TED ANKARA COLLEGE FOUNDATION HIGH SCHOOL

IB HIGH LEVEL CHEMISTRY EXTENDED ESSAY

EFFECT OF DIFFERENT ELECTRODES AND MEMBRANES ON THE ELECTROCATALYTIC ACTIVITY AND THE STABILITY OF POLYMER ELECTROLYTE MEMBRANE FUEL CELLS WITHIN AN ALKALI SOLUTION

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Word Count: 3903 Words

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Abstract

In this project, the electrocatalytic activity and stability of polymer electrolyte fuel cells (PEMFC), which are prepared by using Pt (platinum), Pd (palladium) and Ag (silver) metals; Nylon and Vileda membranes, within a 2 M NaOH (sodium hydroxide) solution, are examined.

The aim of this study is to find alternatives to the Pt metal, which is mostly used in this technology, due to its high cost and limited sources. In addition, it is intended to find membranes that will substitute the Nafion membrane, which is the ideal membrane in PEM fuel cells.

For the fuel cells, which are prepared by using each electrode and membrane, 4 trials are done. In these experiments, for each combination, the potential versus time graphs are drawn to compare the precision and electrocatalytic activity of the fuel cells. Besides, logarithms of hydrogen ion concentrations versus time graphs are drawn to determine the membranes' effect. In the conclusion of the project, the highest electrocatalytic activity is observed in the cells with Pt electrode-Vileda membrane and Pd electrode-Nylon membrane. The results with Ag metal were not satisfactory like the other metals; the cells with Ag metals have low electrocatalytic activity when compared with other membranes. When the membranes are compared for each of the electrodes, similar results are observed. The change in the concentration of hydrogen ions with time is less in the Nylon membrane than in Vileda membrane. Thus, Nylon membrane shows more stable than the Vileda about the transferring of the hydrogen ions.

To conclude, Pd is the best alternative to Pt electrode while Nylon membrane is the best alternative to Nafion membrane. In addition, it is concluded that with each electrode, a variety of membranes must be used to examine the electrocatalytic activity of the PEM fuel cells.
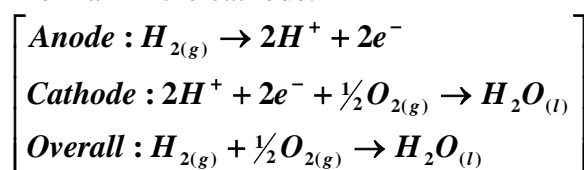
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Introduction

Nowadays, energy has become a much important necessity for humanity, as the technology has developed rapidly. Alternatives to energy sources are searched and investigated due to the fact that the sources are almost used up. One of the alternatives is hydrogen gas, which is the source of fuel cell technology. Fuel cells are the electrochemical energy generators which are continuously fed by active matters. It is thought that fuel cell technology will compensate the energy necessity of human beings in the near future, because of their reliability and high efficiency.

Like in the other electrochemical cells, in fuel cells there are two electrodes. The one, where reduction occurs, is called cathode; the other one, in which oxidation takes place, is called anode. Although there are many kinds of matter that is used as oxidizing agent, it is useful to have oxygen from the air in cathode. As a result, there would not be any problem of carrying a second fuel and its difficulties for the cell. Thus, in an ordinary fuel cell, the fuels are fed in the anode while the oxygen from the air is fed in the cathode. Therefore, the electric energy is formed by the reaction between the fuel in the anode and the oxygen from air in the cathode.

$$\left[\begin{array}{l} \textbf{\textit{Anode}} : \textbf{\textit{H}}_{2(g)} \rightarrow \textbf{\textit{2H}}^{+} + \textbf{\textit{2e}}^{-} \\ \textbf{\textit{Cathode}} : \textbf{\textit{2H}}^{+} + \textbf{\textit{2e}}^{-} + \textbf{\textit{½O}}_{2(g)} \rightarrow \textbf{\textit{H}}_{2}\textbf{\textit{O}}_{(l)} \\ \textbf{\textit{Overall}} : \textbf{\textit{H}}_{2(g)} + \textbf{\textit{½O}}_{2(g)} \rightarrow \textbf{\textit{H}}_{2}\textbf{\textit{O}}_{(l)} \end{array} \right]$$

The most important property of fuel cells differing from ordinary electrochemical cells is the fact that neither the electrodes nor the electrolyte between them are involved in the reaction. In ordinary electrochemical cells, the maximum energy that can be provided depends on the amount of the chemical reactants stored in the cells. As the reactants are used up in the reaction, the cell cannot provide any electric energy. On the other hand, theoretically, fuel cells continue providing electric energy, as they are given the fuel and the oxidant.

Fuel cells are usually classified according to two criteria: i) electrolyte and ii) its operating temperature. In addition, they are classified according to the type and nature of the fuel or the cell's being fed by the fuel directly or not. The type and the structure of the electrocatalysts are also significant in the classification; because the cell's power/mass and power/volume ratios depend on the electrode. To increase these ratios, the electrodes should have high electrocatalytic conductivity. Furthermore, electrode should be able to absorb the reactants with appropriate power and carry on the cell reaction fast enough. Nowadays, most proper electrode is platinum, despite its high cost and its inadequate abundance. For instance, if platinum had been used as an electrocatalyst in all vehicles, the earth would have run out of platinum.

In addition, fuel cells are classified according to their operating temperatures. If the system is operating under 150°C, it is called low temperature cell; if it is operating above 500°C, it is called high temperature cell. If the operating temperature of the cell is increased, the efficiency increases; while the durability decreases. Besides, corrosion of the cell increases. Therefore, while the cell is operating, an approximate temperature, which is appropriate to the durability of the materials, should be chosen.

Nowadays, the most commonly used fuel cells are: AFC (Alkaline fuel cell), PAFC (Phosphoric acid fuel cell), MCFC (Molten carbonate fuel cell), SOFC (Solid oxide fuel cell) and PEMFC (Polymer electrolyte membrane), DMFC (Direct Methanol Fuel Cell). Table below shows the comparison of type of fuel cells:

Fuel Cell Type	Mobile Ion	Operating Temperature (°)	Electrolyte	Example to Electrolyte
AFC	OH^-	50-200	Alkaline solution	KOH
PEMFC	H^+	30-100	Polymer Membrane	Nafion
DMFC	H^+	20-90	Alkaline solution or PEM electrolyte	KOH, NaOH, Nafion
PAFC	H^+	220	Phosphoric Acid	H_2SO_4
MCFC	CO_3^{2-}	650	Molten mixture of alkaline carbonates	$LiAlO_2$
SOFC	O^{2-}	500-1000	Oxygen Ion conducting ceramic	yttria-stabilised zirconia (YSZ)

Table-A Types of Fuel Cells
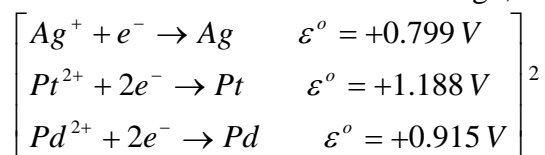
Table-A: Types of fuel cells.

Research Question

In this project, the effect of different electrodes and different membranes within an alkali solution, on the electrocatalytic activity and stability of a simply prepared proton exchange membrane fuel cell, will be examined.

Approach to the Research Question

PEM fuel cells are mostly chosen in recent experiments due to their high efficiency and wide range of use. However, the high cost and limited sources of platinum and the membranes are the disadvantages of PEM fuel cells. The aim of this project is to find a solution to the drawbacks of PEM fuel cell. Alternatives to platinum and membranes will be determined. This project will examine the effect of different electrodes and membranes within an alkali solution, on the *stability* and *electrocatalytic activity* of polymer electrolyte membrane fuel cell. Electrocatalytic activity shows how high the potential difference is; whereas stability shows how precise the results are.

The properties of the metals, which will be used as electrode, are very important. They must be inert so as to supply the electron transfer without reacting with the electrolyte. As a result, active metals like Fe (iron), Mg (magnesium), Zn (zinc) cannot be used as electrodes. In this experiment, Pd (palladium), Ag (silver) and Pt (Platinum) will be used as electrodes; because these are inert metals. Their S*tandard Electrode Potentials*[1] are high, which means that they are good electrocatalysts.

$$\begin{bmatrix} Ag^+ + e^- \rightarrow Ag & \varepsilon^o = +0.799\,V \\ Pt^{2+} + 2e^- \rightarrow Pt & \varepsilon^o = +1.188\,V \\ Pd^{2+} + 2e^- \rightarrow Pd & \varepsilon^o = +0.915\,V \end{bmatrix}^2$$

The membranes that are going to be used in the investigation are:
1.   Nylon Membrane (Cole-Parmer Instruments Company, catalog number: 2916-44)
2.   Microfiber Cleaning Cloth (Vileda Company Product)

Nylon membrane is much cheaper than the Nafion membrane which is the ideal membrane in PEM fuel cells. Actually, it is in similar structure with a Nafion 117 membrane. In addition, Nylon's

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[1] The **standard electrode potential** (abbreviated **E⁰**) is the electrode potential at the standard conditions: temperature 298K, 1 atm pressure and at 1 mol of the activity of redox participants of the half-reaction.

[2] Standard Reduction Potentials of metals: Bard, Allen J. and Larry R Faulkner, Electrochemical Method Fundamental and Applications.

thickness is appropriate for this technology and it is a more complex polymer than the Microfiber cleaning cloth. However, the cleaning cloth has a good quality fibrous structure and it is the cheapest among all membranes.
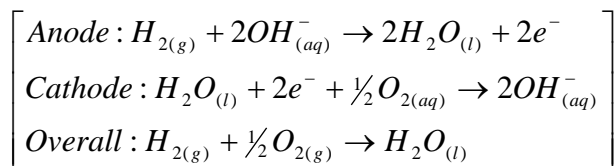
The 3 electrodes and 2 membranes that are mentioned to be used in the study will form 6 different PEM fuel cells. The fuel cells will not be similar to the ones used in the technology because of the high cost and the difficulties in passing the hydrogen gas directly through the membrane. Therefore, an alkali solution will be used in the cell. This is a limiting factor in the project. As a result, the research question is constructed as:

"What is the effect of different electrodes (Pt, Pd, Ag) and different membranes (Nylon, Cleaning cloth-Vileda) within the alkali solution (2M NaOH), on the electrocatalytic activity and stability of a simply prepared, low cost proton exchange membrane fuel cell?"

Background Information

To make a brief summary of the mechanism of PEM fuel cell, there are two half-cells one of which involves oxidation of hydrogen gas and the other involves reduction of oxygen gas. Hydrogen ions, produced by the oxidation of the hydrogen gas, pass directly through the proton exchange membrane, and reduce the oxygen gas. Simultaneously, the electrons, produced by the oxidation of hydrogen gas, go through the voltmeter and then arrive at cathode, for the reduction of oxygen gas. As a result, the movement of the electrons causes a potential difference.

In the project, in addition to the membrane, a dilute basic electrolyte will be used to transfer the hydrogen ions. Instead of giving oxygen gas to cathode, the dilute solution will provide the oxygen gas to the cathode. As a result, the transfer of hydrogen ions will be done by both the membrane and the dilute solution. Besides, the oxygen gas will be gathered in the aqueous form, from the dilute solution. Finally, when the reactions are rearranged, the fuel cell in the project will be according to the following reactions:

$$\begin{bmatrix} Anode: H_{2(g)} + 2OH^-_{(aq)} \rightarrow 2H_2O_{(l)} + 2e^- \\ Cathode: H_2O_{(l)} + 2e^- + \frac{1}{2}O_{2(aq)} \rightarrow 2OH^-_{(aq)} \\ Overall: H_{2(g)} + \frac{1}{2}O_{2(g)} \rightarrow H_2O_{(l)} \end{bmatrix}$$

Nernst Equation:

In the project, to calculate the concentration of hydrogen ions, the Nernst Equation, which is used to calculate the relation between the electrode potential and the concentration of the cell components, will be used:

$$\left[\varepsilon_{cathode} = \varepsilon^o - \frac{0.05916}{n} \log(Q) \right]^3$$

where ε^o is the Standard Electrode Potential of the cell, Q is the equilibrium constant of the reaction, n is the number of electrons that are transferred and ε is the calculated electrode potential with respect to the concentrations of the cell components.

In addition, the electrode potential of the cell is in the following relation with cathode's and anode's potential:

$$\left[\varepsilon^o = \varepsilon_{cathode} - \varepsilon_{anode} \right]^4$$

where $\varepsilon_{cathode}$ is the reduction potential of cathode and ε_{anode} is the reduction potential of anode.

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[3] Nernst Equation: Zumdahl, Page 853

[4] Electrode potential of a cell using half reduction potentials of anode and cathode: Zumdahl, Page 842

Data Collection

Anode:

$$H_{2(g)} \rightarrow 2H^{+}_{(aq)} + 2e^{-}$$

Cathode:

$$H_2O_{(l)} + 2e^{-} + \tfrac{1}{2}O_{2(aq)} \rightarrow 2OH^{-}_{(aq)}$$
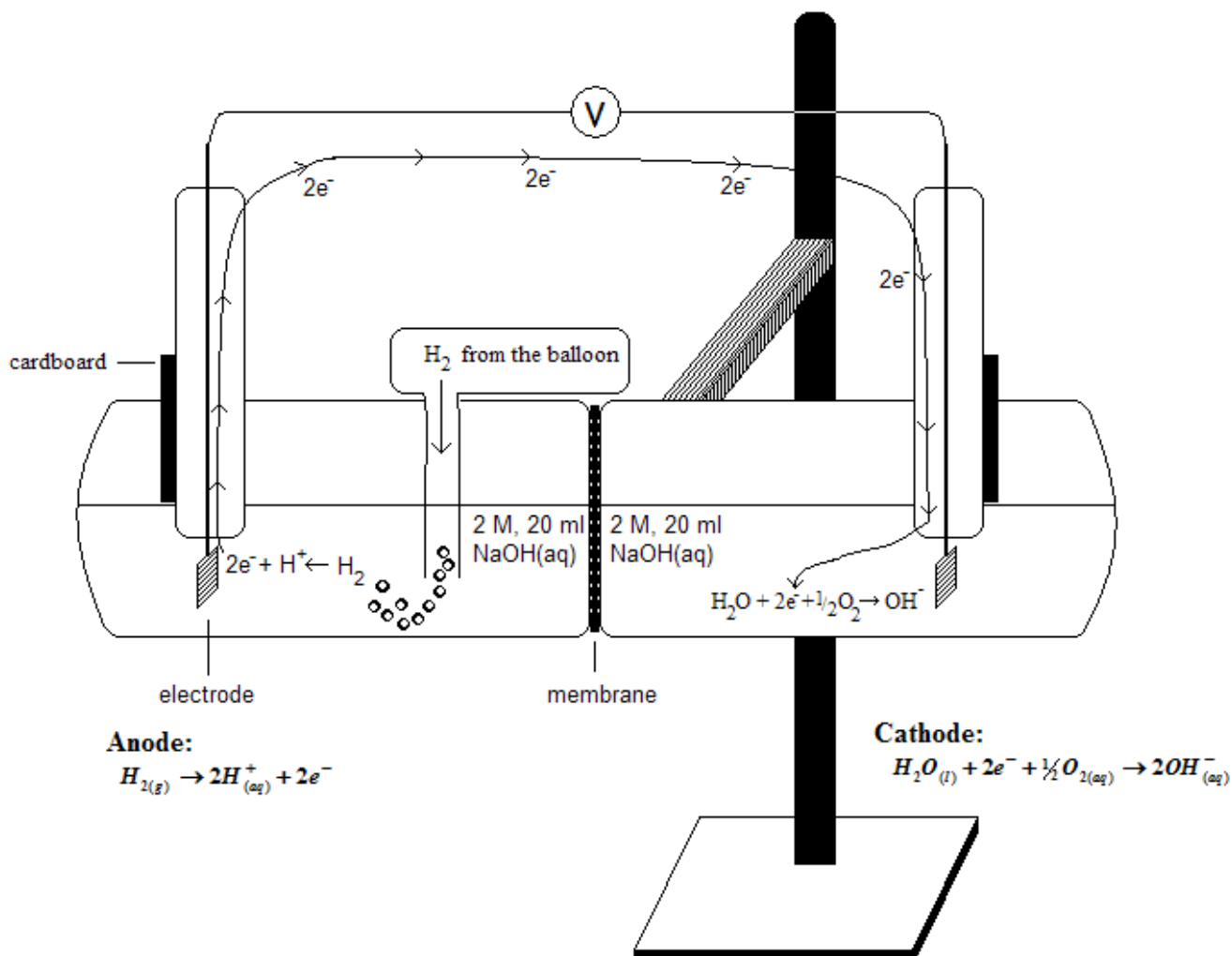
Figure-1 shows the display of the experiment.

The apparatus is prepared according to the methods in Appendix 1. Finally, the apparatus was set as shown in picture-5.3 and figure-1. After that, the experiment will be done:

i. Voltmeter is turned on and the initial potential difference is written down.

ii. Then the roller clamp is opened by rolling it 1.0 cm so the bubbles appeared in the anode. When the gas reached the anode, simultaneously the chronometer was started.

iii. At every 15th second from the beginning the potential difference is recorded. After 3 minutes the gas is stopped; but recording the potential difference every 15 seconds is continued. Recording data is stopped after it had been 5 minutes from the beginning. The experiment is repeated for 4 times so that 4 trials would be done.

The experiment, which includes Ag electrode and nylon membrane, was done so far. Including this experiment, the experiments with the following materials is done:
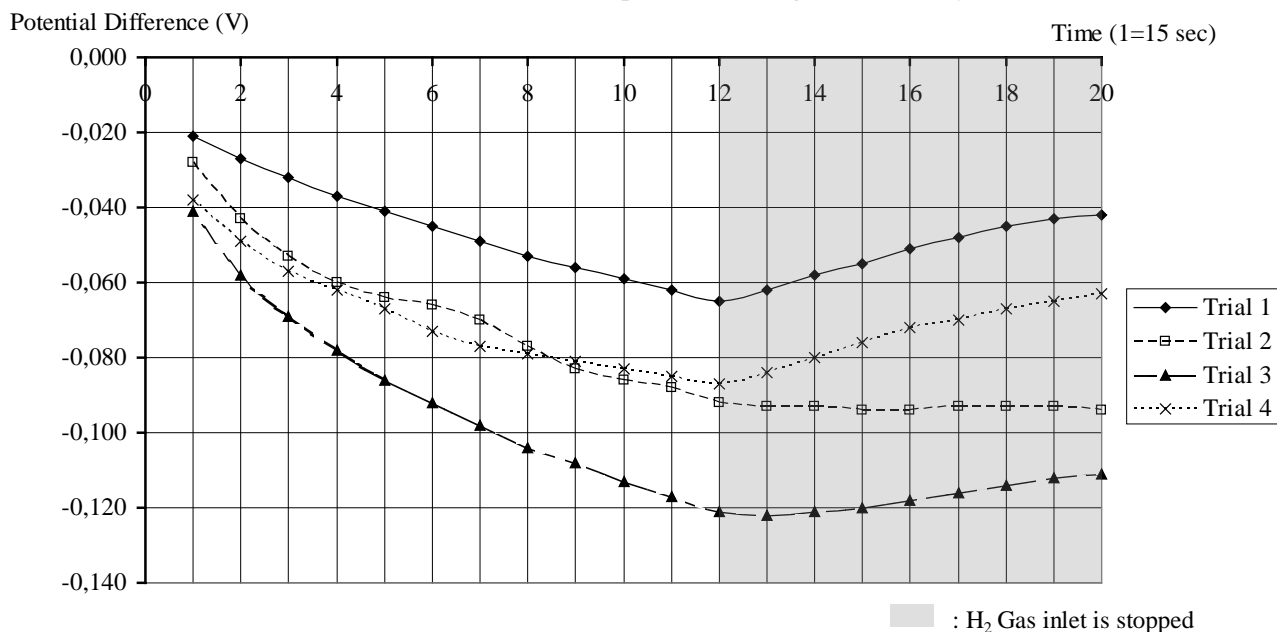
- Ag electrode-Nylon membrane
- Ag electrode-Vileda membrane
- Pt electrode-Nylon membrane
- Pt electrode-Vileda membrane
- Pd electrode-Nylon membrane
- Pd electrode-Vileda membrane

EXPERIMENT A - Ag Electrode-Nylon Membrane:

Table-1 Electrode: Ag, Membrane: Nylon				
Time (1=15 s)	Potential Difference_ E(V) ±0.001			
	Trial 1	Trial 2	Trial 3	Trial 4
Initial	-0,001	-0,014	0,003	-0,015
1	-0,021	-0,028	-0,041	-0,038
2	-0,027	-0,043	-0,058	-0,049
3	-0,032	-0,053	-0,069	-0,057
4	-0,037	-0,060	-0,078	-0,062
5	-0,041	-0,064	-0,086	-0,067
6	-0,045	-0,066	-0,092	-0,073
7	-0,049	-0,070	-0,098	-0,077
8	-0,053	-0,077	-0,104	-0,079
9	-0,056	-0,083	-0,108	-0,081
10	-0,059	-0,086	-0,113	-0,083
11	-0,062	-0,088	-0,117	-0,085
12	-0,065	-0,092	-0,121	-0,087
13	-0,062	-0,093	-0,122	-0,084
14	-0,058	-0,093	-0,121	-0,080
15	-0,055	-0,094	-0,120	-0,076
16	-0,051	-0,094	-0,118	-0,072
17	-0,048	-0,093	-0,116	-0,070
18	-0,045	-0,093	-0,114	-0,067
19	-0,043	-0,093	-0,112	-0,065
20	-0,042	-0,094	-0,111	-0,063

Table-1: The potential difference-E(V) read on the voltmeter at every 15 seconds for 4 trials, in the experiment where electrode is Ag, membrane is nylon.

Potential Difference vs Time Graph (Electrode:Ag, Membrane:Nylon)

Graph-1: The potential difference-E(V) read on the voltmeter at every 15 seconds for 4 trials, in the experiment where electrode is Ag, membrane is nylon.
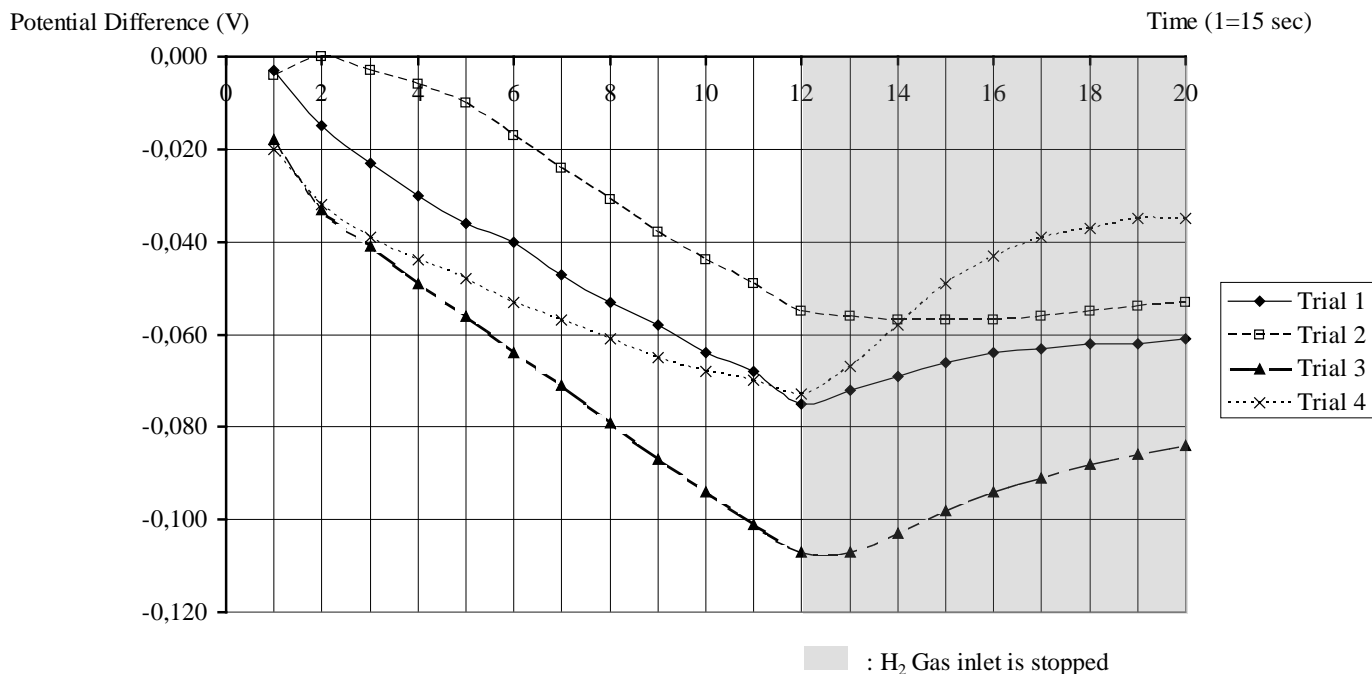
According to the Graph-1, the data in the second trial is not appropriate with the data in other three trials. Therefore, in the calculation of the mean values, second trial will not be taken into consideration.

EXPERIMENT B - Ag Electrode-Vileda Membrane:

Table-2 Electrode: Ag, Membrane: Vileda				
Time (1=15 s)	Potential Difference_ E(V) ±0.001			
	Trial 1	Trial 2	Trial 3	Trial 4
Initial	0,012	0,013	0,011	0,002
1	-0,003	-0,004	-0,018	-0,020
2	-0,015	0,000	-0,033	-0,032
3	-0,023	-0,003	-0,041	-0,039
4	-0,030	-0,006	-0,049	-0,044
5	-0,036	-0,010	-0,056	-0,048
6	-0,040	-0,017	-0,064	-0,053
7	-0,047	-0,024	-0,071	-0,057
8	-0,053	-0,031	-0,079	-0,061
9	-0,058	-0,038	-0,087	-0,065
10	-0,064	-0,044	-0,094	-0,068
11	-0,068	-0,049	-0,101	-0,070
12	-0,075	-0,055	-0,107	-0,073
13	-0,072	-0,056	-0,107	-0,067
14	-0,069	-0,057	-0,103	-0,058
15	-0,066	-0,057	-0,098	-0,049
16	-0,064	-0,057	-0,094	-0,043
17	-0,063	-0,056	-0,091	-0,039
18	-0,062	-0,055	-0,088	-0,037
19	-0,062	-0,054	-0,086	-0,035
20	-0,061	-0,053	-0,084	-0,035

Table-2: The potential difference-E(V) read on the voltmeter at every 15 seconds for 4 trials, in the experiment where electrode is Ag, membrane is vileda.

Potential Difference vs Time Graph (Electrode:Ag, Membrane:Vileda)
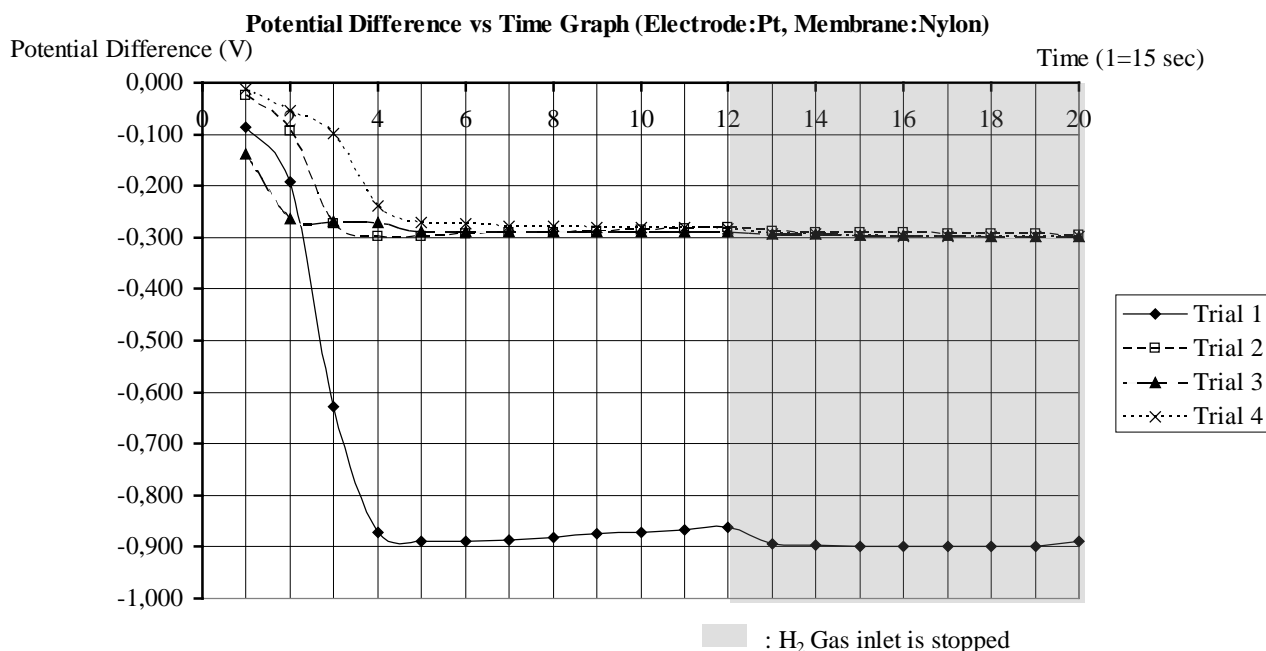

: H_2 Gas inlet is stopped

Graph-2: The potential difference-E(V) read on the voltmeter at every 15 seconds for 4 trials, in the experiment where electrode is Ag, membrane is vileda.

According to the Graph-2, second trial is not appropriate with the data in other three trials. Therefore, in the calculation of the mean values, second trial will not be taken into consideration.

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EXPERIMENT C - Pt Electrode-Nylon Membrane:

Table-3 Electrode: Pt, Membrane: Nylon			
Time (1=15 s)	Potential Difference_ E(V) ±0.001		
	Trial 1	Trial 2	Trial 3	Trial 4
Initial	0,000	0,000	0,002	-0,004
1	-0,086	-0,024	-0,138	-0,013
2	-0,191	-0,093	-0,264	-0,055
3	-0,629	-0,274	-0,268	-0,098
4	-0,872	-0,297	-0,270	-0,238
5	-0,889	-0,297	-0,288	-0,271
6	-0,890	-0,294	-0,288	-0,274
7	-0,886	-0,291	-0,288	-0,278
8	-0,883	-0,290	-0,289	-0,279
9	-0,875	-0,288	-0,289	-0,280
10	-0,871	-0,285	-0,289	-0,282
11	-0,866	-0,283	-0,288	-0,282
12	-0,861	-0,280	-0,288	-0,284
13	-0,893	-0,289	-0,293	-0,292
14	-0,896	-0,290	-0,294	-0,294
15	-0,898	-0,290	-0,295	-0,296
16	-0,899	-0,291	-0,296	-0,297
17	-0,899	-0,292	-0,296	-0,297
18	-0,900	-0,293	-0,297	-0,298
19	-0,900	-0,293	-0,297	-0,299
20	-0,889	-0,295	-0,298	-0,299

Table-3: The potential difference-E(V) read on the voltmeter at every 15 seconds for 4 trials, in the experiment where electrode is Pt, membrane is nylon.

Graph-3: The potential difference-E(V) read on the voltmeter at every 15 seconds for 4 trials, in the experiment where electrode is Pt, membrane is nylon.

According to the Graph-3, it is obvious that the first trial is not appropriate with the data in other three trials. Therefore, in the calculation of the mean values, first trial will not be taken into consideration.

EXPERIMENT D - Pt Electrode-Vileda Membrane:

Table-4 Electrode: Pt, Membrane: Vileda				
Time (1=15 s)	Potential Difference_ E(V) ±0.001			
	Trial 1	Trial 2	Trial 3	Trial 4
Initial	0,013	-0,005	0,010	0,003
1	-0,044	-0,813	-0,046	-0,037
2	-0,063	-0,880	-0,092	-0,074
3	-0,096	-0,885	-0,157	-0,118
4	-0,159	-0,889	-0,195	-0,168
5	-0,806	-0,890	-0,407	-0,248
6	-0,860	-0,891	-0,676	-0,426
7	-0,863	-0,892	-0,814	-0,733
8	-0,865	-0,892	-0,848	-0,835
9	-0,872	-0,893	-0,884	-0,860
10	-0,881	-0,893	-0,898	-0,864
11	-0,886	-0,894	-0,904	-0,863
12	-0,891	-0,894	-0,904	-0,863
13	-0,891	-0,894	-0,905	-0,878
14	-0,886	-0,887	-0,900	-0,883
15	-0,878	-0,878	-0,891	-0,884
16	-0,871	-0,863	-0,880	-0,862
17	-0,866	-0,840	-0,865	-0,869
18	-0,861	-0,812	-0,849	-0,853
19	-0,855	-0,778	-0,827	-0,864
20	-0,850	-0,779	-0,807	-0,852

Table-4: The potential difference-E(V) read on the voltmeter at every 15 seconds for 4 trials, in the experiment where electrode is Pt, membrane is vileda.

Potential Difference vs Time Graph (Electrode:Pt, Membrane:Vileda)

: H_2 Gas inlet is stopped
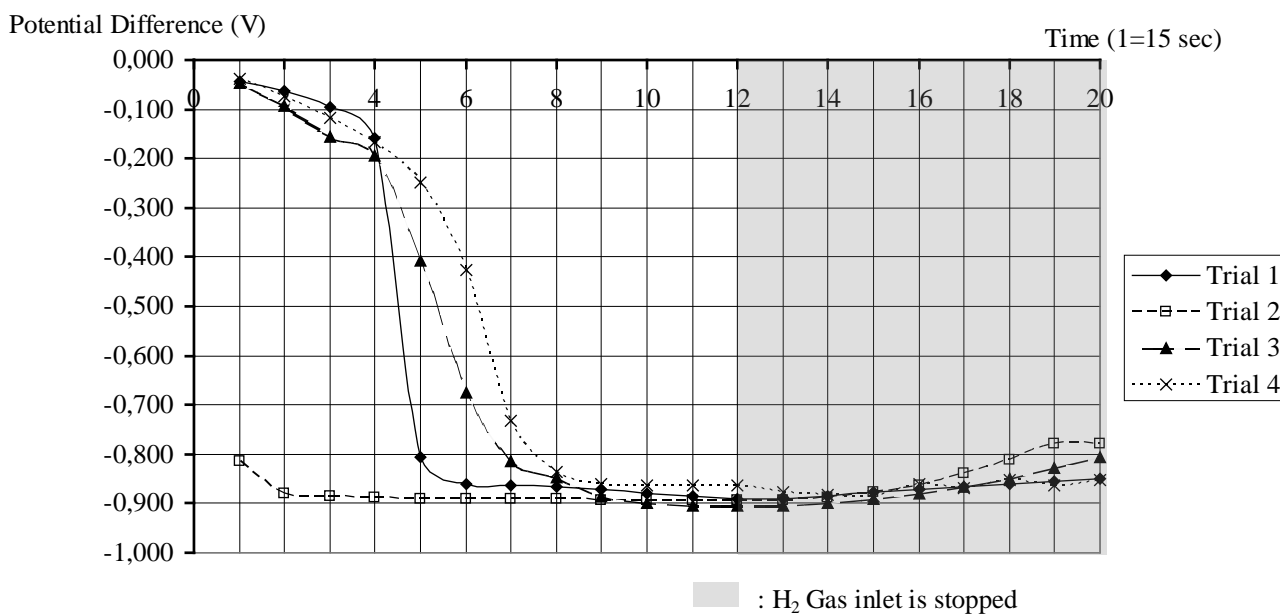
Graph-4: The potential difference-E(V) read on the voltmeter at every 15 seconds for 4 trials, in the experiment where electrode is Pt, membrane is vileda.

There is a quick change in potential difference in the second trial, although the data are coherent, later on. However, this trial will not be included in the calculations of the mean values.

EXPERIMENT E - Pd Electrode-Nylon Membrane:

Table-5 Electrode: Pd, Membrane: Nylon				
Time	**Potential Difference_ E(V) ±0.001**			
(1=15 s)	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**
Initial	-0,006	0,008	0,002	-0,004
1	-0,044	-0,042	-0,005	-0,049
2	-0,077	-0,061	-0,028	-0,070
3	-0,111	-0,074	-0,035	-0,102
4	-0,149	-0,119	-0,046	-0,212
5	-0,247	-0,192	-0,059	-0,550
6	-0,493	-0,417	-0,081	-0,631
7	-0,619	-0,570	-0,153	-0,661
8	-0,660	-0,633	-0,297	-0,668
9	-0,681	-0,671	-0,372	-0,670
10	-0,692	-0,694	-0,405	-0,670
11	-0,700	-0,711	-0,426	-0,672
12	-0,706	-0,721	-0,440	-0,673
13	-0,729	-0,726	-0,448	-0,673
14	-0,721	-0,727	-0,449	-0,670
15	-0,727	-0,725	-0,449	-0,671
16	-0,722	-0,726	-0,449	-0,677
17	-0,719	-0,727	-0,450	-0,684
18	-0,724	-0,727	-0,451	-0,690
19	-0,724	-0,726	-0,456	-0,695
20	-0,724	-0,726	-0,457	-0,698

Table-5: The potential difference-E(V) read on the voltmeter at every 15 seconds for 4 trials, in the experiment where electrode is Pd, membrane is Nylon.

Potential Difference vs Time Graph (Electrode:Pd, Membrane:Nylon)
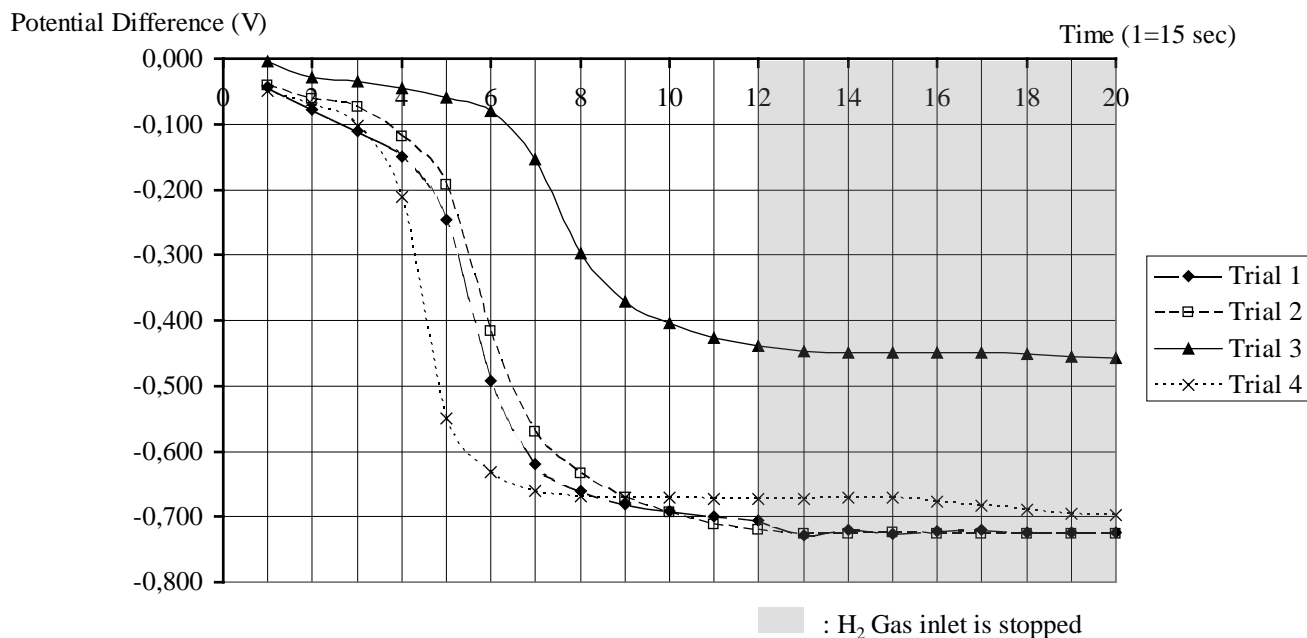
Graph-5: The potential difference-E(V) read on the voltmeter at every 15 seconds for 4 trials, in the experiment where electrode is Pd, membrane is nylon.
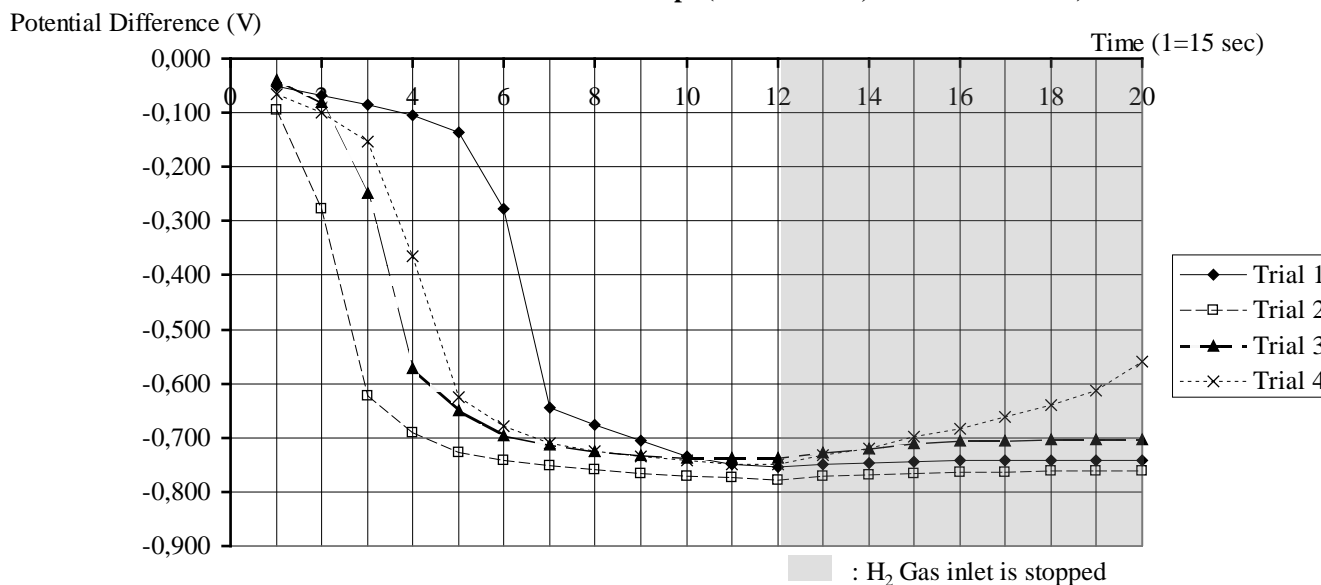
According to the graph-5, third trial is inconsistent with the other trials. As a result, it will not be included in the calculation of the mean values of potential differences.

EXPERIMENT F - Pd Electrode-Vileda Membrane:

Table-6 Electrode: Pd, Membrane: Vileda			
Time (1=15 s)	**Potential Difference_ E(V) ±0.001**		
	Trial 1	**Trial 2**	**Trial 3**	**Trial 4**
Initial	-0,010	0,006	0,016	-0,014
1	-0,050	-0,094	-0,038	-0,065
2	-0,068	-0,278	-0,081	-0,100
3	-0,084	-0,623	-0,249	-0,153
4	-0,105	-0,692	-0,572	-0,365
5	-0,137	-0,728	-0,649	-0,624
6	-0,277	-0,743	-0,695	-0,678
7	-0,644	-0,752	-0,713	-0,710
8	-0,676	-0,760	-0,724	-0,726
9	-0,706	-0,765	-0,731	-0,734
10	-0,735	-0,770	-0,736	-0,742
11	-0,748	-0,774	-0,738	-0,748
12	-0,754	-0,778	-0,738	-0,750
13	-0,750	-0,772	-0,728	-0,733
14	-0,746	-0,768	-0,719	-0,719
15	-0,744	-0,766	-0,710	-0,699
16	-0,743	-0,764	-0,706	-0,683
17	-0,742	-0,763	-0,705	-0,662
18	-0,742	-0,762	-0,703	-0,640
19	-0,742	-0,762	-0,704	-0,614
20	-0,741	-0,761	-0,704	-0,560

Table-6: The potential difference-E(V) read on the voltmeter at every 15 seconds for 4 trials, in the experiment where electrode is Pd, membrane is vileda.

Graph-6: The potential difference-E(V) read on the voltmeter at every 15 seconds for 4 trials, in the experiment where electrode is Pd, membrane is vileda.

According to the graph-6, the fourth trial is incoherent with other trials so it will not be involved in mean value calculations.

Data Analysis

Calculation of the Potential in the Cathode

In this part, the mean value of the trials in each experiment will be calculated. In addition, the logarithm of hydrogen ion concentrations will be calculated. In these calculations, the Nernst Equation explained in page 4 and 5 will be used.

$$\left[\varepsilon_{cathode} = \varepsilon^o - \frac{0.05916}{n} \log(Q) \right]$$

Q is the equilibrium constant of the reaction in the cathode. The reaction was:

$$H_2O_{(l)} + 2e^- + \tfrac{1}{2}O_{2(aq)} \rightarrow 2OH^-_{(aq)} \text{ ; so Q will be:}$$
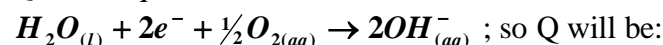
$$Q = \frac{\left[OH^- \right]^2}{\left[O_2 \right]^{\frac{1}{2}}}$$

It is known that there is 1 atm of dissolved oxygen in water. It is considered that the pressure of the gas is 1 atm at room temperature. Its concentration will be calculated by using the ideal gas equation:

$$\left[PV = nRT \right]^5$$

where P is the pressure, V is the volume, n is the number of moles of gas, R is the ideal gas constant and T is the temperature. As it was mentioned before n/V is equal to concentration. Therefore, concentration of oxygen will be:

$$\frac{n}{V} = Molarity = \frac{P}{RT} \qquad where \ R = 0.082 \, dm^3 \, atm \, mol^{-1} \, K^{-1}$$

$$Molarity = \frac{1 \, atm}{298.15K \times 0.082 \, dm^3 \, atm \, mol^{-1} \, K^{-1}}$$

$$Molarity \cong 0.04 \, mole \, dm^{-3} \rightarrow concentration \ of \ oxygen$$

As a result, all the variables are known in the equation of Q:

$$Q = \frac{\left[OH^- \right]^2}{\left[O_2 \right]^{\frac{1}{2}}}$$

Concentration of hydroxide ion is 2 M as the NaOH solution was also 2 M, concentration of oxygen is calculated as 0.04 M. If these values are put in the equation above:

$$Q = 2^2/0.04^{1/2} = 20$$

If the Q value is put in the Nernst Equation:

$$\varepsilon_{cathode} = \varepsilon^o - \frac{0.05916}{2} \log(20)$$

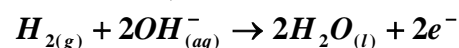$$\cdots \ = \varepsilon^o - \frac{0.05916}{2} \times 1.301$$

$$\cdots \ = 0.401 - 0.03849$$

$$\varepsilon_{cathode} \cong 0.363V$$

$$\varepsilon^o = \textbf{Standard Reduction Potential of the cathode reaction} = \textbf{0.401 V}$$

Calculation of the Potential in the Anode

In the anode, the reaction was:

$$H_{2(g)} + 2OH^-_{(aq)} \rightarrow 2H_2O_{(l)} + 2e^-$$

---

[5] Ideal Gas Equation: Zumdahl, page 619

From the Nernst Equation: $\left[\varepsilon_{anode} = \varepsilon^o - \dfrac{0.0591}{n}\log(Q) \right]$, Q is:

$$Q = \frac{[H_2O]^2}{[H_2][OH^-]^2}$$

In the reaction, the concentration of hydroxide ion coming from the water can be neglected when considered with the concentration of hydroxide ion coming from the 2 M NaOH solution. As it is known, water is ionized according to the following reaction:

$$H_2O \rightarrow H^+_{(aq)} + OH^-_{(aq)} \qquad \Rightarrow [H_2O] = [H^+][OH^-]$$

If concentrat ion of hydroxide ion is neglected :

$$[H_2O] = [H^+] \quad \Rightarrow Q = \frac{[H^+]^2}{[H_2][OH^-]^2}$$

In the experiment, pressure of hydrogen gas was 2.6 atm. Therefore, the concentration of hydrogen gas:

$$\frac{n}{V} = Molarity = \frac{P}{RT}$$

$$Molarity = \frac{2.6\,atm}{298.15K \times 0.082\,dm^3\,atm\,mol^{-1}\,K^{-1}}$$

$$Molarity = 0.106\,mole\,dm^{-3} \rightarrow concentration\ of\ hydrogen\ gas$$

When the concentration of hydrogen gas and the hydroxide is substituted in the Nernst Equation:

$$\varepsilon_{anode} = \varepsilon^o - \frac{0.05916}{2}\log\left(\frac{[H^+]^2}{[H_2][OH^-]^2}\right)$$

$$\varepsilon_{anode} = 0.02958\log\frac{4 \times 0.106}{[H^+]^2}$$

Finding the Equation for the Logarithm of the Hydrogen Ion Concentrations
The potential of the cell is equal to:

$$\varepsilon_{cell} = \varepsilon_{cathode} - \varepsilon_{anode}$$

$$\cdots\ = 0.363 - 0.02958\log\frac{0.424}{[H^+]^2}$$

$$\cdots\ = 0.363 - 0.02958(-0.373 - 2\log[H^+])$$

$$\cdots\ = 0.363 + 0.011 + 0.05916\log[H^+]$$

$$\cdots\ = 0.374 + 0.05916\log[H^+]$$

$$\log[H^+] = \frac{\varepsilon_{cell} - 0.374}{0.05916}$$

where ε_{cell} is the potential difference at every 15 seconds.

Before calculating the logarithm of hydrogen ion concentrations, the mean value of the potential differences will be calculated. However, in each experiment, one trial, that is incoherent with

other three trials, will not be used in the calculations. The trials that will not be used are expressed before. Therefore, the mean values and the standard deviations are expressed below in table-7.

Calculation of the Mean Values of the Potentials

	Table-7 Mean Values of Potential Differences											
Time (1=15 s)	Experiment with Ag Electrode and Nylon Membrane		Experiment with Ag Electrode and Vileda Membrane		Experiment with Pt Electrode and Nylon Membrane		Experiment with Pt Electrode and Vileda Membrane		Experiment with Pd Electrode and Nylon Membrane		Experiment with Pd Electrode and Vileda Membrane	
	Potential Difference E (V) (±0.001)	Standard deviation	Potential Difference E (V) (±0.001)	Standard deviation	Potential Difference E (V) (±0.001)	Standard deviation	Potential Difference E (V) (±0.001)	Standard deviation	Potential Difference E (V) (±0.001)	Standard deviation	Potential Difference E (V) (±0.001)	Standard deviation
Initial	-0,004	0,009	0,008	0,006	-0,001	0,003	0,009	0,005	-0,001	0,008	0,004	0,013
1	-0,033	0,011	-0,014	0,009	-0,058	0,069	-0,042	0,005	-0,045	0,004	-0,061	0,029
2	-0,045	0,016	-0,027	0,010	-0,137	0,111	-0,076	0,015	-0,069	0,008	-0,142	0,118
3	-0,053	0,019	-0,034	0,010	-0,213	0,100	-0,124	0,031	-0,096	0,019	-0,319	0,276
4	-0,059	0,021	-0,041	0,010	-0,268	0,030	-0,174	0,019	-0,160	0,047	-0,456	0,310
5	-0,065	0,023	-0,047	0,010	-0,285	0,013	-0,487	0.287	-0,330	0,193	-0,505	0,321
6	-0,070	0,024	-0,052	0,012	-0,285	0,010	-0,654	0,218	-0,514	0,108	-0,572	0,256
7	-0,075	0,025	-0,058	0,012	-0,286	0,007	-0,803	0,066	-0,617	0,046	-0,703	0,055
8	-0,079	0,026	-0,064	0,013	-0,286	0,006	-0,849	0,015	-0,654	0,018	-0,720	0,042
9	-0,082	0,026	-0,070	0,015	-0,286	0,005	-0,872	0,012	-0,674	0,006	-0,734	0,030
10	-0,085	0,027	-0,075	0,016	-0,285	0,004	-0,881	0,017	-0,685	0,013	-0,747	0,020
11	-0,088	0,028	-0,080	0,019	-0,284	0,003	-0,884	0,021	-0,694	0,020	-0,753	0,019
12	-0,091	0,028	-0,085	0,019	-0,284	0,004	-0,886	0,021	-0,700	0,025	-0,757	0,020
13	-0,089	0,030	-0,082	0,022	-0,291	0,002	-0,891	0,014	-0,709	0,032	-0,750	0,022
14	-0,086	0,032	-0,077	0,023	-0,293	0,002	-0,890	0,009	-0,706	0,031	-0,744	0,025
15	-0,084	0,033	-0,071	0,025	-0,294	0,003	-0,884	0,007	-0,708	0,032	-0,740	0,028
16	-0,080	0,034	-0,067	0,026	-0,295	0,003	-0,871	0,009	-0,708	0,027	-0,738	0,029
17	-0,078	0,035	-0,064	0,026	-0,295	0,003	-0,867	0,002	-0,710	0,023	-0,737	0,029
18	-0,075	0,035	-0,062	0,026	-0,296	0,003	-0,854	0,006	-0,714	0,021	-0,736	0,030
19	-0,073	0,035	-0,061	0,026	-0,296	0,003	-0,849	0,019	-0,715	0,017	-0,736	0,029
20	-0,072	0,035	-0,060	0,025	-0,297	0,002	-0,836	0,025	-0,716	0,016	-0,735	0,029

Table-7: The mean values and the standard deviations of potential differences, of each experiment's three trials.

Calculation of the Logarithm of the Hydrogen Ion Concentrations

Now, the logarithm of hydrogen ion concentrations will be calculated by using the potential differences-E(V) and the formula derived by using the Nernst Equation:

$$\log[H^+] = \frac{\varepsilon_{cell} - 0.374}{0.05916}$$

One example will be calculated by using the potential difference at 15th second of the experiment with Ag electrode and Nylon membrane:

$$\log[H^+] = \frac{\varepsilon_{cell} - 0.374}{0.05916}$$

Since $\varepsilon_{cell} = -0.033$;

$$\log[H^+] = \frac{-0.033 - 0.374}{0.05916}$$

$$\log[H^+] = -6.880$$

By using the same method, logarithm of hydrogen ion concentrations for the potential differences in Table-7 are calculated. The results are showed in Table-8 below:

| Time (1=15 s) | Experiment with Ag Electrode and Nylon Membrane | | Experiment with Ag Electrode and Vileda Membrane | | Experiment with Pt Electrode and Nylon Membrane | | Experiment with Pt Electrode and Vileda Membrane | | Experiment with Pd Electrode and Nylon Membrane | | Experiment with Pd Electrode and Vileda Membrane | |
	Potential Difference E (V) (±0.001)	Logarithm of Hydrogen Ion Concentrations (mole.dm^{-3})	Potential Difference E (V) (±0.001)	Logarithm of Hydrogen Ion Concentrations (mole.dm^{-3})	Potential Difference E (V) (±0.001)	Logarithm of Hydrogen Ion Concentrations (mole.dm^{-3})	Potential Difference E (V) (±0.001)	Logarithm of Hydrogen Ion Concentrations (mole.dm^{-3})	Potential Difference E (V) (±0.001)	Logarithm of Hydrogen Ion Concentrations (mole.dm^{-3})	Potential Difference E (V) (±0.001)	Logarithm of Hydrogen Ion Concentrations (mole.dm^{-3})
0	-0,004	-6,389	0,008	-6,187	-0,001	-6,339	0,005	-6,237	-0,001	-6,339	0,004	-6,254
1	-0,033	-6,880	-0,014	-6,558	-0,058	-7,302	-0,235	-10,294	-0,045	-7,082	-0,061	-7,353
2	-0,045	-7,082	-0,027	-6,778	-0,137	-8,638	-0,277	-11,004	-0,069	-7,488	-0,142	-8,722
3	-0,053	-7,218	-0,034	-6,897	-0,213	-9,922	-0,314	-11,629	-0,096	-7,945	-0,319	-11,714
4	-0,059	-7,319	-0,041	-7,015	-0,268	-10,852	-0,353	-12,289	-0,160	-9,026	-0,456	-14,030
5	-0,065	-7,421	-0,047	-7,116	-0,285	-11,139	-0,588	-16,261	-0,330	-11,900	-0,505	-14,858
6	-0,070	-7,505	-0,052	-7,201	-0,285	-11,139	-0,713	-18,374	-0,514	-15,010	-0,572	-15,991
7	-0,075	-7,590	-0,058	-7,302	-0,286	-11,156	-0,826	-20,284	-0,617	-16,751	-0,703	-18,205
8	-0,079	-7,657	-0,064	-7,404	-0,286	-11,156	-0,860	-20,859	-0,654	-17,377	-0,720	-18,492
9	-0,082	-7,708	-0,070	-7,505	-0,286	-11,156	-0,877	-21,146	-0,674	-17,715	-0,734	-18,729
10	-0,085	-7,759	-0,075	-7,590	-0,285	-11,139	-0,884	-21,264	-0,685	-17,901	-0,747	-18,949
11	-0,088	-7,809	-0,080	-7,674	-0,284	-11,122	-0,887	-21,315	-0,694	-18,053	-0,753	-19,050
12	-0,091	-7,860	-0,085	-7,759	-0,284	-11,122	-0,888	-21,332	-0,700	-18,154	-0,757	-19,118
13	-0,089	-7,826	-0,082	-7,708	-0,291	-11,241	-0,892	-21,400	-0,709	-18,306	-0,750	-18,999
14	-0,086	-7,776	-0,077	-7,623	-0,293	-11,275	-0,889	-21,349	-0,706	-18,256	-0,744	-18,898
15	-0,084	-7,742	-0,071	-7,522	-0,294	-11,291	-0,883	-21,247	-0,708	-18,289	-0,740	-18,830
16	-0,080	-7,674	-0,067	-7,454	-0,295	-11,308	-0,869	-21,011	-0,708	-18,289	-0,738	-18,796
17	-0,078	-7,640	-0,064	-7,404	-0,295	-11,308	-0,860	-20,859	-0,710	-18,323	-0,737	-18,780
18	-0,075	-7,590	-0,062	-7,370	-0,296	-11,325	-0,844	-20,584	-0,714	-18,391	-0,736	-18,763
19	-0,073	-7,556	-0,061	-7,353	-0,296	-11,325	-0,831	-20,368	-0,715	-18,408	-0,736	-18,763
20	-0,072	-7,539	-0,060	-7,336	-0,297	-11,342	-0,822	-20,216	-0,716	-18,425	-0,735	-18,746

Table-8 Logarithm of Hydrogen Ion Concentrations of Potential Differences

Table-8: The logarithm of hydrogen ion concentrations and potential differences for each experiment.

The table-9 that shows the error calculations of the logarithm of hydrogen ion concentrations is shown in Appendix 2.

Now, to compare the electrodes, two graphs, where type of electrode is independent and type of membrane is constant, will be drawn. The electrodes will be compared according to the electrocatalytic activity (i.e. Higher the potential difference higher the electrocatalytic activity).

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Potential vs Time Graph in Vileda for Each Electrode
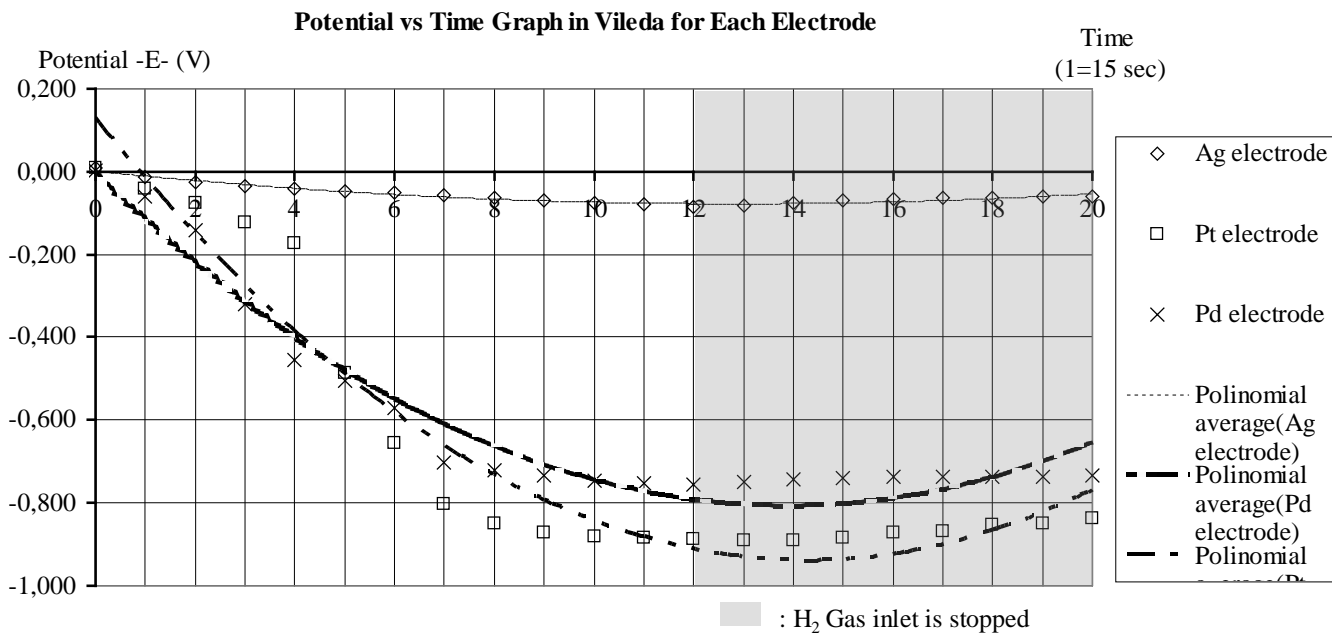
Graph-7: The potential versus time graph in Nylon membrane, for each electrode.

Potential vs Time Graph in Nylon for Each Electrode
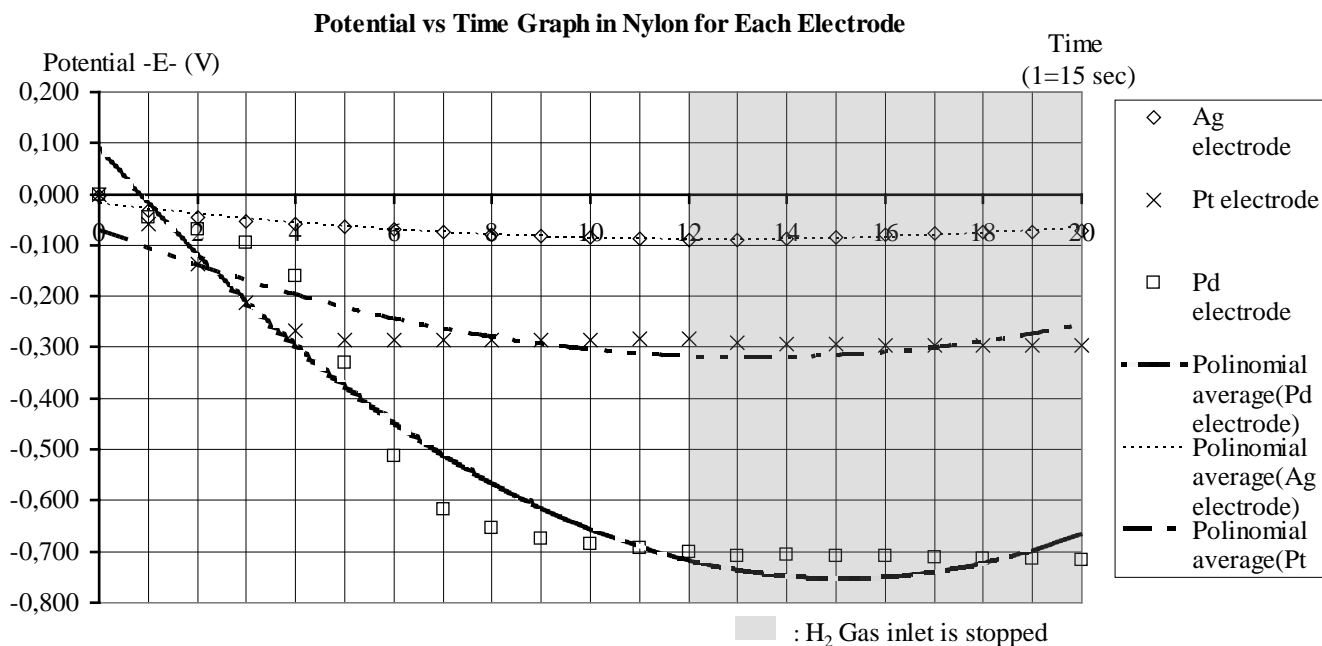
**Graph-8:** The potential versus time graph in Vileda membrane, for each electrode.

Now, to compare the membranes, three graphs, where type of electrode is constant and type of membrane is independent, will be drawn. The membranes will be compared according to the change in the logarithm of hydrogen ion concentration with time.

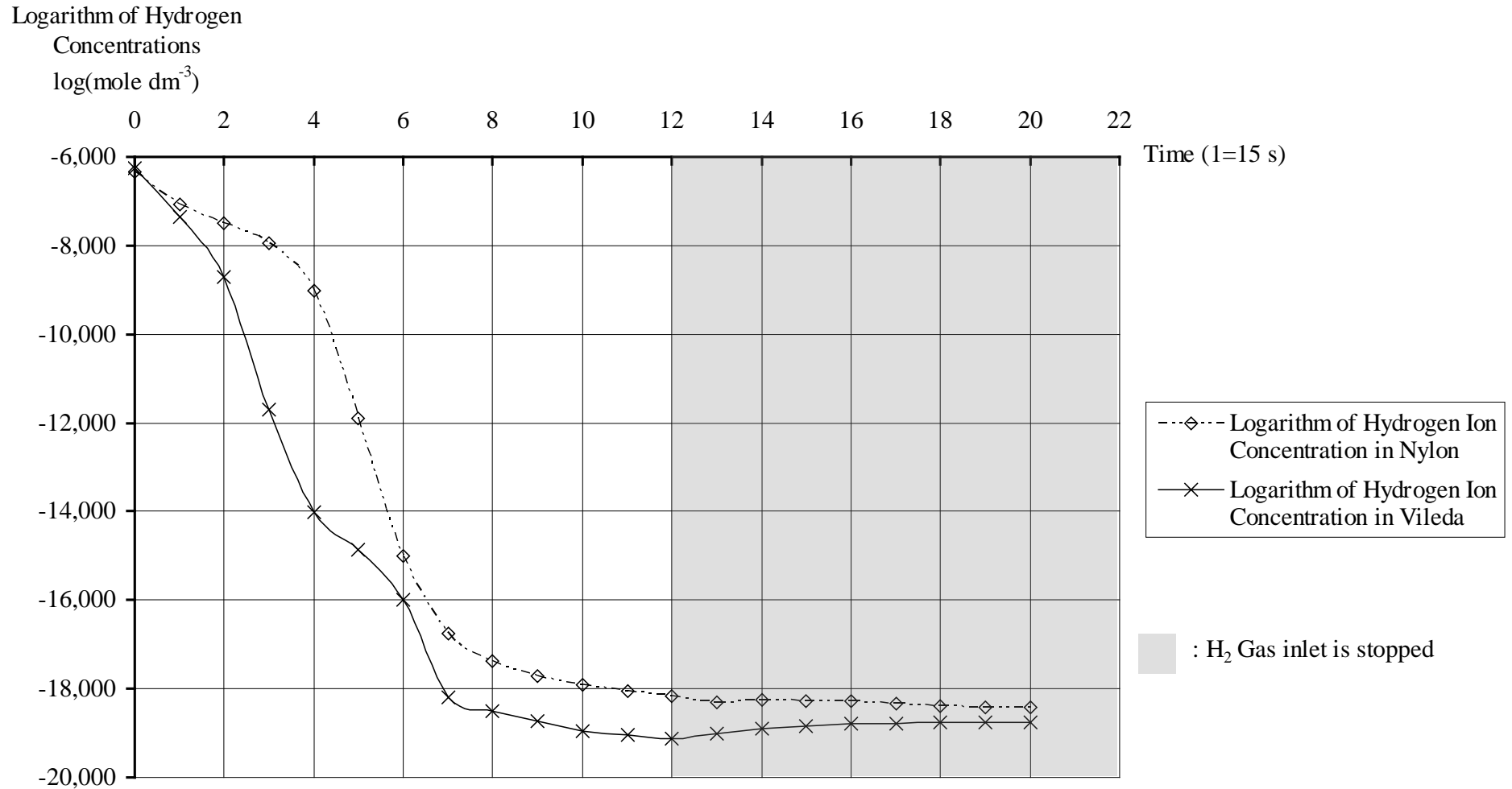**Logarithm of Hydrogen Ion Concentration vs Time in Ag Electrode for Each Membrane**
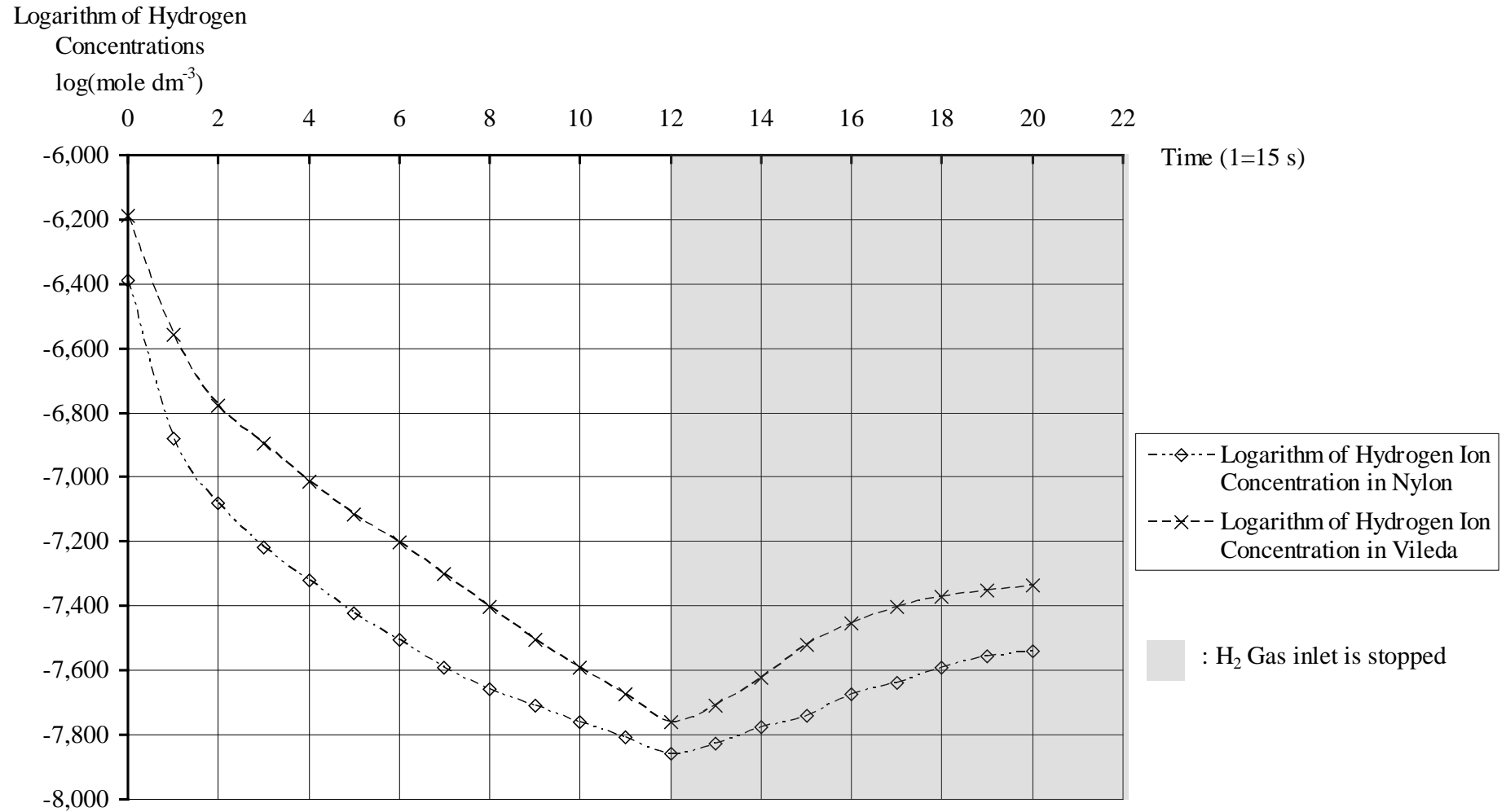
Graph-9: The change in logarithm of hydrogen concentration with time in Ag electrode, for each membrane.

Logarithm of Hydrogen Ion Concentration vs Time in Pt Electrode for Each Membrane
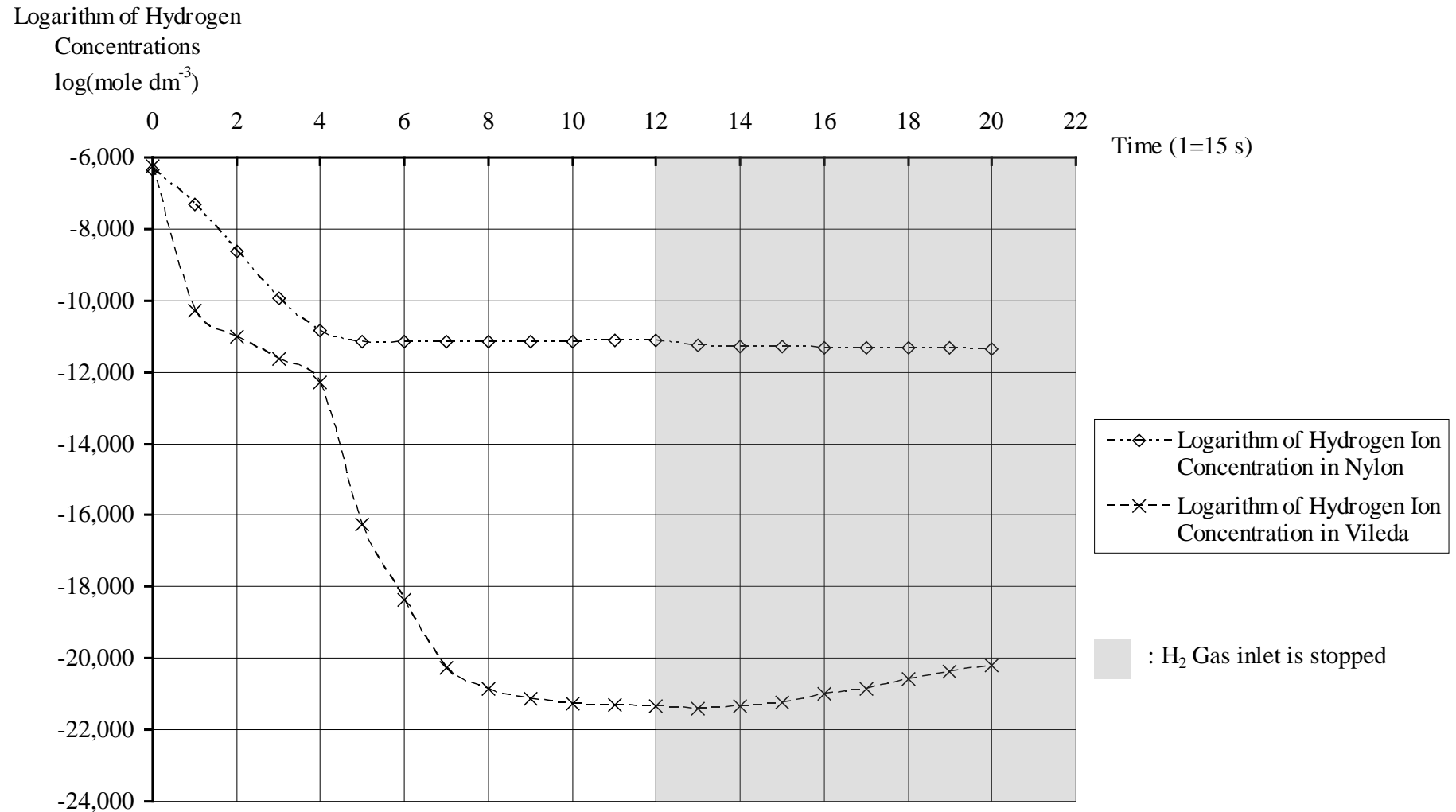
Graph-10: The change in logarithm of hydrogen concentration with time in Pt electrode, for each membrane.

Logarithm of Hydrogen Ion Concentration vs Time in Pd Electrode for Each Membrane

Graph-11: The change in logarithm of hydrogen concentration with time in Pd electrode, for each membrane.

Conclusion

In this project, by using three types of metals and two types of membranes, the electrocatalytic activity and the stability of PEM fuel cells within NaOH solution, are compared.

The potentials of the Ag electrode, in the fuel cells with Nylon and Vileda membranes are given in Graph-1 and 2 respectively. 4 trials were made for each cell having different membranes, and the results are shown in these graphs. As it can be seen from these graphs, the precision of the Ag electrode is low.

In Graph-3 and 4, the change in Pt electrode's potential with time, for each membrane, is given. In three of the four trials, the results are precise, for both membranes. Especially, in the experiment with Pt electrode and nylon membrane, the precision is high.

The potentials for each trial of the fuel cells with Pd electrode and each membrane are given in graph-5 and 6 respectively. As it can be seen from these graphs, the precision of the Pd electrode is high. In addition, all of these results can be deduced from the standard deviation values, which are given in table-7.

The average curves are drawn for the potentials of the cells with each electrode for Nylon and Vileda membrane in Graph-7 and 8 respectively. According to Graph-7, the highest electrocatalytic activity is in the Pd electrode for the Nylon membrane. Then, Pt and Ag electrodes follow it respectively. According to Graph-8, for the cells with the Vileda membrane, the highest electrocatalytic activity is gathered with the Pt electrode which is followed by Pd and Ag electrodes respectively. When the standard reduction potentials which are +0.799, +0.915 and +1.188 for Ag, Pd and Pt respectively, are taken into consideration, Pt is the most inert metal and its electrocatalytic activity should be the highest. However, the cells with Nylon membrane prove this fact only; where the cells with Vileda membrane have the highest electrocatalytic activity, with the Pd electrode. Consequently, different results are deduced for different membranes of one electrode. In addition, the most precise results are reached in the fuel cells with Pt electrode and Nylon membrane.

The hydrogen ion concentrations, which are given in table-8, are used to draw Graph-9, 10 and 11. These graphs show the change in hydrogen ion concentrations for each membrane, in different electrodes.

The change in the logarithm of hydrogen ion concentrations, for each membrane in Ag electrode, is given in Graph-9. According to this graph, the hydrogen ion concentration is decreasing gradually, until the 3rd minute when the gas inlet is stopped. In this period, as the gas is given into the system, hydrogen ions are transferred from anode to the cathode, by the help of the membranes. When

the gas inlet is stopped, the hydrogen ion concentration starts to increase in anode. As a result, the hydrogen ion concentration reaches equilibrium by the membranes. As it can be seen from the graph, the final increase of the hydrogen ion concentration is more in Vileda than it is in Nylon membrane. Therefore, it can be deduced that change in hydrogen ion concentration in the fuel cells with Nylon membrane is more stable than the change in the cell with Vileda.

In the fuel cells with the Pt electrode, change in the logarithm of the hydrogen ion concentrations for each membrane, is given in Graph-10. Before the gas is stopped, the decrease in the hydrogen ion concentration in the fuel cells with Nylon membrane is less than the decrease in the cells with Vileda. Consequently, again the change in Nylon is much more stable. After the gas is stopped, in the cells with Nylon, the hydrogen ion concentration in anode continues decreasing more slowly than before; while in vileda, it starts to increase a little.

In Graph-11, the change in logarithm of the hydrogen concentration of the cells with Pd electrode, for each membrane is given. The results in the Graph-11 are similar to the results in Graph-10. The decrease in the hydrogen ion concentration of the Nylon-fuel cell is less than the decrease in the Vileda-fuel cell. Afterwards, when the gas inlet is stopped, in Nylon-fuel cell, the hydrogen ion concentration reaches equilibrium by decreasing slowly. Besides, in the anode of the Vileda-fuel cell, the hydrogen ion concentration is increased to reach equilibrium.

Evaluation

Unlike an ordinary PEM fuel cell, in this project, alkali solution (2 M NaOH) is used as the electrolyte, besides the membrane. According to the literature researches, although there have been many experiments made; no projects are reached that used basic solution as the electrolyte, besides the membrane. The aim of this second electrolyte was, to increase the transfer of ions between the electrodes; as NaOH is a strong electrolyte. This was a limiting factor in the project, which may have caused low potentials in the fuel cells.

Furthermore, although the calculation of the logarithm of hydrogen ion concentrations seemed to be correct theoretically; most probably there is an error in the results, which are so low. The most important factor, that caused this error, may be the negligence of the hydroxide ion concentration that is coming from the ionization of water. Another factor that caused this error may be the difficulties in the handling of the roller clamp of the IV set, which was used in giving the hydrogen gas into the system. The gas was not given with the same strength in all trials. A little of the alkali solution spurted in some trials.

In addition, the apparatus of the fuel cells, in this project, were simpler than an ideal PEM fuel cell. Simple film containers were used which were not appropriate in this technology. In addition, the way of conducting the ions is also much simpler; because of the use of alkali solution besides the membrane. This apparatus may be developed so as to derive more precise and reliable results.

The aim of this project was to determine alternatives to the type of electrolytes and electrodes in PEM fuel cells. The drawbacks of the PEM fuel cells are the limited sources for the Pt electrode and the high cost of the electrolyte and Pt. As the fuel cell technology is becoming more important, this project is chosen.

In the project, fuel cells, prepared by using Vileda and Nylon membranes with Pt, Pd and Ag electrodes, are examined. It is expected that Nylon membrane with Pt electrode would give the highest electrocatalytic activity and stability. When the results of this project are evaluated, the best alternative to the Pt electrode is found to be Pd. However, during the experiments with the Pd metal, the falling off of the metal into solution showed that it is difficult to work with Pd. For the membranes, it is concluded that Nylon gave more stable results than Vileda. The reason is the fact that Vileda is produced to be used in textile industry. However, the highest electrocatalytic activity was measured in the cells with Pt-Vileda membrane and Pd-Nylon membrane. Finally, the fact that Pd and Pt electrodes lead to different results with different membranes, is important. As a result, to determine the fuel cells with highest stability and electrocatalytic activity; combinations, which are formed by using various metals and membranes, must be tested.

(3903 Words)

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Appendix 1

Experimental Procedure

Materials:
- 4 pieces of 250 cm^3 volumetric flask
- Electronic balance (±0.0001 g) (Gec Avery-model:931913)
- 80 g NaOH solid (purity 99.9% from Merck)
- Scissors
- Ruler (±0.05 cm-showing 0.1 cm)
- 48 pieces of film containers (the ones shown in picture-2.1)
- Cyano acrylate glue
- Parafilm (Pechiney Plastic Packaging)
- Ag, Pd, Pt electrodes 2 pieces from each (Johnson Matthey & Co. Ltd.)
- Cardboard (0.1 cm thick)
- Right stand
- 50 cm^3 graduated cylinder (±1 cm^3)
- 12 pieces of nylon membrane (45μm thick-47 mm diameter-Cole Parmer Nylon Membranes Catalog number: 2916-44)
- Vileda (Area:15 cm*15 cm)
- Hydrogen gas (HABAŞ company)
- Balloon
- Protek 505 digital multimeter (±0.001 V-showing 1 V)
- 2 pieces of crocodile clips
- IV set

1. Preparing 2M, 250 cm³ NaOH (sodium hydroxide) solution:

First of all, it is needed to calculate the mass of NaOH in the 2 M, 250 ml solution:

$$\left[Molarity = \frac{mass\big/molar\ mass}{volume} \right]_6$$

It is known that:

Molarity = 2 mole/dm^3

Molar Mass of NaOH = 40 g/mole

Volume = 250 cm^3 = 0.25 dm^3

To calculate the mass:

$$2\ mole\ dm^{-3} = \frac{x\big/40g\ mole^{-1}}{0.25\ dm^3}$$

$$x = 20\ g$$

Method:
i. 100 ml distilled water is poured into the 250 ml volumetric flask.

ii. 20 g NaOH is weighed by using the electronic balance. 20 g NaOH is put in the flask and it is shaken by using hand. **Note:** These are done as fast as we can and also carefully; because NaOH immediately reacts with oxygen in the air.

iii. When all NaOH is dissolved, distilled water is poured until the level comes to the 250 ml mark on the flask.

iv. Overall the steps i, ii and iii are repeated for 4 times so that we would have 4 pieces of 2 M, 250 ml NaOH solution.

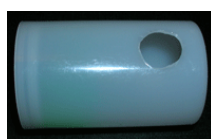## 2. Preparing cells by using film containers (shown in picture-2.1):

i. The middle part of the lid is cut by using the scissors.(See picture-2.2)

ii. On the side of the container, a hole having 1.0 cm diameter and having a distance of 0.5 cm from the bottom of the container is cut. (See picture-2.4)

iii. On another container the steps i and ii are repeated. Besides, another hole having a diameter of 0.8 cm and a distance of 1.5 cm to the other hole, is cut on that container.(See picture-2.3)

iv. Before fixing the lid on the film containers, some glue is poured on the opening of the container and the part of the lid that will touch the container when closed. Immediately, the lid is fit on the film container thoroughly. This step is repeated for the other container.

v. 24 pieces of containers which have 1 hole; 24 pieces of containers which have 2 holes are prepared according to step i, ii, iii, iv and v.

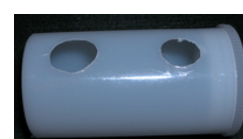**Picture-2.1** shows a film container.
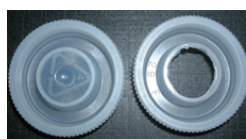
Picture-2.2 shows ordinary lid and the cut

Picture-2.4 shows cathode, with one hole.

Picture-2.3 shows anode, with two holes.

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[6] Equation to find the molarity of a solution: Zumdahl, 514

### 3. Preparing fuel cell by using film containers and the membranes:

i. A film container is put upside down on the vileda and the circumference of the membrane is determined by using a pencil.

Picture-3.1 shows vileda membrane.

ii. Using the scissors, that piece is cut carefully.

iii. Steps i and ii are repeated, for 12 times so that we will have 12 pieces of vileda membrane. (see picture-3.1)

iv. Steps i, ii and iii are repeated using the nylon membrane instead of vileda.

v. Using the 1-hole-cells (24 pieces) and 2-holes-cells (24 pieces) and each membrane (vileda*12 and nylon*12) 24 pieces of fuel cells are prepared as in picture-3.3. Glue is poured on the boundaries of the lids where the membrane

Picture-3.2 shows nylon membranes in their box.

will touch. Then, the containers are fit to the membrane tightly. On the cell, the holes must be on the same line. Later on, 2.0 cm wide and 10.0 cm long parafilm is cut and it is rolled around the midpoint where the membrane was stuck.
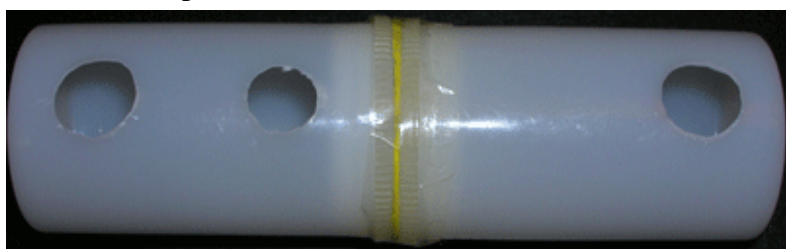
Picture-3.3 shows fuel cell (with vileda membrane) without the electrode and the alkali solution.

→As a result 12 pieces of the fuel cell like in picture-3.3 and 12 pieces of the same with nylon membrane instead of vileda should have been prepared.

4. Preparing the electrodes and fitting them on the fuel cell:

Cross sectional diameter of the glass rods, to which the electrodes are attached by the glassworker in Ankara Science Faculty, is 0.9 cm. To fit them into the holes (having 1.0 cm diameter) on the fuel cells:

i. By using the scissors, 6 pieces of 0.9 cm wide and 3.0 cm long from the 0.1 cm thick cardboard is cut. For each electrode one piece will be used.

ii. The cardboards are fit around the glasses of the electrodes. The cardboard's place is adjusted so that the electrode will not touch to the film container when electrode is in the hole.

5. Preparing fuel cells-final step:

i. One of the fuel cells with **nylon** membrane is clamped to the right stand from the midpoint, where the membrane was stuck.

ii. Totally, 40 cm^3 of the 2 M NaOH solution is poured into anode and cathode of the cell. First, the solution is poured into a graduated cylinder. Then, 20 cm^3 of the solution is poured both into the anode and cathode.

iii. Carefully two of the **Ag electrodes** are taken and placed into the holes of the cathode and anode. In the anode, it is placed into the greater hole. The second hole will be used for the H_2 gas.

iv. The balloon is attached to the filling chamber of an IV set (see picture 5.1). Then 1.0 cm wide 5.0 cm long parafilm is rolled around the part where balloon is attached.

v. The IV set's tube is attached to the opening of the hydrogen gas tube from the HABAŞ company. The gas is let into the balloon. **Note:** The pressure of the gas that is being taken into the balloon must be 2.6 atm. In addition, the roller clamp of the IV set must be opened so the gas would easily reach the balloon. The gas is stopped when the balloon's diameter is 20.0 cm approximately (see picture 5.2). While detaching the balloon from the opening of the gas tube, the roller clamp must be closed. Then, the IV set's tube is inserted into the hole of the anode, being sure that it is inside the NaOH solution

vi. The voltmeter's positive and negative poles are attached to the cathode and anode of the cell by using crocodile clips. (See picture-5.3)

Picture-5.1 shows the IV set

Picture-5.2 shows the display of the fuel cell.

Picture-5.3 shows final display of the experiment.

Appendix 2

Time (1=15 s)	Experiment with Ag Electrode and Nylon Membrane		Experiment with Ag Electrode and Vileda Membrane		Experiment with Pt Electrode and Nylon Membrane		Experiment with Pt Electrode and Vileda Membrane		Experiment with Pd Electrode and Nylon Membrane		Experiment with Pd Electrode and Vileda Membrane	
	Table-9 Logarithm of Hydrogen Ion Concentrations and the Calculated Errors											
	Logarithm of Hydrogen Ion Concentrations (mole.dm^{-3})	Error Value of Logarithm of Concentration of [H+] (±)	Logarithm of Hydrogen Ion Concentrations (mole.dm^{-3})	Error Value of Concentration of [H+] (±)	Logarithm of Hydrogen Ion Concentrations (mole.dm^{-3})	Error Value of Concentration of [H+] (±)	Logarithm of Hydrogen Ion Concentrations (mole.dm^{-3})	Error Value of Concentration of [H+] (±)	Logarithm of Hydrogen Ion Concentrations (mole.dm^{-3})	Error Value of Concentration of [H+] (±)	Logarithm of Hydrogen Ion Concentrations (mole.dm^{-3})	Error Value of Concentration of [H+] (±)
d	-6,389	0,0006	-6,187	0,0004	-6,339	0,0002	-6,237	0,0003	-6,339	0,0005	-6,254	0,0008
1	-6,880	0,0008	-6,558	0,0006	-7,302	0,0050	-10,294	0,0004	-7,082	0,0003	-7,353	0,0021
2	-7,082	0,0011	-6,778	0,0007	-8,638	0,0096	-11,004	0,0011	-7,488	0,0006	-8,722	0,0100
3	-7,218	0,0014	-6,897	0,0007	-9,922	0,0099	-11,629	0,0026	-7,945	0,0015	-11,714	0,0320
4	-7,319	0,0015	-7,015	0,0007	-10,852	0,0033	-12,289	0,0018	-9,026	0,0042	-14,030	0,0430
5	-7,421	0,0017	-7,116	0,0007	-11,139	0,0014	-16,261	0,0420	-11,900	0,0230	-14,858	0,0480
6	-7,505	0,0018	-7,201	0,0009	-11,139	0,0011	-18,374	0,0380	-15,010	0,0160	-15,991	0,0410
7	-7,590	0,0019	-7,302	0,0009	-11,156	0,0008	-20,284	0,0130	-16,751	0,0077	-18,205	0,0100
8	-7,657	0,0020	-7,404	0,0010	-11,156	0,0007	-20,859	0,0031	-17,377	0,0031	-18,492	0,0078
9	-7,708	0,0020	-7,505	0,0011	-11,156	0,0006	-21,146	0,0025	-17,715	0,0011	-18,729	0,0056
10	-7,759	0,0021	-7,590	0,0012	-11,139	0,0005	-21,264	0,0036	-17,901	0,0023	-18,949	0,0038
11	-7,809	0,0022	-7,674	0,0015	-11,122	0,0003	-21,315	0,0045	-18,053	0,0036	-19,050	0,0036
12	-7,860	0,0022	-7,759	0,0015	-11,122	0,0004	-21,332	0,0045	-18,154	0,0045	-19,118	0,0038
13	-7,826	0,0023	-7,708	0,0017	-11,241	0,0002	-21,400	0,0030	-18,306	0,0059	-18,999	0,0042
14	-7,776	0,0025	-7,623	0,0018	-11,275	0,0002	-21,349	0,0019	-18,256	0,0057	-18,898	0,0047
15	-7,742	0,0026	-7,522	0,0019	-11,291	0,0003	-21,247	0,0015	-18,289	0,0059	-18,830	0,0053
16	-7,674	0,0026	-7,454	0,0019	-11,308	0,0003	-21,011	0,0019	-18,289	0,0049	-18,796	0,0055
17	-7,640	0,0027	-7,404	0,0019	-11,308	0,0003	-20,859	0,0004	-18,323	0,0042	-18,780	0,0054
18	-7,590	0,0027	-7,370	0,0019	-11,325	0,0003	-20,584	0,0012	-18,391	0,0039	-18,763	0,0056
19	-7,556	0,0026	-7,353	0,0019	-11,325	0,0003	-20,368	0,0039	-18,408	0,0031	-18,763	0,0054
20	-7,539	0,0026	-7,336	0,0018	-11,342	0,0002	-20,216	0,0051	-18,425	0,0029	-18,746	0,0054

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