 184 | 20.5 | 4.8 | 160 | 14.5 | 5.0 | 159 | 3.4 | 5.4 | 270 | -6.4 | 5.0 |
| 7 | 113 | 28.0 | 4.0 | 178 | 20.8 | 4.9 | 145 | 15.3 | 5.1 | 158 | 4.8 | 5.4 | 267 | -3.0 | 5.4 |
| 9 | 110 | 25.4 | 4.0 | 173 | 21.2 | 4.5 | 129 | 16.0 | 4.4 | 154 | 7.6 | 5.4 | 269 | -1.2 | 5.5 |
| 13 | 108 | 21.6 | 3.9 | 163 | 22.3 | 4.7 | 110 | 17.5 | 5.2 | 153 | 6.8 | 5.6 | 254 | -0.2 | 5.6 |
| 17 | 105 | 19.2 | 3.8 | 156 | 22.3 | 4.5 | 106 | 19.5 | 3.8 | 153 | 5.5 | 5.5 | 255 | 0.3 | 5.4 |
| 21 | 102 | 16.8 | 4.0 | 153 | 22.6 | 4.6 | 106 | 20.0 | 4.4 | 150 | 4.5 | 5.4 | --- | 0.0 | 5.5 |
| 25 | 100 | 17.0 | 4.0 | 148 | 23.0 | 4.4 | 105 | 20.6 | 4.0 | 153 | 4.5 | 5.1 | 254 | 0.2 | 5.5 |
| 29 | 99 | 16.4 | 4.4 | 148 | 23.2 | 4.7 | 99 | 22.5 | 4.8 | 155 | 5.7 | 5.3 | 253 | 1.0 | 5.5 |

HEAD LEVEL EXPERIMENT

| TIME | FRESH WATER THRU PAPER IN. COND.=4.5 T=23°C | | | FRESH WATER THRU GLASS IN. COND.=4.6 T=23°C | | | AGED WATER THRU PAPER IN. COND.=3.7 T=22°C | | |
|---|---|---|---|---|---|---|---|---|---|
| | FLOW | VOLTS | COND. | FLOW | VOLTS | COND. | FLOW | VOLTS | COND. |
| 1 | 133 | 11.0 | 5.1 | 158 | -25.0 | 7.1 | 159 | 16.0 | 5.0 |
| 3 | 129 | 14.1 | 4.2 | 153 | -22.5 | 5.7 | 155 | 13.3 | 4.4 |
| 5 | 129 | 14.4 | 5.8 | 150 | -19.5 | 4.8 | 155 | 11.0 | 4.0 |
| 7 | 128 | 12.5 | 4.0 | 148 | -14.2 | 4.4 | 154 | 9.4 | 3.7 |
| 9 | 128 | 12.0 | 3.7 | 148 | -11.7 | 4.0 | 153 | 9.4 | 3.5 |
| 13 | 125 | 12.5 | 3.7 | 145 | -9.0 | 4.4 | 152 | 9.2 | 3.4 |
| 17 | 125 | 12.8 | 4.0 | 146 | -7.8 | 4.2 | 152 | 8.8 | 3.3 |
| 21 | 122 | 13.0 | 3.7 | 147 | -7.3 | 4.3 | 150 | 9.5 | 3.3 |
| 25 | 119 | 13.2 | 3.7 | 150 | -7.3 | 4.4 | 149 | 11.2 | 3.3 |
| 29 | 115 | 12.8 | 3.5 | 148 | -6.2 | 4.2 | 147 | 11.5 | 3.2 |
| 35 | 114 | 12.7 | 3.5 | 148 | -5.5 | 4.0 | | | |
| 41 | 111 | 12.9 | 3.6 | 144 | -5.3 | 3.9 | | | |
| 47 | 110 | 13.5 | 3.4 | 143 | -5.2 | 4.0 | | | |
| 53 | 110 | 15.0 | 3.6 | 148 | -5.0 | 4.2 | | | |
| 59 | 108 | 16.0 | 3.4 | 143 | -5.0 | 4.1 | | | |

| TIME | AGED WATER THRU GLASS IN. COND.=3.9 T=23°C | | | AGITATED WATER THRU PAPER IN. COND.=4.4 T=23°C | | | pH 3.0 HCl THRU GLASS IN. COND.=35 T=22°C | | |
|---|---|---|---|---|---|---|---|---|---|
| | FLOW | VOLTS | COND. | FLOW | VOLTS | COND. | FLOW | VOLTS | COND. |
| 1 | 163 | -13.2 | 6.6 | 138 | 16.2 | 4.8 | 163 | 2.2 | 36 |
| 3 | 163 | -18.5 | 5.2 | 140 | 13.5 | 3.7 | 162 | 0.7 | 37 |
| 5 | 160 | -24.6 | 5.0 | 139 | 12.7 | 3.8 | 162 | 1.0 | 38 |
| 7 | 160 | -23.8 | 4.0 | 138 | 13.0 | 3.4 | 158 | 1.2 | 38 |
| 9 | 159 | -22.5 | 3.8 | 138 | 12.8 | 3.3 | 159 | 1.7 | 37 |
| 13 | 159 | -20.6 | 3.6 | 135 | 13.6 | 3.5 | 163 | 2.0 | 38 |
| 17 | 159 | -18.6 | 3.6 | 135 | 14.7 | 3.2 | 160 | 2.2 | 38 |
| 21 | 159 | -17.0 | 3.6 | 133 | 15.2 | 3.3 | 162 | 2.6 | 38 |
| 25 | 158 | -15.5 | 3.8 | 130 | 15.4 | 3.6 | 160 | 2.8 | 38 |
| 29 | 157 | -15.5 | 3.6 | 133 | 15.7 | 3.6 | 159 | 3.2 | 38 |

GLASS VERSUS PAPER EXPERIMENT

| TIME | CONTROL IN. COND.=3.3 T=23°C FLOW | VOLTS | COND. | SWIRLING IN. COND.=4.6 T=23°C FLOW | VOLTS | COND. | CONT. MIXING IN. COND.=3.3 T=23°C FLOW | VOLTS | COND. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 110 | 11.9 | 3.6 | 163 | 13.4 | 4.4 | 127 | 3.3 | 4.2 |
| 3 | 96 | 10.2 | 3.1 | 157 | 14.0 | 4.4 | 123 | 11.9 | 3.5 |
| 5 | 92 | 11.2 | 2.8 | 155 | 15.6 | 3.5 | 120 | 12.2 | 3.0 |
| 7 | 90 | 12.0 | 2.9 | 156 | 16.6 | 3.8 | 119 | 10.6 | 3.0 |
| 9 | 89 | 12.6 | 2.7 | 156 | 17.1 | 3.9 | 119 | 10.0 | 2.9 |
| 13 | 86 | 14.6 | 2.2 | 155 | 19.2 | 3.7 | 119 | 10.4 | 2.8 |
| 17 | 88 | 15.5 | 2.3 | 154 | 20.0 | 3.8 | 121 | 10.2 | 2.7 |
| 21 | 86 | 15.8 | 2.7 | 155 | 20.0 | 3.6 | 123 | 9.1 | 2.9 |
| 25 | 86 | 16.2 | 2.7 | 154 | 18.8 | 3.6 | 123 | 9.0 | 3.2 |
| 29 | 86 | 16.7 | 2.1 | 154 | 18.5 | 3.5 | 123 | 10.3 | 3.0 |

AGITATION EXPERIMENT

| TIME | SIPHONED OFF TOP LAYERS IN. COND.=4.2 T=23°C FLOW | COND. | FROM BOTTOM LAYERS THRU SPIGOT IN. COND.=4.2 T=23°C FLOW | COND. |
|---|---|---|---|---|
| 1 | 113 | 5.0 | 110 | 6.0 |
| 3 | 98 | 5.2 | 93 | 4.8 |
| 5 | 95 | 4.4 | 90 | 4.4 |
| 7 | 97 | 4.4 | 85 | 4.3 |
| 9 | 98 | 4.2 | 88 | 4.4 |
| 13 | 98 | 4.2 | 85 | 4.4 |
| 17 | 100 | 4.0 | 73 | 3.9 |
| 21 | 100 | 4.0 | 73 | 3.9 |
| 25 | 93 | 3.8 | 67 | 4.0 |
| 29 | 93 | 3.8 | 63 | 4.0 |

SETTLING EXPERIMENT