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Canada Centre for
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Western Research Centre / Centre de recherche de l'Ouest



Water pollution

Canada

WRC 93-005 (TR)

01-000 4646



THE COST OF ELECTROCOAGULATION

J.C. Donini, J. Kan, J. Szykarczuk,
T.A. Hassan, and K.L. Kar
Division Report WRC 93-05 (TR)

January, 1993

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J.C. Donini^{*}, J. Kan^{**}, J. Szykarczuk^{**},
T.A. Hassan^{**}, and K.L. Kar^{***}

ABSTRACT

The electrocoagulation of kaolinite and bentonite suspensions was studied in a pilot electrocoagulation system at the Western Research Centre of CANMET to assess the cost and efficiency of the process. Factors affecting cost such as, the formation of passivation layers on electrode plates and the recirculation and concentration of sodium chloride were examined. Colorimetry was used to analyze aluminum content in the suspension. The results were used to calculate the cost due to the consumption of electrode material, i.e., aluminum, during the process. Total cost was assumed to comprise the energy cost and the cost of aluminum electrode material. Comparison was based on the settling properties of the treated product: turbidity, settling rate, and cake height.

In most cases, aluminum efficiency averaged around 200% and aluminum material cost accounted for 80% of the total cost. Experimental results also showed that although higher concentrations of sodium chloride could only slightly increase aluminum efficiency and the electrode efficiency, the higher concentrations resulted in much greater total cost. This was caused by the greater current generated due to the increased conductivity of the suspension, which in turn, dissolved a larger amount of aluminum. The recirculation loop installed on the cell system increased the flow rate by 3 to 10 times, enhancing the mass transport between the electrodes and resulting in both lower cost and better settling properties. During the two-month experiment the electrodes were coated by clayish layers which gradually became thicker, while the performance of the cell system deteriorated. The term "electrode efficiency" was defined to evaluate the change in efficiency of the electrodes due to the formation of passivation layers. The electrode efficiency was found to be as high as 94% for virgin electrode plates and to decline to as low as 10% for the same system operated two months later. During this time interval the current waveform became greatly distorted and less and less current was driven by the same voltage applied.

^{*} Head Surface Science and Applications; ^{**} Post Doctoral Fellow; ^{***} Senior Technician, Fuel Processing Laboratory, Coal Research Laboratories, CANMET, Energy Mines and Resources Canada, Devon, Alberta.

LE COÛT DE L'ÉLECTROCOAGULATION

J.C. Donini*, J. Kan**, J. Szykarczuk**,
T.A. Hassan** et K.L. Kar***

RÉSUMÉ

On a étudié l'électrocoagulation de suspensions de kaolinite et de bentonite dans le système pilote d'électrocoagulation du Centre de recherche de l'Ouest de CANMET, en vue d'évaluer le coût et l'efficacité du procédé. On a examiné les facteurs influant sur le coût, comme la formation de couches de passivation sur les électrodes et la recirculation et la concentration du chlorure de sodium. On a dosé, par colorimétrie, l'aluminium dans la suspension et on a utilisé les résultats pour calculer le coût associé à la consommation du métal constituant l'électrode, c.-à-d. la consommation d'aluminium, durant le procédé. On suppose que le coût total comprend le coût de l'énergie et le coût de l'aluminium constituant l'électrode. On a basé la comparaison sur les propriétés de précipitation du produit traité, soit turbidité, vitesse de précipitation et épaisseur du précipité.

Dans la plupart des cas, l'efficacité en aluminium était en moyenne de 200 %, tandis que le coût de l'aluminium représentait 80 % du coût total. Même si des concentrations plus élevées de chlorure de sodium ne permettaient d'accroître que légèrement l'efficacité en aluminium et l'efficacité des électrodes, comme l'indiquaient aussi les résultats expérimentaux, l'utilisation de telles concentrations augmentait de beaucoup le coût total, car l'accroissement du courant en raison de la conductivité plus élevée de la suspension se traduisait alors par la dissolution d'une plus grande quantité d'aluminium. La boucle de recirculation installée sur le système de cellules permettait d'augmenter de 3 à 10 fois le débit, ce qui se traduisait par un transport accru de masse entre les électrodes ainsi que par des coûts plus faibles et de meilleures propriétés de précipitation. Pendant l'expérience de deux mois, des couches argileuses devenant graduellement plus épaisses se sont déposées sur les électrodes et le rendement du système de cellules s'est détérioré. "L'efficacité des électrodes" est une mesure de la diminution de l'efficacité en raison de la formation de couches de passivation sur les électrodes. L'efficacité d'électrodes vierges pouvait atteindre 94 % et diminuer parfois jusqu'à 10 % après deux mois d'utilisation. Durant cette période, la forme d'onde du courant se déformait considérablement et la même tension appliquée déplaçait de moins en moins de courant.

*Chef, Science des surfaces et applications; **stagiaire postdoctoral; ***technicien principal, Laboratoire de traitement des combustibles, Laboratoires de recherche sur la charbon, CANMET, Énergie, Mines et Ressources Canada, Devon (Alberta).

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INTRODUCTION

During the recent decades, research on waste water treatment using electrocoagulation has shown that electrocoagulation could be an attractive and suitable method in separating solids from waste water (1,2). The research has also shown that electrocoagulation works well for a large range of applications (1-5).

If electrocoagulation systems are to be practically applicable to environmental problems, the cost and efficiency of electrocoagulation systems become critical. Unfortunately, not much work has been published in this area even though industrial-scale electrocoagulation units have been available in the market (4,6,7). Therefore, studies on the cost reduction and cost-affecting factors in electrocoagulation systems are necessary, especially in view of the role these factors must play in future system design.

Thus the purpose of this work is to study the cost incurred during experiments (which comprises the costs of energy and the aluminum electrode consumed.) Particular attention was given to the effect on cost of sodium chloride concentration, flow rate with and without recirculation, and the formation of the passivation layers. This work is also intended to investigate how the concentration of sodium chloride affects aluminum efficiency, how much of the cost is due to the cost of aluminum, and the efficiency of electrode.

A recent experiment of aluminum treatment on the same clay suspension showed about 20 ppm of aluminum was needed to get a good clarity. This could cost \$0.14/m³ from the material alone (assuming aluminum material costs \$7/kg). Donini et al. (1) pointed out that for both electrocoagulation and aluminum salts treatment (aluminum sulphate and aluminum chloride), the mechanisms of coagulation are similar. The difference is mainly in the way aluminum ions are delivered. Several questions remain: what is the optimum aluminum dosage and how much does it cost? Further, what is the least cost and how may it be achieved? and finally, how does the water and suspended solids chemistry affect optimization?

EXPERIMENTAL

THE PILOT ELECTROCOAGULATION SYSTEM

The pilot electrocoagulation system consisted of the power supply, the electrocoagulation cell, the auxillary equipment, and the control data acquisition system. Detailed information can be obtained from the CANMET report by Donini et al.(2). In this experiment, the cell contained four parallel electrode plates and the curcuit was as shown in Fig. 22. The gap between the two neighboring electrode plates was 6 cm. The plate was 16.5 cm high and 58 cm wide.

MATERIALS

Aqueous suspensions of 0.16 wt% kaolinite and 0.04 wt% bentonite were used as feed material. Concentration of sodium chloride was adjusted from 0 to 0.1 wt% and, in most cases, it was fixed at 0.03 wt%. pH values of the feed were measured for each experiment and listed in tables.

ALUMINUM ANALYSIS

To measure aluminum concentration in a sample suspension, there were two alternatives for WRC/CANMET: the colorimetric method and the ICP (inductively coupled plasma) method.

The colorimetric method of determining aluminum content used pyrocatechol violet which had a colour reaction with aluminum. After stabilization of the colour, the colorimeter was used to measure the absorbency of the complex, which led to the aluminum content.

In this study, aluminum content was based on colorimetric measurement only. However, the ICP method was also applied for the purpose of calibration. Comparison showed that the two methods gave very similar results.

The consumption of the aluminum electrode material for unit volume of feed was obtained from the difference of the aluminum contents in the product and the feed.

Assuming the efficiency of aluminum dissolved due to electric current is 100%, a relation between current and aluminum content can be set by the Faraday law:

$$I_{Al} = 0.1787 * Q * \text{Aluminum Content} \quad \text{Eq 1}$$

where I_{Al} is the current for producing aluminum ion electrically.

Since total aluminum content is the sum of the aluminum dissolved electrically and chemically, aluminum efficiency, η_{Al} , is defined as:

$$\eta_{Al} = \frac{I_{eq}}{I_{ac}} \quad \text{Eq 2}$$

where I_{eq} is the equivalent current calculated by Eq 7 from the total aluminum content measured and I_{ac} is the actual current measured during the process.

INSTRUMENTATION

Cole-Parmer Model 5800-00 solution analyzer was used to measure pH and conductivity of the feed and the processed product. To measure the temperatures of the fluids, two thermocouples were mounted on the cell system, one on the inlet pipe and the other on the outlet. The power supply for the pilot plant was designed by Zeton Inc. for operation under

either current or voltage control. In this experiment, most of the runs were under voltage control except for the run on November 20, 1991. Square voltage waves were generated and pulse duration was set at 300 seconds. Voltage, current, and pulse duration were measured and recorded in the computer every two seconds under the control of the commercially available software, Specifix. The settling rate of the sludge/supernatant interface was determined manually in a 1-L cylinder by recording the interface height with time. The average settling rate for the first 30 minutes was used in this report. The Hach Ratio/XR turbidimeter was used to measure the turbidity of the feed and product. Turbidity of supernatant was determined for samples taken from the settling cylinder after 10, 45, and 120 minutes of settling. Only turbidity values measured after 10 minutes of settling were used in compiling this report. The cake height was the height of the sludge/supernatant interface measured after 15 hours of settling.

CALCULATION OF COST

Based on the voltage and current data measured every two seconds, the average power during one cycle is defined as:

$$\text{Average power, } N = \frac{1}{k} \sum V_i I_i \quad \text{Eq 3}$$

where $i=1,2,\dots,k$, and k is the total number of the sampled data group in one cycle. V and I are the electric voltage and current respectively.

$$E = \frac{N}{60 * Q} \quad \text{Eq 4}$$

where Q is the flow rate of the product in litres per minute and E is the energy consumed per unit volume of feed in kilowatt-hours per cubic metre.

Assuming an energy price of \$0.05/kWh (1), the energy cost is given by

$$\text{Energy Cost}^* = \frac{0.05}{60} * \frac{V * I}{Q} \quad \left[\frac{\$}{M^3} \right] \quad \text{Eq 5}$$

where energy cost is in dollars per cubic metre, V , and I are the average voltage and average current, respectively.

$$\text{Aluminum Cost} = \frac{7}{1000} * \text{Aluminum Content} \quad \text{Eq 6}$$

where the unit of aluminum cost is in dollars per cubic metre; 7/1000 is the cost factor based on the cost of aluminum at \$7.00/kg; aluminum content is in units of ppm.

$$\text{Total Cost} = \text{Energy Cost} + \text{Aluminum Cost} \quad \text{Eq 7}$$

Substituting Eq 5 and Eq 6 into Eq 7, we have:

$$\text{Total Cost} = \frac{0.05 * V * I}{60 * Q} + \frac{7}{1000} * \text{Aluminum Content} \quad \text{Eq 8}$$

Eqs 5-7 are used to calculate the costs based on the

experimental data collected. Energy and aluminum costs, their percentages of total cost, and the total cost are listed in Tables 1-9.

RESULTS AND DISCUSSION

EFFECT OF CONCENTRATION OF SODIUM CHLORIDE

Concentration of sodium chloride was varied from 0 to 0.1 wt% and the corresponding solution conductivity values were measured. As expected, conductivity was found to increase linearly with the concentration of sodium chloride (Fig. 1). The current generated by a controlled voltage also showed a strong linear relation with the increasing concentration (Fig. 2). Total aluminum content measured was also directly proportional to current. This resulted in a linear relationship between aluminum content and concentration of sodium chloride (Fig. 3). It is interesting to note that the changing concentration of sodium chloride changed both the conductivity of the solution and the resistance due to the formation of a passivation layer, and resulted in the linear relationship between the aluminum content and the concentration of sodium chloride. In other words, it is possible to obtain empirically a correlation between aluminum content and concentration of sodium chloride for a specific system and set voltage, most likely a linear relation as follows:

$$\text{Aluminum Content} = k_1 \eta_{Al} C_{NaCl} + k_2 \quad \text{Eq 9}$$

where k_1 , k_2 are empirical constants, and k_2 is small; η_{Al} is the aluminum efficiency; C_{NaCl} is the concentration of sodium chloride.

Since aluminum cost is directly proportional to aluminum content, the total cost could also be estimated at a given voltage and C_{NaCl} by substituting Eq 9 into Eq 6.

$$\text{Total Cost} = \frac{0.05VI}{60Q} + \frac{7}{1000} [k_1 \eta_{Al} C_{NaCl} + k_2] \quad \text{Eq 10}$$

It can be seen from the above equation that total cost is directly proportional to the current at a given voltage and sodium chloride concentration.

Aluminum efficiency (Fig. 4) increased with the concentration of sodium chloride when the sodium chloride concentration was smaller than 0.05%. If 190-200% is estimated to be the average aluminum efficiency, the relative error for most of the data would fall within 25%. Parameters measured such as voltage, current, and flow rate, as well as aluminum efficiency and the calculated cost are listed in Tables 1-4.

It seems that aluminum cost accounted for about 80% of the total cost in both experiments (Fig. 5 & 6).

To further analyze the effect of η_{Al} on cost, Eq 7 and 8 can be combined:

$$\text{Aluminum Content} = \eta_{Al} * \frac{I}{0.1787 * Q} \quad \text{Eq 11}$$

By substituting Eq 11 into Eq 6, we have:

$$\text{or } Total\ Cost = \frac{0.05VI}{60Q} + \frac{7}{1000} * \frac{\eta_{Al}I}{0.1787*Q} \quad \text{Eq 12a}$$

$$Total\ Cost = \frac{I}{Q} * 0.03917 [0.02127V + \eta_{Al}] \quad \text{Eq 12b}$$

That is, aluminum cost is the largest contribution to the total cost. This is based on the assumption that aluminum efficiency is approximately 200% and voltage is about 20 v. It should be noted that when voltage becomes higher, the energy cost term in Eq 12b increases.

Table 1 and Fig. 7-9 display the effect of sodium chloride concentration on the settling properties. The data show that the higher the concentration of sodium chloride, i.e., the higher the current and energy input, the better the turbidity of supernatant obtained and the lower the settling rate and higher cake height. During coagulation, a stronger current generally results in looser flocs which settle more slowly, they contain more water, and at the same time make clearer supernatant.

EFFECT OF RECIRCULATION

It is believed that a high turbulence level not only enhances mass transport, but also reduces the passivation layers near the electrode plates. Turbulence can be increased by increasing the flow rate inside the cell. However, when the

flow rate is increased, the residence time and the energy consumed per unit volume of feed is decreased. In order to maintain the same residence time while increasing the flow through the cell to induce turbulence, a recirculation loop was installed (see Fig. 10). With recirculation, the flow through the cell is greatly increased. For each unit volume of feed, the time taken for passing the cell becomes proportionately less, while part of that volume passes through the cell a correspondingly greater number of times, resulting in a total residence time the same as that without recirculation. A detailed mathematical derivation is presented in Appendix A.

Tables 5-7 list most of the parameters and results obtained from the test. With recirculation, energy consumed per unit volume of feed was controlled at lower value for all the chosen flow rates (Fig. 11).

Figures 12 and 13 show that the total cost and aluminum content were consistently lower when recirculation was used for the whole flow rate range than when recirculation was not used. The percentages of energy cost and aluminum cost of the total cost were very close in both cases (Fig. 14), although aluminum efficiency was found to be higher when recirculation was used (Fig. 15). In most cases, the turbidity with recirculation was lower than that without recirculation (Fig. 16).

The more interesting discovery was that recirculation

caused a consistently faster settling rate and much lower cake height (Fig. 17 & 18). This is contrary to the usual results where better clarity implies lower settling rate and higher cake height. This is an important result since high clarity and low cake volume (i.e., height) are desirable. The authors reason that the high shear rate obtained due to high flow rate made the flocs more compact and, therefore, they settled faster and contained less water.

EFFECT OF THE FORMATION OF PASSIVATION LAYERS

The growth of the passivation layers on the electrode plates and their effect on cell performance were observed and measured.

Changing Electric Current Waveforms

When the controlled voltage waveform is square, the current wave should follow. However, it was noticed that the current waveforms were gradually changing and deviating from square form although the voltage was fixed and other parameters were kept almost constant during the ongoing experiments. The change of the waveforms can be seen in the following:

a) The deviation from rectangular waveform and the fluctuation of current increased with time. In January 1992, the

fluctuation reached more than 0.5 of the average current in the corresponding positive period while early in the previous November no fluctuation had been noticeable and a rectangular current pattern was obtained (refer to Fig. 19 & 20).

b) The ratio between current and voltage (see Table 8) decreased from 3.75 on November 21, 1991 to 0.233 on January 21, 1992 showing a great deterioration in the efficiency of the electrodes.

c) At first, current waves were symmetric. Gradually they became asymmetric between the positive period and the negative period. The difference between average current in the two periods was about half of the average current in the corresponding positive period.

Detailed information can be obtained from Table 8 and Fig. 19 & 20.

Observation of the Electrodes

After all the experiments were completed, the cell was separated and the electrodes removed. A layer of non-metallic substance was found sticking on each side of the electrodes. This layer could be scraped off. Its outer surface looked as white as clay and the inside surface looked as dark as metal.

The scraped-off chips were hard, brittle and fragile. The substance was carefully weighed after it was dry. The weights of the scraped layers are listed below:

Polarity I	Weight, g	Polarity II	Weight, g
side 1	34.7	side 2	43.9
side 4	31.0	side 3	42.0
side 5	31.9	side 6	44.7

Figure 21 shows the electric circuit of the cell electrodes. It should be noted that sides 1, 4, and 5 belong to one polarity and sides 2, 3, and 6 to the opposite polarity. That means the layer on one side of the electrodes is thicker than that on the other side and the total difference is 32.9 g.

Table 9 presents the experimental results with respect to elapsed time of operation. As discussed above, the ratio between current and voltage dropped dramatically from 3.75 in November to 0.233 in January, and a substantial clayish layer was formed on the electrodes. The results showed that, as time passed, there was an increasing resistance between the two electrodes and more energy was wasted on heating the passivation layers. In order to quantitatively estimate the energy wasted, Donini et al.(1) suggested that the total voltage measured consisted of three voltage drops :

$$V_{AP} = V_k + V_{MT} + V_{IR} \quad \text{Eq 13}$$

where V_{AP} is applied overpotential (potential on voltmeter); V_k is kinetic overvoltage; V_{MT} is mass-transfer overvoltage, and V_{IR} is IR drop.

The IR drop is described by the following relation :

$$V_{IR} = \frac{I * d}{A * \kappa} = I * R_u \quad \text{Eq 14}$$

where I is current [a]; d is inter-electrode distance [m]; A is active anode surface area [m²]; κ is specific conductivity [10³ mS/m]; and $R_u = d/(A.\kappa)$ is the resistance of the suspension of the cell assuming there is no passivation layer generated. IR drop is a function of the geometry of the cell, the solution conductivity of cell, and the solution conductivity.

Eq 13 can be rewritten as:

$$V_{AP} = V_w + V_{IR} \quad \text{Eq 15}$$

where V_w is the wasted voltage drop.

$$V_w = V_k + V_{MT} \quad \text{Eq 16}$$

Based on the same current generated, the IR drop, V_{IR} stays constant according to Eq 14. As the passivation layer becomes thicker and thicker, the total voltage applied, V_{ap} , must be increased to maintain the same current. This increase is caused solely by the increase in the resistance of the

passivation layers, R_w . The total resistance, R_T , is thus the sum of R_w , the resistance of the passivation layers and R_U , the ideal system resistance.

$$R_T = R_U + R_w \quad \text{Eq 17}$$

where R_T can be calculated by the measured values of actual voltage and current:

$$R_T = \frac{V}{I} \quad \text{Eq 18}$$

The electrode efficiency, η_{ele} , is thus defined as:

$$\eta_{ele} = \frac{R_U}{R_T} = \frac{V_{IR}}{V} \quad \text{Eq 19}$$

The electrode efficiency, η_{ele} , is a measure of how much energy goes to the IR drop and how much energy is wasted on the passivation layers.

Figures 23 & 24 show that electrode efficiency changed sharply with time from 84.63% on November 21 to 10.43% on January 21. The percentage of cost wasted on R_w increased with time up to 22.92% of the total cost.

Neither aluminum efficiency nor aluminum cost showed obvious correlation with time (Table 9). Aluminum cost still accounted for most of the total cost although the percentage of the energy cost was increasing. It should be noted that the increase in energy cost was caused merely by the increasing thickness of the passivation layers. In brief, during the

early stage of the experiment, the cost wasted on the passivation layers was generally small compared with aluminum cost. At the end of the experiment, this increased to 22.93% of the total cost which could no longer be neglected. The effect of the increasing resistance of the passivation layers on the electrode efficiency can also be observed in Fig. 25 & 26, i.e., electrode efficiency was always found to be higher for earlier experiments. It is now possible to compare the effect of electrode efficiency on cost with that of aluminum efficiency. Substitute $V = V_{IR}/\eta_{ele} = IR_U/\eta_{ele}$ into Eq 12b and we have :

$$Total\ Cost = \frac{I}{Q} * 0.03917 \left(0.02127 \frac{I * R_U}{\eta_{ele}} + \eta_{Al} \right) \quad Eq\ 20$$

As can be seen from Eq 20, when electrode efficiency decreases from 90% to 10%, the energy cost is nine times as great.

CONCLUSIONS

1. Aluminum cost accounts for about 80% of the total cost in the case studied. It increases directly with current.
2. When concentration of sodium chloride is smaller than 0.05%, the electrical efficiency of the aluminum dispersion was about 200%; aluminum efficiency increases slightly with concentration of sodium chloride.
3. Proper recirculation enhances the mass transport in the cell and reduces the total cost while improving floc structure for faster settling and lower cake height. A better electrocoagulation cell design should be able to optimize the hydrodynamic conditions inside the cell and the whole system.
4. The current generated is sensitive to the thickness of the passivation layers. Although the formation of passivation layers represents only a small increase in the cost initially, this layer substantially reduces the current generated by the same voltage because the resistance of the suspension is relatively low.
5. At high voltage and low electrode efficiency, energy cost can be comparable to aluminum cost.
6. Based on controlled voltage, the higher the concentration of NaCl, the greater the current and the higher the cost. When current is kept constant, energy cost is reduced due to a lower voltage drop and aluminum cost is slightly increased due to the increase in aluminum efficiency. Further study is suggested.

ACKNOWLEDGMENTS

The authors thank Dexter Woo and Jack Zalischuk for helping with the experiment and Zohra Ali for processing data. Thanks also to co-op students Leo Cheng for processing data and Ildiko Ignacz for measuring aluminum content.

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Table 1 - Effect of sodium chloride concentration, comparison of experimental results for December 2, 1991, January 13, 1992, and January 21, 1992

Date	CNaCl (%)	Voltage (v)	Current (a)	Energy Rate (kWh/m3)	Aluminum content (ppm)	Aluminum Efficiency (%)	Electrode Efficiency (%)	*Power Cost (\$/m3)	**Aluminum Cost (\$/m3)	Total Cost (\$/m3)	Turbidity (NTU)	Cake Height (cm)	Settling Rate (cm/s)
Dec 2	0	18	2.29	0.1144	14.35	596.57	9.49	0.01	0.10	0.11	227	1.7	0.0181
Dec 2	0.0045	18	13.59	0.6796	24.95	186.01	49.31	0.03	0.17	0.21	121	2.1	0.0177
Dec 2	0.0075	18	17.64	0.882	46.15	271.95	55.35	0.04	0.32	0.37	60	2.4	0.0172
Dec 2	0.015	18	26.37	1.3184	64.08	253.82	65.14	0.07	0.45	0.51	53	2.6	0.0171
Dec 2	0.02	18	29.95	1.4974	86.91	306.11	65.61	0.07	0.61	0.68	78	3.2	0.0163
Dec 2	0.025	18	32.18	1.609	127.68	420.16	62.27	0.08	0.89	0.97	30	3.2	0.0152
Dec 2	0.03	18	34.23	1.7117	101.59	313.45	60.22	0.09	0.71	0.80	22	3.8	0.0144
Jan 13	0.02	18	9.00	0.45	13.26	137.96	19.35	0.02	0.09	0.12	169.5	1.5	0.0183
Jan 13	0.03	18	10.94	0.547	15.17	132.21	21.53	0.03	0.11	0.13	88.1	1.9	0.0178
Jan 13	0.04	18	12.88	0.644	22.5	173.32	14.95	0.03	0.16	0.19	—	1.9	0.0179
Jan 13	0.05	18	15.60	0.78	29.84	193.55	19.69	0.04	0.21	0.25	73.7	2.1	0.0177
Jan 13	0.06	18	18.04	0.902	34.73	196.44	20.53	0.05	0.24	0.29	58.6	2.1	0.0173
Jan 13	0.07	18	20.90	1.045	46.15	228.14	21.86	0.05	0.32	0.38	40.5	2.2	0.0170
Jan 13	0.08	18	24.24	1.212	59.19	254.39	23.85	0.06	0.41	0.47	29	2.5	0.0162
Jan 13	0.09	18	26.78	1.339	59.19	230.26	23.92	0.07	0.41	0.48	20.2	2.5	0.0162
Jan 21	0	30	7.82	0.631	5.38	34.55	10.09	0.03	0.04	0.07	234	1.25	0.0187
Jan 21	0.02	30	9.66	0.779	10.27	84.08	10.04	0.04	0.07	0.11	128.7	1.3	0.0184
Jan 21	0.03	30	11.98	0.966	20.06	158.35	10.43	0.05	0.14	0.19	59.5	1.4	0.0182
Jan 21	0.04	30	14.48	1.168	24.13	162.10	10.62	0.06	0.17	0.23	55.6	1.4	0.0181
Jan 21	0.05	30	17.17	1.385	41.26	247.22	11.08	0.07	0.29	0.36	42.6	1.6	0.0179
Jan 21	0.06	30	19.98	1.611	33.1	167.28	11.31	0.08	0.23	0.31	55.9	1.5	0.0181
Jan 21	0.08	30	24.48	1.974	32.29	132.85	12.09	0.10	0.23	0.32	72.7	1.5	0.0180
Jan 21	0.1	30	32.20	2.597	37.99	120.59	13.12	0.13	0.27	0.40	52.9	1.7	0.0177

* Assumes power cost @ \$0.05/kWh.

**Assumes aluminum cost @ \$7.00/kg.

Table 2 - Effect of sodium chloride concentration, December 2, 1991

SAMPLE#	Flow Rate (cm ³ /s)	CNaCl (%)	pH	Feed Conductivity (mS/cm)	Energy Rate (kWh/m ³)	Aluminum Content (ppm)	Equivalent Current (a)	Voltage (v)	Current (a)
1	100	0	7.71	0.28	0.1144	14.35	13.65	18	2.288
2	100	0.0045	7.84	0.32	0.6796	24.95	25.28	18	13.592
3	100	0.0075	7.79	0.37	0.882	46.15	47.97	18	17.64
4	100	0.015	8.42	0.47	1.3184	64.08	66.93	18	26.368
5	100	0.02	8.13	0.53	1.4974	86.91	91.68	18	29.948
6	100	0.025	8.72	0.6	1.609	127.68	135.21	18	32.18
7	100	0.03	8.26	0.66	1.7117	101.59	107.31	18	34.234
SAMPLE#	Useful Resistance (ohms)	Total Resistance (ohms)	Electrode Efficiency (%)	Aluminum Efficiency (%)	*Power Cost (\$/m ³)	**Aluminum Cost (\$/m ³)	Total Cost (\$/m ³)		
1	0.75	7.87	9.49	596.57	0.01	0.10	0.11		
2	0.65	1.32	49.31	186.01	0.03	0.17	0.21		
3	0.56	1.02	55.35	271.95	0.04	0.32	0.37		
4	0.44	0.68	65.14	253.82	0.07	0.45	0.51		
5	0.39	0.60	65.61	306.11	0.07	0.61	0.68		
6	0.35	0.56	62.27	420.16	0.08	0.89	0.97		
7	0.32	0.53	60.22	313.45	0.09	0.71	0.80		

*Assumes power cost @ \$0.05/kWh.

**Assumes aluminum cost @ \$7.00/kg.

Table 3 - Effect of sodium chloride concentration, January 13, 1992

SAMPLE#	Flow Rate (cm ³ /s)	CNaCl (%)	pH	Conductivity (mS/cm)	Energy Rate (kWh/m ³)	Aluminum Content (ppm)	Equivalent Current (a)	Voltage (v)	Current (a)
1	100	0.02	8.19	0.54	0.45	13.26	12.42	18	9.00
2	100	0.03	8.22	0.59	0.547	15.17	14.46	18	10.94
3	100	0.04	7.92	1	0.644	22.5	22.32	18	12.88
4	100	0.05	8.1	0.92	0.78	29.84	30.19	18	15.60
5	100	0.06	8.31	1.02	0.902	34.73	35.44	18	18.04
6	100	0.07	8.33	1.11	1.045	46.15	47.68	18	20.90
7	100	0.08	8.64	1.18	1.212	59.19	61.66	18	24.24
8	100	0.09	8.75	1.3	1.339	59.19	61.66	18	26.78
SAMPLE#	Useful Resistance (ohms)	Total Resistance (ohms)	Electrode Efficiency (%)	Aluminum Efficiency (%)	*Power Cost (\$/m ³)	**Aluminum Cost (\$/m ³)	Total Cost (\$/m ³)		
1	0.39	2.00	19.35	137.96	0.023	0.093	0.115		
2	0.35	1.65	21.53	132.21	0.027	0.106	0.134		
3	0.21	1.40	14.95	173.32	0.032	0.158	0.190		
4	0.23	1.15	19.69	193.55	0.039	0.209	0.248		
5	0.20	1.00	20.53	196.44	0.045	0.243	0.288		
6	0.19	0.86	21.86	228.14	0.052	0.323	0.375		
7	0.18	0.74	23.85	254.39	0.061	0.414	0.475		
8	0.16	0.67	23.92	230.26	0.067	0.414	0.481		

*Assumes power cost @ \$0.05/kWh.

**Assumes aluminum cost @ \$7.00/kg.

Table 4 - Effect of sodium chloride concentration, January 21, 1992

SAMPLE#	Flow Rate (cm ³ /s)	CNaCl (%)	pH	Conductivity (mS/cm)	Energy Rate (kWh/m ³)	Aluminum Content (ppm)	Equivalent Current (a)	Voltage (v)	Current (a)
1	103.33	0.01	8.39	0.54	0.631	5.38	2.70	30	7.82
2	103.33	0.02	8.15	0.67	0.779	10.27	8.12	30	9.66
3	103.33	0.03	8.2	0.8	0.966	20.06	18.97	30	11.98
4	103.33	0.04	8.41	0.95	1.168	24.13	23.48	30	14.48
5	103.33	0.05	8.29	1.08	1.385	41.26	42.46	30	17.17
6	103.33	0.06	8.47	1.23	1.611	33.1	33.42	30	19.98
7	103.33	0.08	8.41	1.41	1.974	32.29	32.52	30	24.48
8	103.33	0.1	8.01	1.71	2.597	37.99	38.83	30	32.20
SAMPLE#	Useful Resistance (ohms)	Total Resistance (ohms)	Electrode Efficiency (%)	Aluminum Efficiency (%)	*Power Cost (\$/m ³)	**Aluminum Cost (\$/m ³)	Total Cost (\$/m ³)		
1	0.39	3.83	10.09	34.55	0.03	0.04	0.07		
2	0.31	3.11	10.04	84.08	0.04	0.07	0.11		
3	0.26	2.50	10.43	158.35	0.05	0.14	0.19		
4	0.22	2.07	10.62	162.10	0.06	0.17	0.23		
5	0.19	1.75	11.08	247.22	0.07	0.29	0.36		
6	0.17	1.50	11.31	167.28	0.08	0.23	0.31		
7	0.15	1.23	12.09	132.85	0.10	0.23	0.32		
8	0.12	0.93	13.12	120.59	0.13	0.27	0.40		

*Assumes power cost @ \$0.05/kWh.

**Assumes aluminum cost @ \$7.00/kg.

Table 5 - Effect of circulation, comparison of results with recirculation and without recirculation

	Flow Rate (cm ³ /s)	Voltage (v)	Current (a)	Energy Rate (kWh/m ³)	Aluminum Content (ppm)	Aluminum Efficiency (%)	Electrode Efficiency (%)	*Power Cost (\$/m ³)	**Aluminum Cost (\$/m ³)	Total Cost (\$/m ³)	Turbidity (NTU)	Cake Height (cm)	Settling Rate (cm/s)
without circ.	33.33	18	32.80	4.92	85.28	85.29	42.31	0.25	0.60	0.84	40.3	2.8	0.016
without circ.	88.33	18	25.62	1.45	49.41	156.77	33.05	0.07	0.35	0.42	82	2.3	0.017
without circ.	163.33	18	22.54	0.69	24.13	133.02	29.08	0.03	0.17	0.20	122.6	2	0.018
without circ.	220.00	18	19.80	0.45	20.87	165.12	25.54	0.02	0.15	0.17	137.2	2	0.018
without circ.	285.00	18	16.53	0.29	15.98	165.82	21.32	0.01	0.11	0.13	114.6	1.9	0.018
without circ.	393.33	18	14.95	0.19	16.8	276.24	19.28	0.01	0.12	0.13	167.6	1.8	0.018
without circ.	471.67	18	13.21	0.14	13.53	249.68	17.04	0.01	0.09	0.10	239	1.7	0.018
with recirc.	33.33	18	15.55	2.333	82.02	187.81	18.43	0.12	0.57	0.69	46.7	2.3	0.017
with recirc.	88.33	18	14.30	0.810	36.36	238.82	16.95	0.04	0.25	0.30	53.5	1.6	0.018
with recirc.	158.33	18	12.00	0.379	23.32	325.68	14.22	0.02	0.16	0.18	62.2	1.4	0.018
with recirc.	223.33	18	13.14	0.294	11.09	196.87	15.56	0.01	0.08	0.09	51.8	1.3	0.019
with recirc.	290.00	18	12.93	0.223	10	233.44	15.32	0.01	0.07	0.08	73.2	1.2	0.019
with recirc.	388.33	18	12.74	0.164	6.41	200.06	15.09	0.01	0.04	0.05	173.3	1.1	0.019
with recirc.	433.33	18	12.67	0.146	4.94	170.51	15.01	0.01	0.03	0.04	186	1.2	0.019

* Assumes power cost @ \$0.05/kWh.

**Assumes aluminum cost @ \$7.00/kg.

Table 6 - Effect of flow rate, without recirculation

SAMPLE#	Flow Rate (cm3/s)	CNaCl (%)	pH	Conductivity (mS/cm)	Energy Rate (kWh/m3)	Aluminum Content (ppm)	Equivalent Current (a)	Voltage (v)	Current (a)
1	33.33	0.05	8.67	0.83	4.92	85.28	27.97	18	32.80
2	88.33	0.05	8.36	0.9	1.45	49.41	40.16	18	25.62
3	163.33	0.05	7.98	0.91	0.69	24.13	29.98	18	22.54
4	220.00	0.05	8.07	0.9	0.45	20.87	32.69	18	19.80
5	285.00	0.05	8.17	0.9	0.29	15.98	27.41	18	16.53
6	393.33	0.05	8.16	0.9	0.19	16.8	41.29	18	14.95
7	471.67	0.05	8.14	0.89	0.14	13.53	32.97	18	13.21
SAMPLE#	Useful Resistance (ohms)	Total Resistance (ohms)	Electrode Efficiency (%)	Aluminum Efficiency (%)	*Power Cost (\$/m3)	**Aluminum Cost (\$/m3)	Total Cost (\$/m3)		
1	0.23	0.55	42.31	85.29	0.25	0.60	0.84		
2	0.23	0.70	33.05	156.77	0.07	0.35	0.42		
3	0.23	0.80	29.08	133.02	0.03	0.17	0.20		
4	0.23	0.91	25.54	165.12	0.02	0.15	0.17		
5	0.23	1.09	21.32	165.82	0.01	0.11	0.13		
6	0.23	1.20	19.28	276.24	0.01	0.12	0.13		
7	0.23	1.36	17.04	249.68	0.01	0.09	0.10		

*Assumes power cost @ \$0.05/kWh.

**Assumes aluminum cost @ \$7.00/kg.

Table 7 - Effect of flow rate, with recirculation

SAMPLE#	Flow Rate (cm ³ /s)	CNaCl (%)	pH	Conductivity (mS/cm)	Energy Rate (kWh/m ³)	Aluminum Content (ppm)	Equivalent Current (a)	Voltage (v)	Current (a)
1	33.33	0.05	8.04	0.99	2.333	82.02	29.21	18	15.55
2	88.33	0.05	8.18	0.98	0.810	36.36	34.16	18	14.30
3	158.33	0.05	8.3	0.97	0.379	23.32	39.10	18	12.00
4	223.33	0.05	8.23	0.98	0.294	11.09	25.86	18	13.14
5	290.00	0.05	8.35	0.98	0.223	10	30.19	18	12.93
6	388.33	0.05	8.31	0.98	0.164	6.41	25.48	18	12.74
7	433.33	0.05	8.24	0.97	0.146	4.94	21.61	18	12.67
SAMPLE#	Useful Resistance (ohms)	Total Resistance (ohms)	Electrode Efficiency (%)	Aluminum Efficiency (%)	*Power Cost (\$/m ³)	**Aluminum Cost (\$/m ³)	Total Cost (\$/m ³)		
1	0.21	1.16	18.43	187.81	0.12	0.57	0.69		
2	0.21	1.26	16.95	238.82	0.04	0.25	0.30		
3	0.21	1.50	14.22	325.68	0.02	0.16	0.18		
4	0.21	1.37	15.56	196.87	0.01	0.08	0.09		
5	0.21	1.39	15.32	233.44	0.01	0.07	0.08		
6	0.21	1.41	15.09	200.06	0.01	0.04	0.05		
7	0.21	1.42	15.01	170.51	0.01	0.03	0.04		

*Assumes power cost @ \$0.05/kWh.

**Assumes aluminum cost @ \$7.00/kg.

Table 8 - The changing electric waveform

DATE	AVERAGE CURRENT [AMPS]	AVERAGE VOLTAGE [VOLTS]	RATIO BETWEEN CURRENT AND VOLTAGE
NOV 21	75	20	3.750
NOV 27	41	20	2.050
DEC 2	35	18	1.944
JAN 13	12.5	18	0.694
JAN 16	20.5	18	1.139
JAN 20	12.5	18	0.694
JAN 21	8.5	30	0.283

Table 9 - The effect of the formation of passivation layers

Date	Conc (%)	Energy Rate (kWh/m ³)	Aluminum Content (ppm)	Voltage (v)	Current (a)	Aluminum Efficiency (%)	Electrode Efficiency (%)	**Power Cost (\$/m ³)	***Aluminum Cost (\$/m ³)
NOV 21	0.03	3.736	148.88	21.88	65.56	256.01	84.63	0.187	1.042
DEC 2	0.03	1.7117	101.59	18	34.234	313.45	60.22	0.09	0.71
DEC 9	0.03	*1.556	60.82	18	30	209.80	49.76	0.078	0.426
JAN 13	0.06	0.902	34.73	18	18.04	196.44	20.53	0.05	0.24
JAN 20	0.05	0.810	36.36	18	14.30	238.82	16.95	0.04	0.25
JAN 21	0.03	0.966	20.06	30	11.98	158.35	10.43	0.05	0.14
Date	Total Cost (\$/m ³)	Turbidity 10 min. (NTU)	Cake Height (cm)	Settling Rate (cm/s)	Percent of Cost Wasted on Rw (%)	Cost wasted on Rw (\$/m ³)			
NOV 21	1.229	10	7.5	0.0039	2.34	0.029			
DEC 2	0.80	22	3.8	0.0145	4.27	0.034			
DEC 9	0.504	55	2.8	0.0156	7.76	0.039			
JAN 13	0.29	58.6	2.1	0.0173	13.70	0.040			
JAN 20	0.30	53.5	1.6	0.0180	11.40	0.034			
JAN 21	0.19	59.5	1.4	0.0182	22.92	0.043			

*Based on the estimated voltage and current.

** Assumes power cost @ \$0.05/kWh.

***Assumes aluminum cost @ \$7.00/kg.

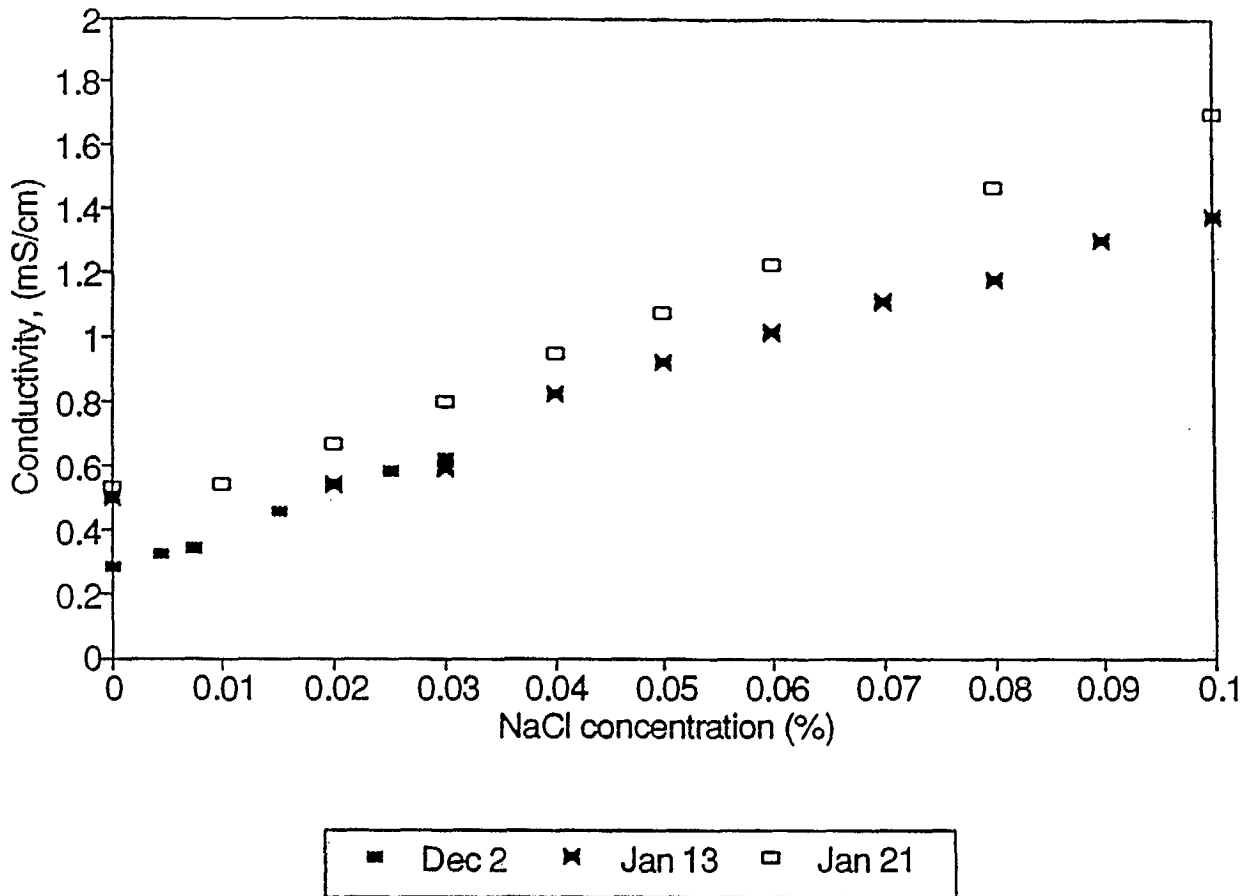


Fig. 1 - Effect of sodium chloride concentration on conductivity

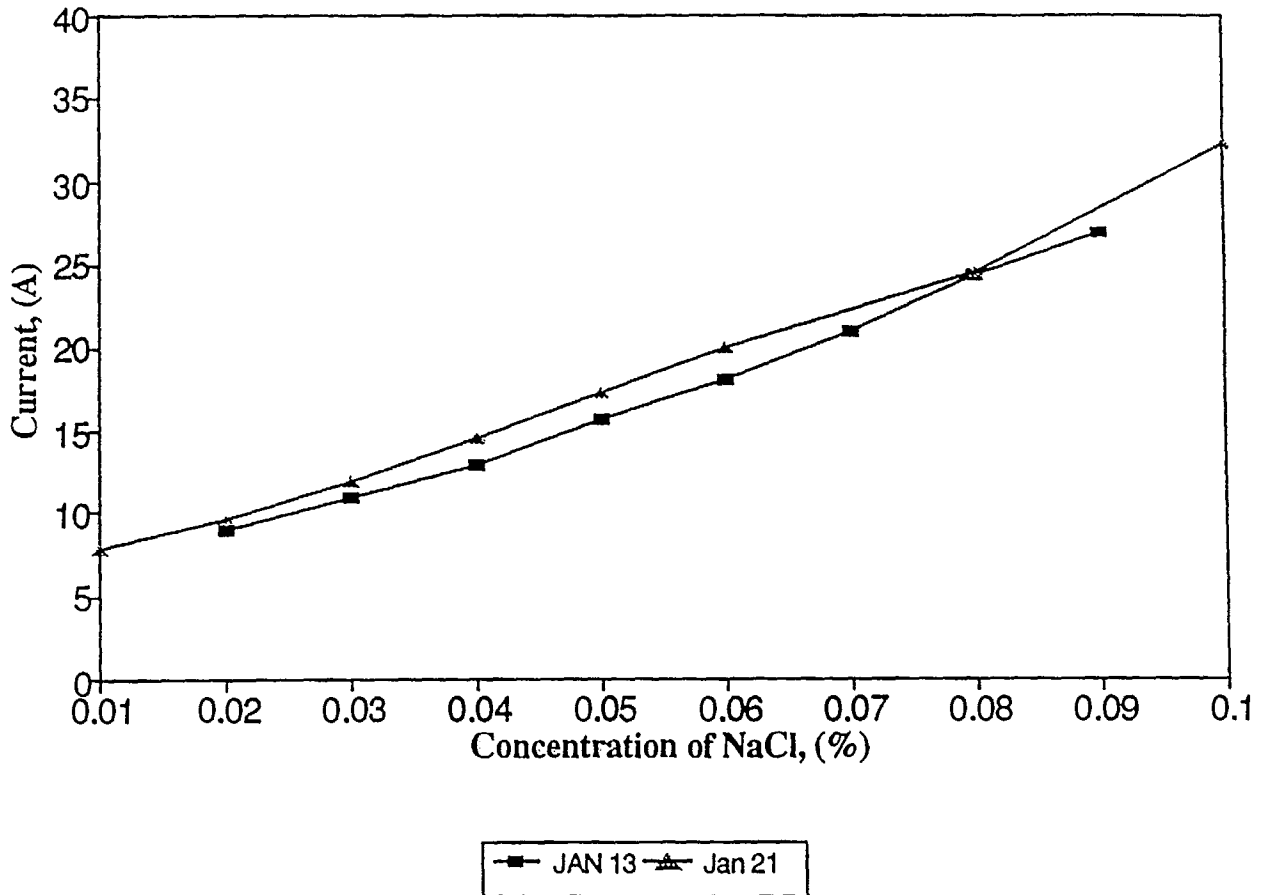


Fig. 2 - Effect of sodium chloride concentration on current

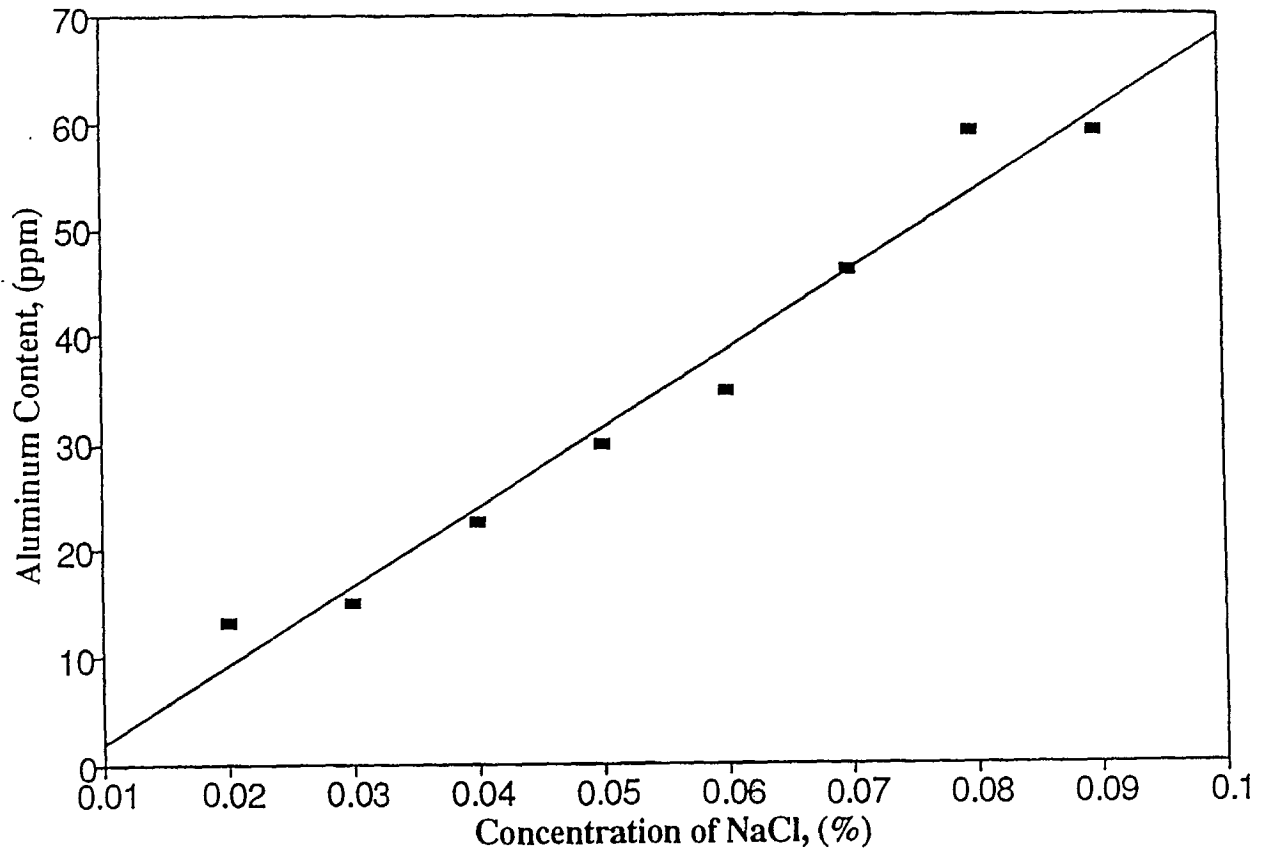


Fig. 3 - Effect of sodium chloride concentration on aluminum content

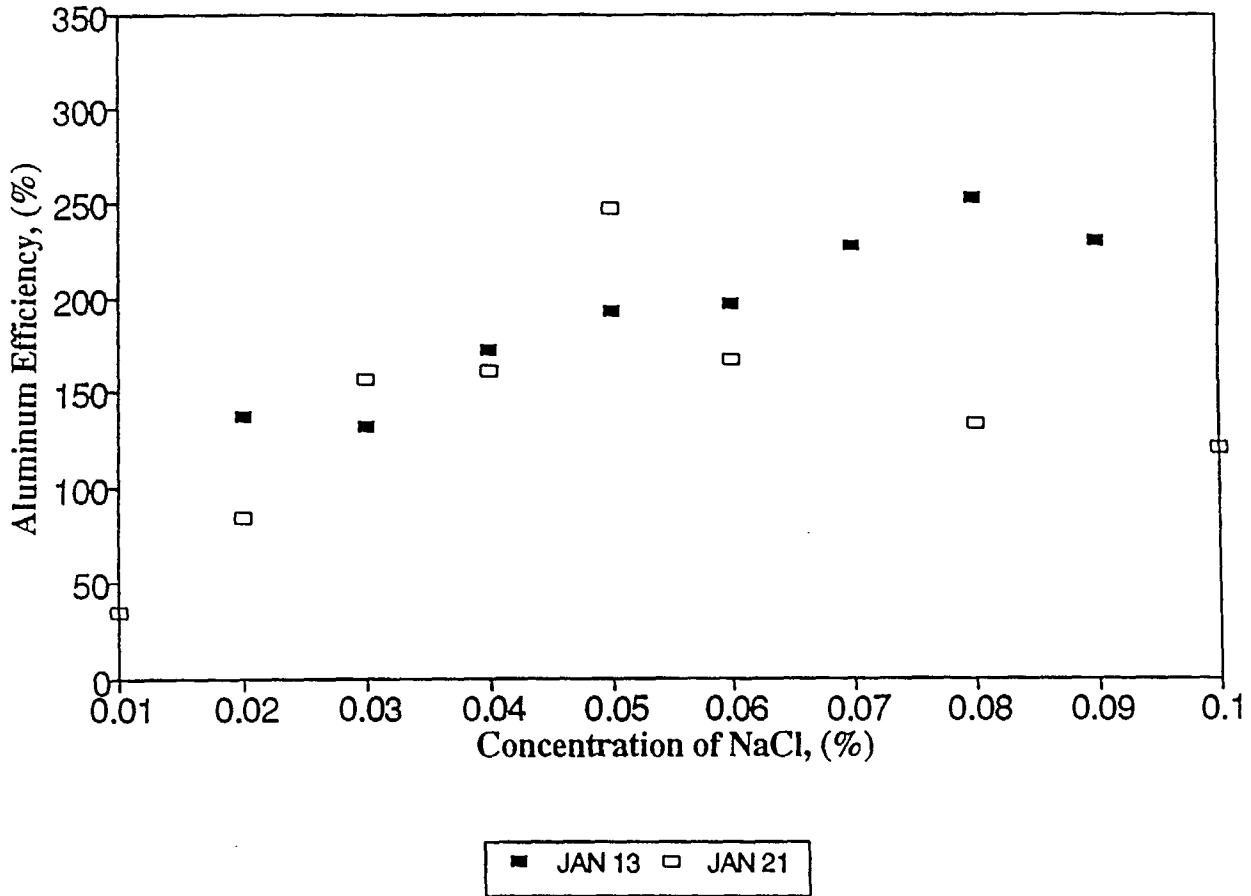
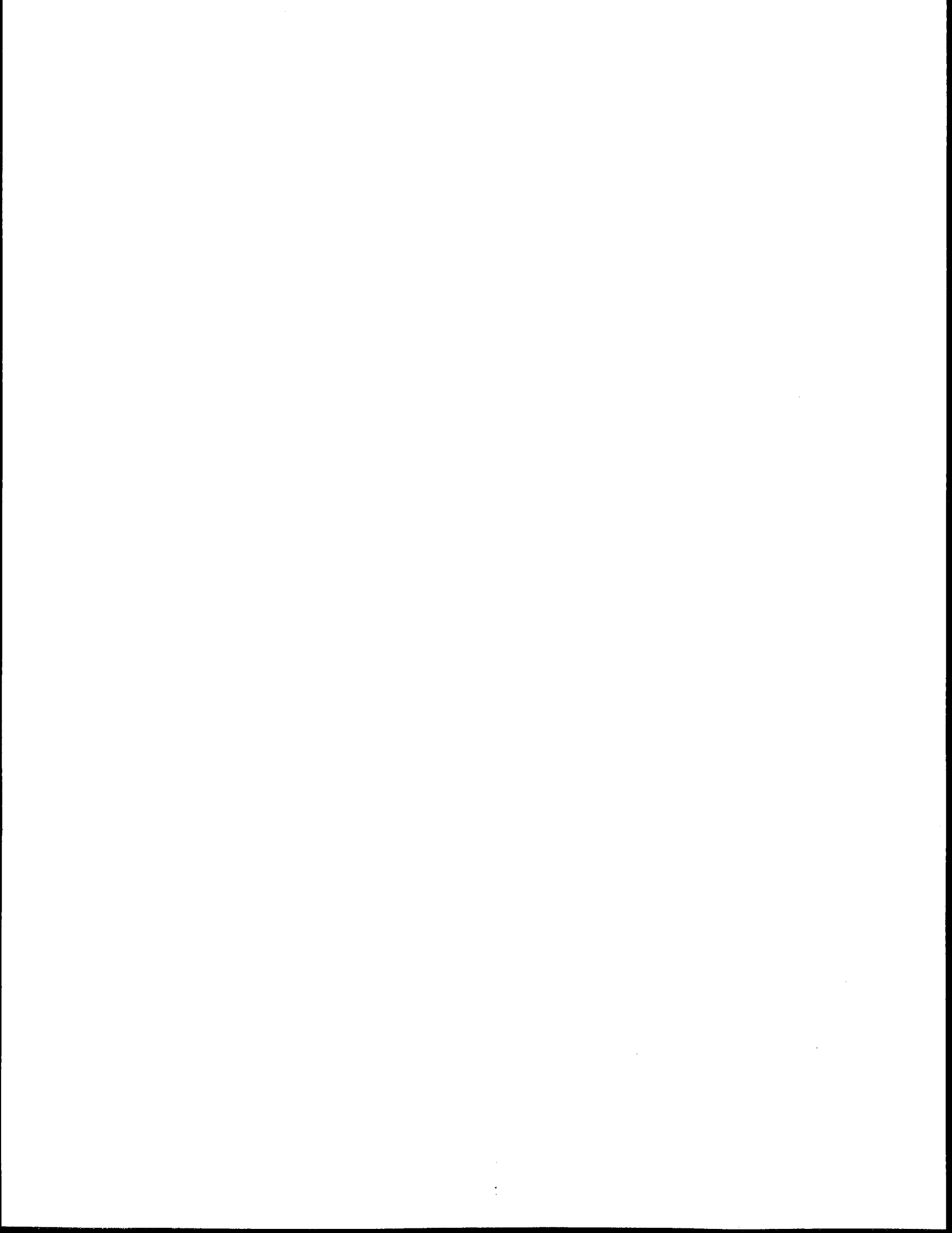


Fig. 4 - Effect of sodium chloride concentration on aluminum efficiency





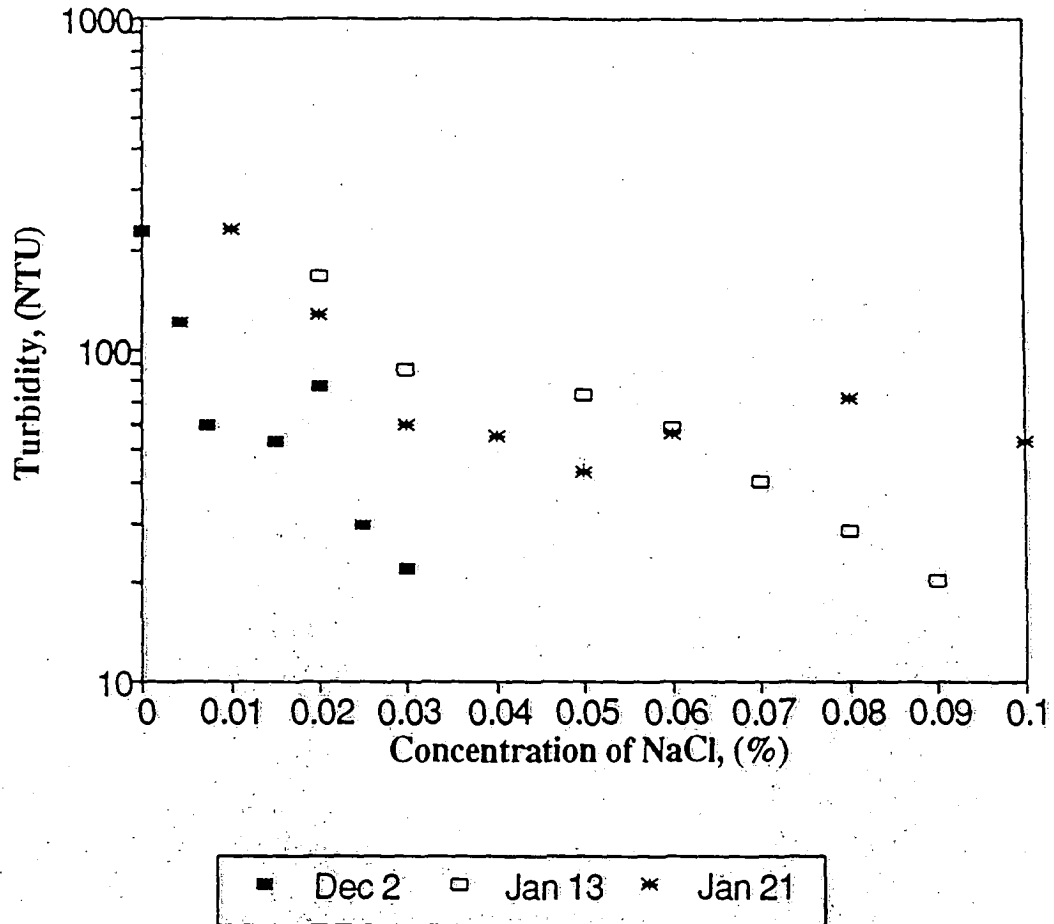


Fig. 8 - Effect of sodium chloride concentration on turbidity

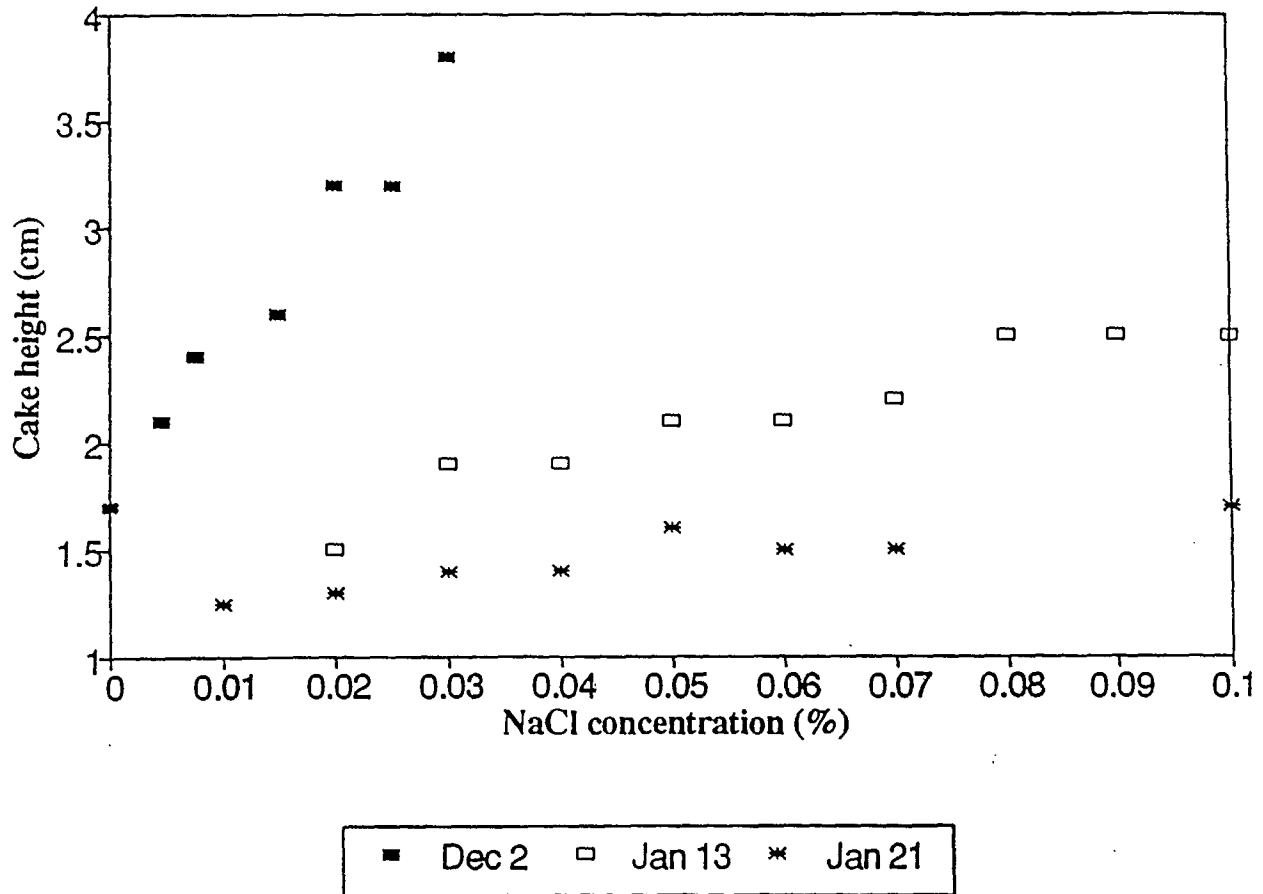


Fig. 7 - Effect of sodium chloride concentration on cake height

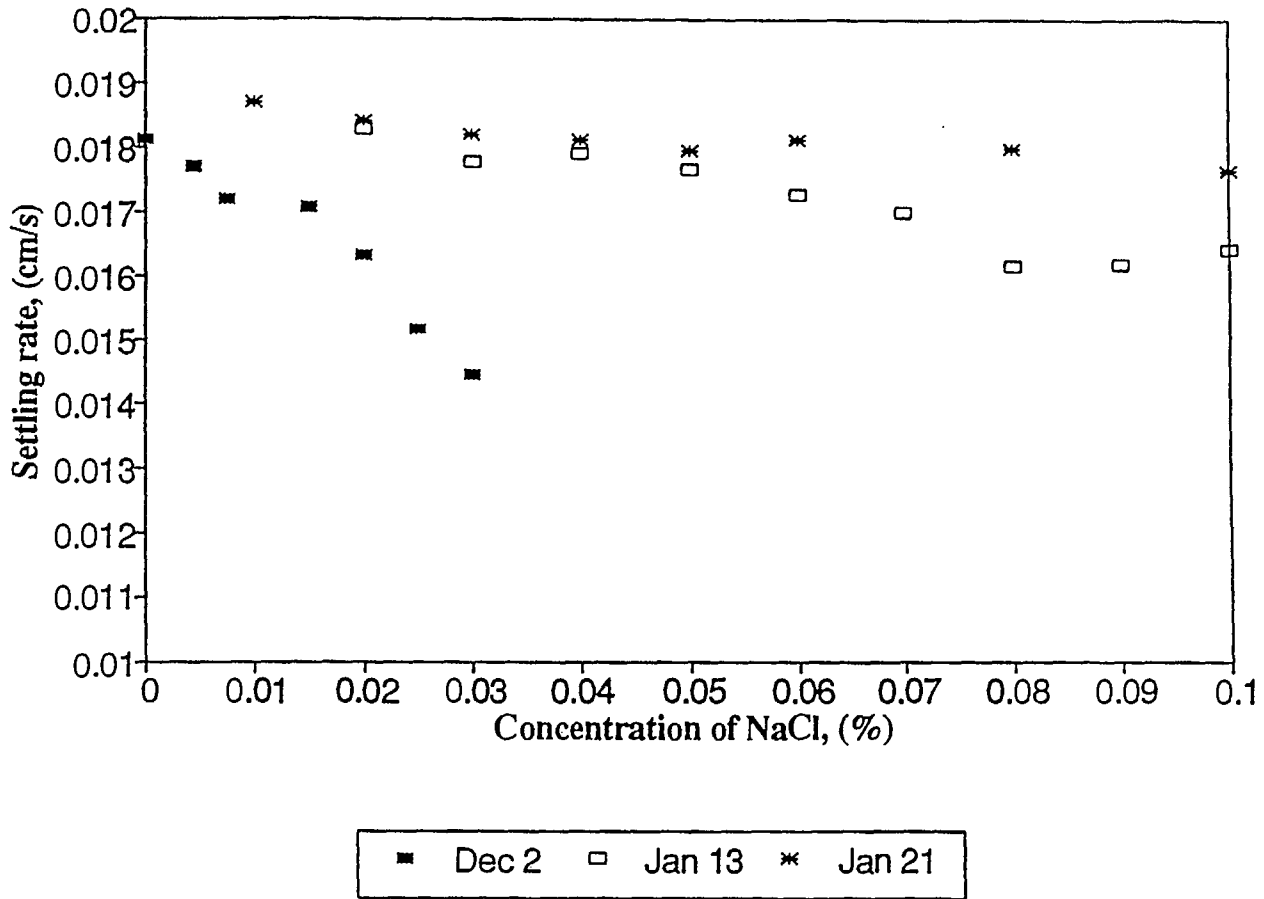


Fig. 9 - Effect of sodium chloride concentration on settling rate

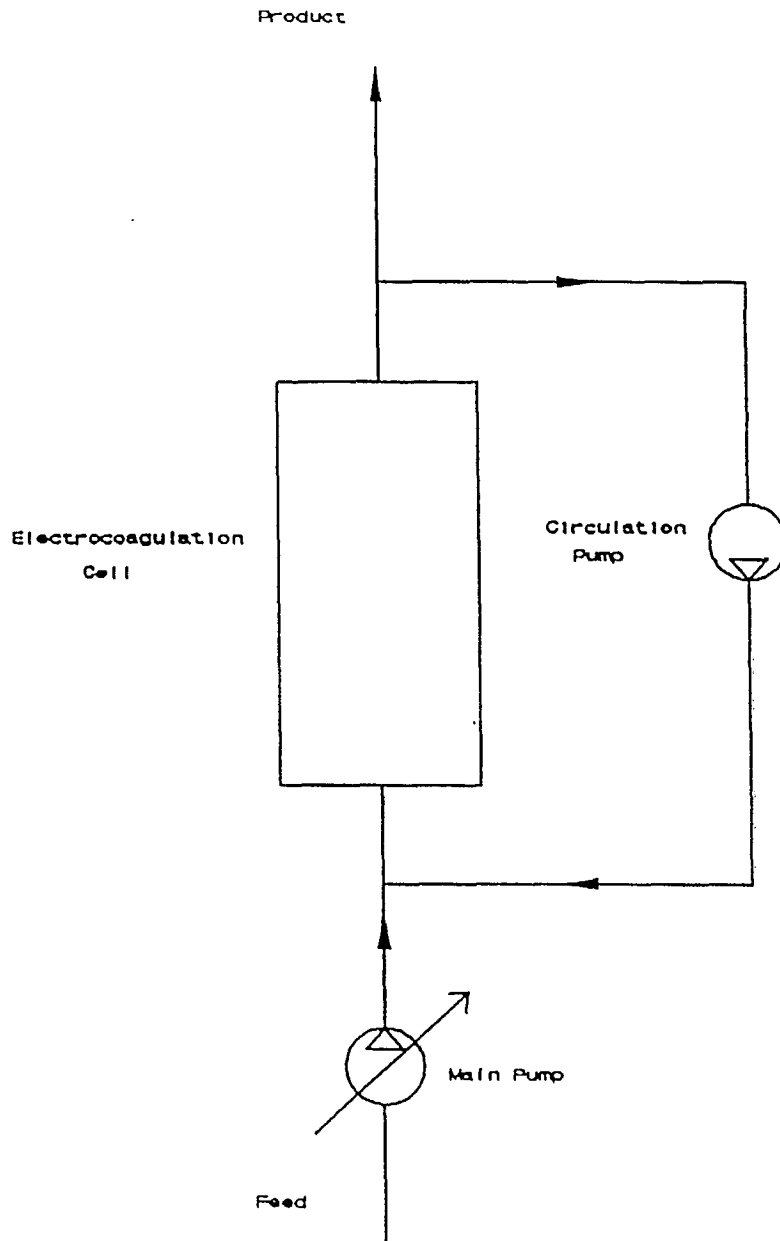


Fig. 10 - Schematic diagram of the flow circuit

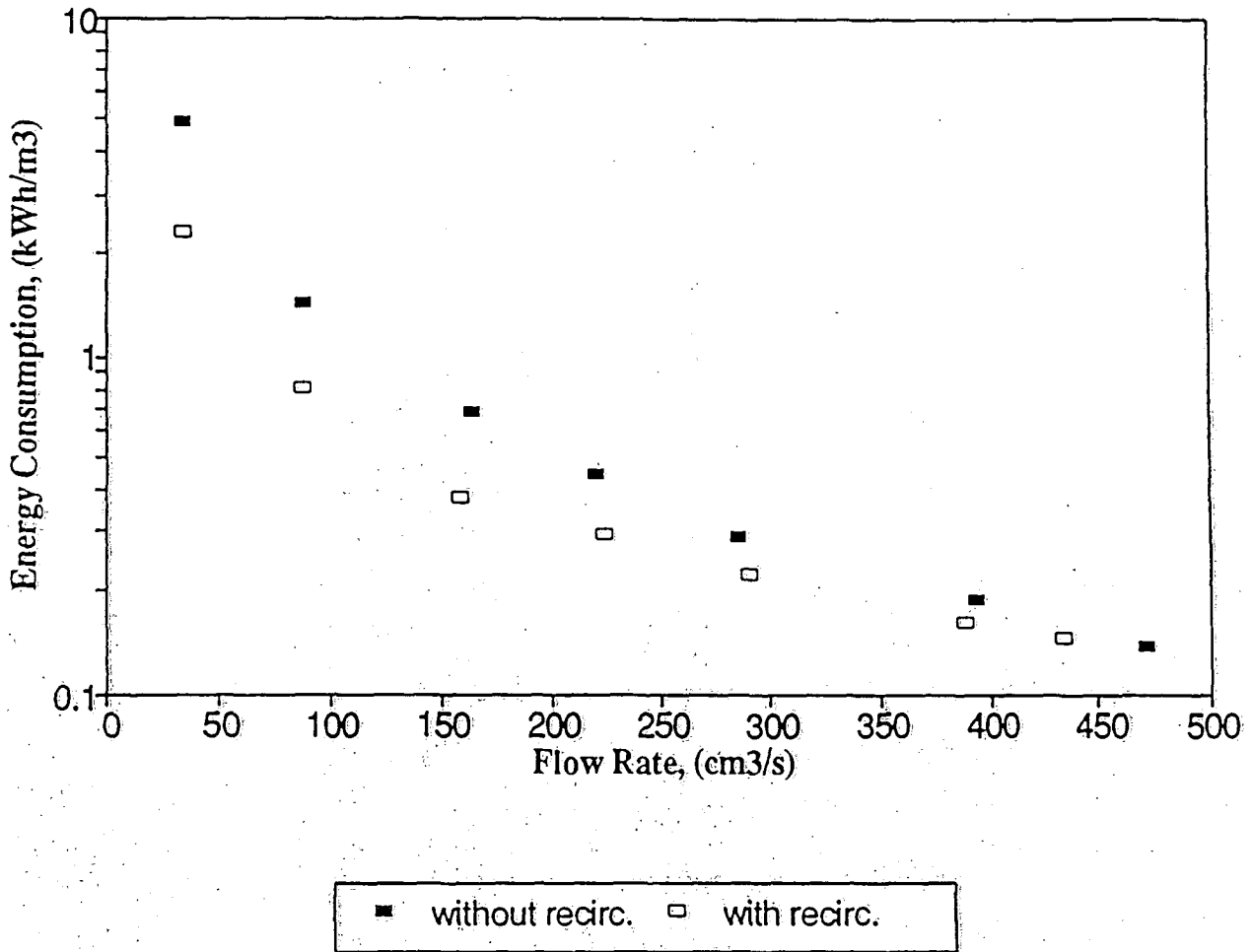


Fig. 11 - Effect of flow rate on energy consumption

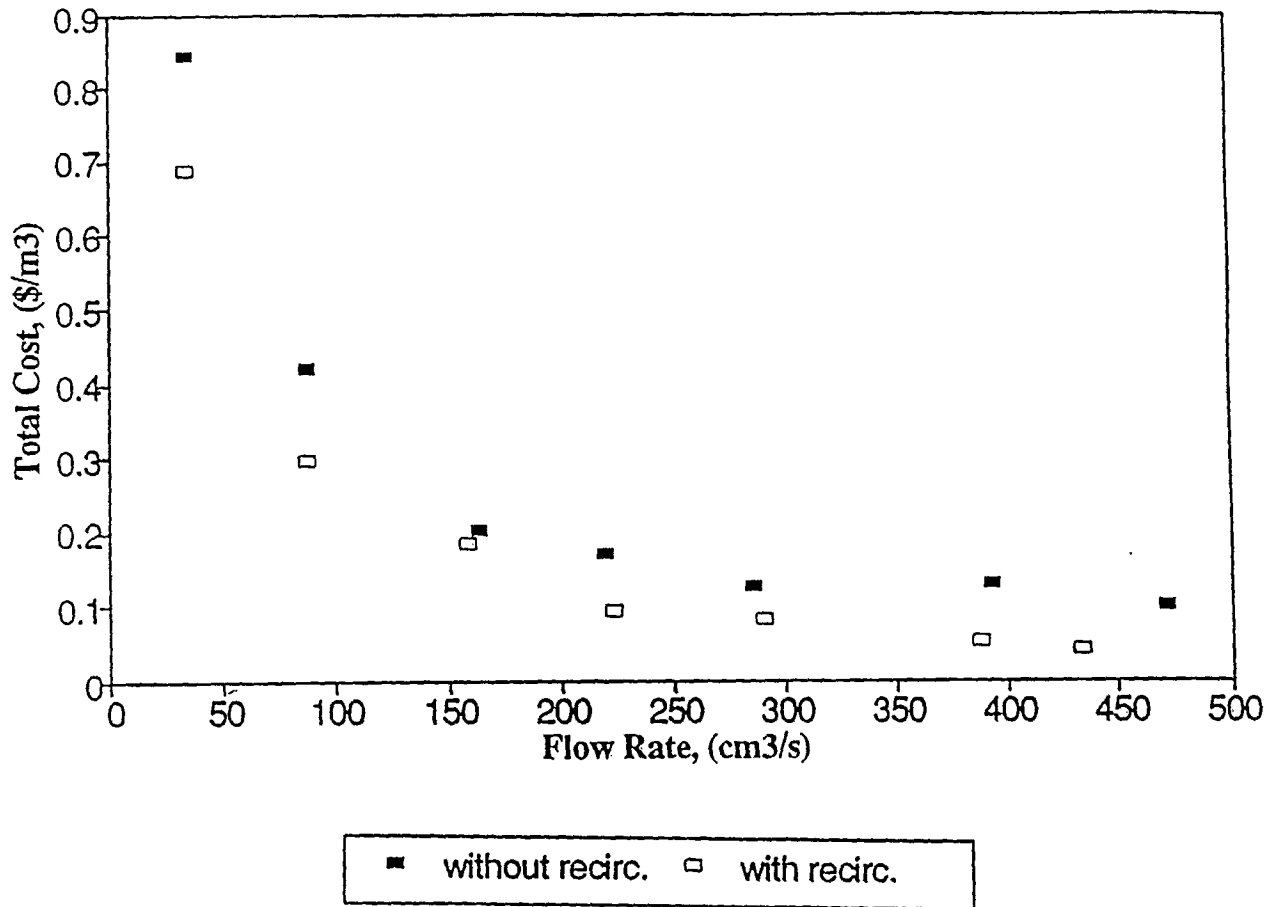


Fig. 12 - Effect of flow rate on total cost

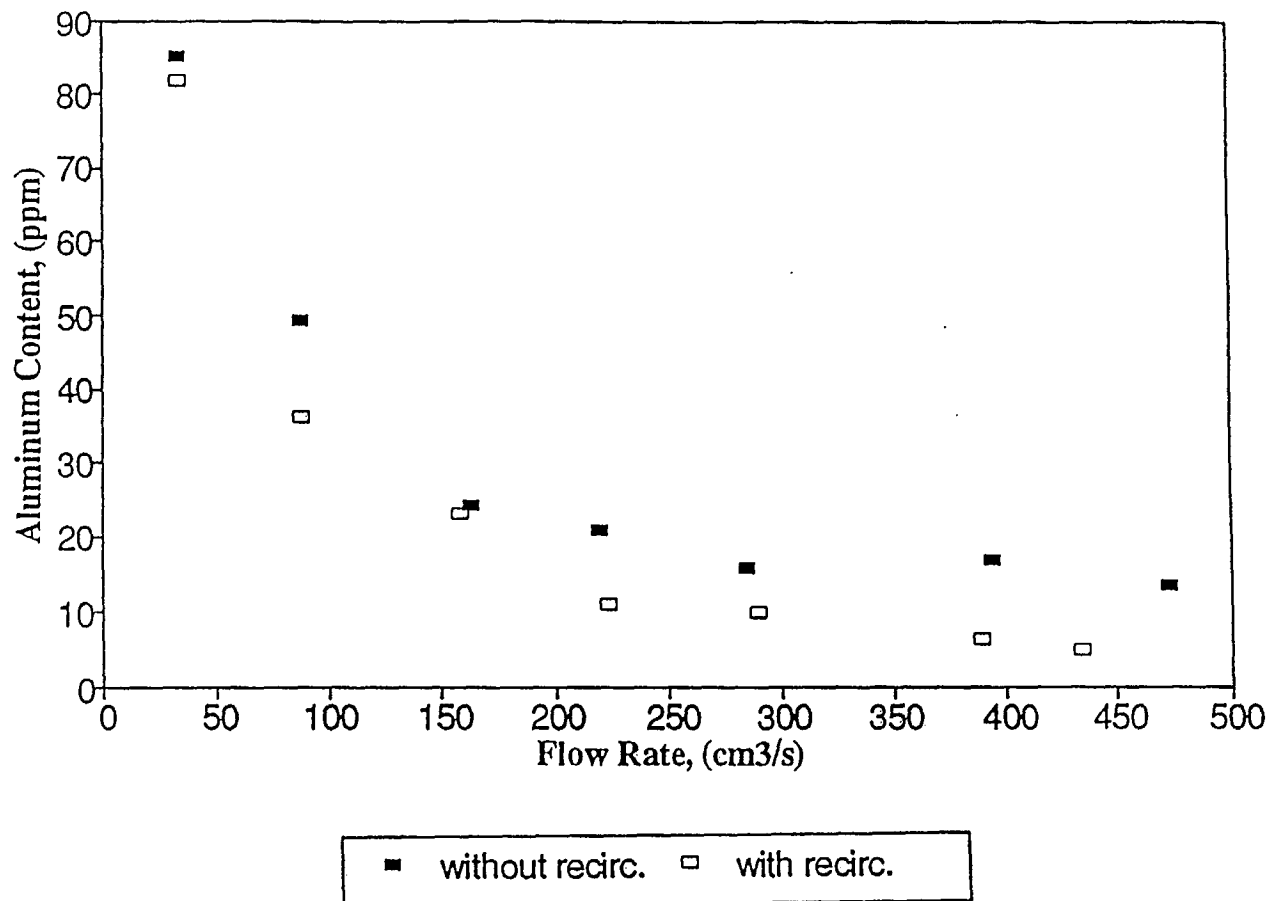


Fig. 13 - Effect of flow rate on aluminum content

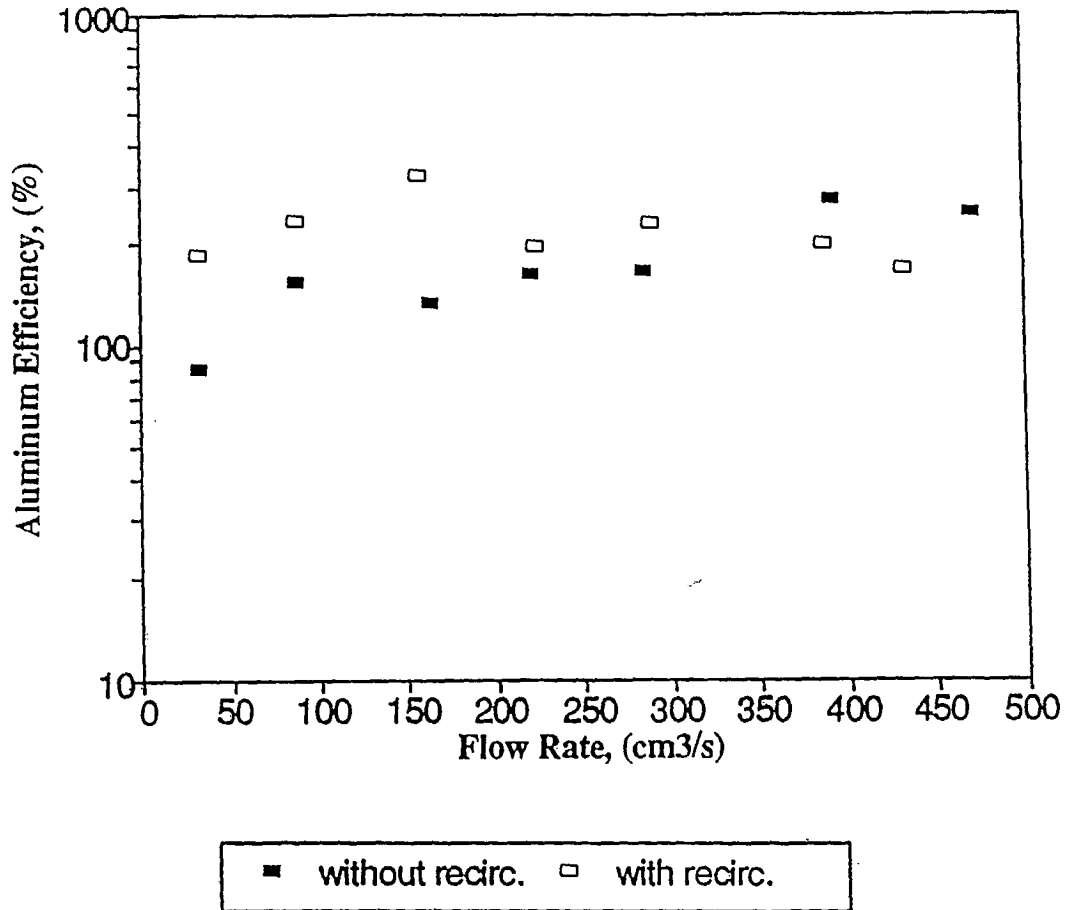


Fig. 15 - Effect of flow rate on aluminum efficiency

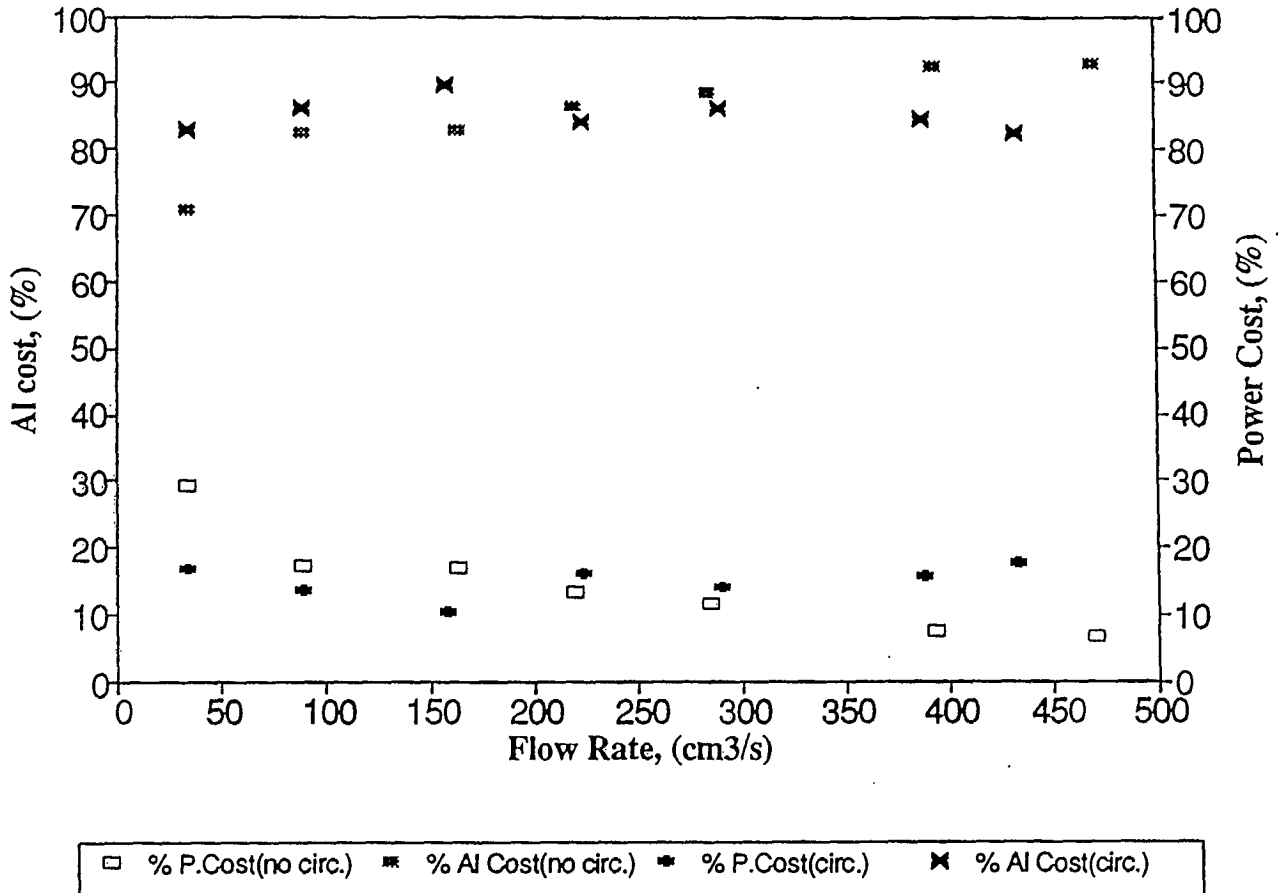


Fig. 14 - Effect of flow rate on aluminum and power cost

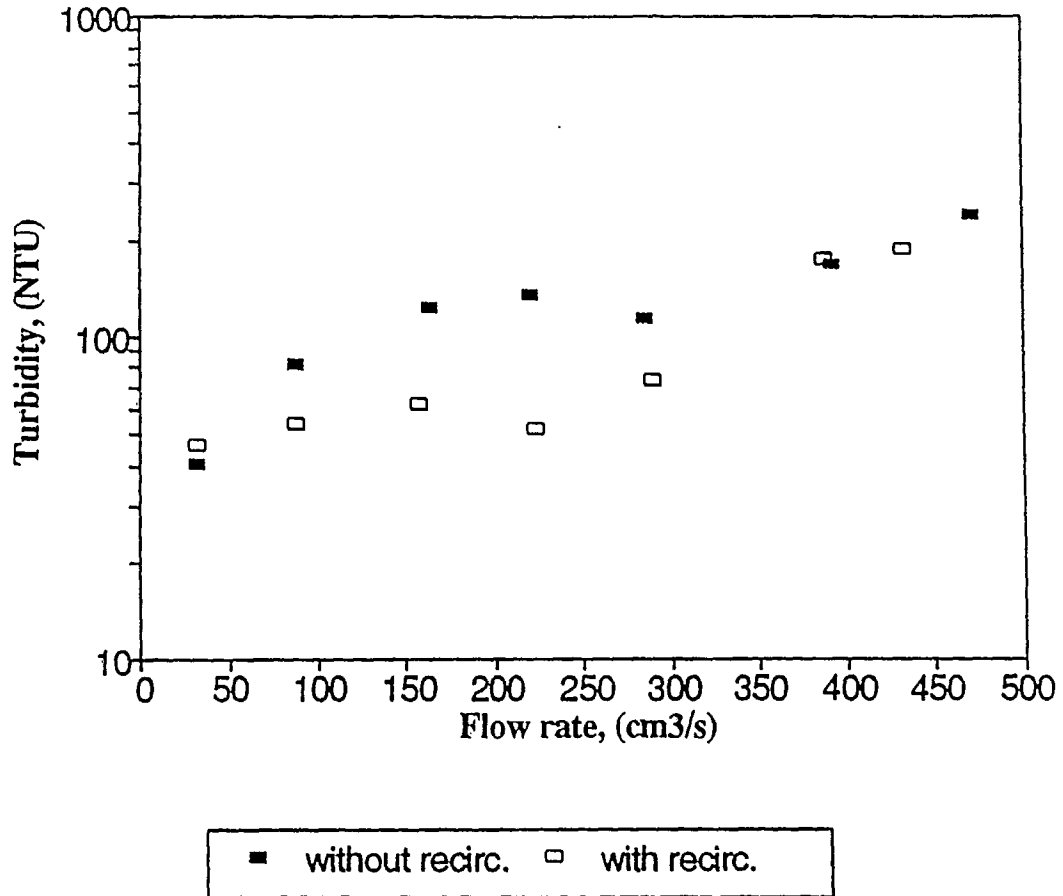


Fig. 16 - Effect of flow rate on turbidity

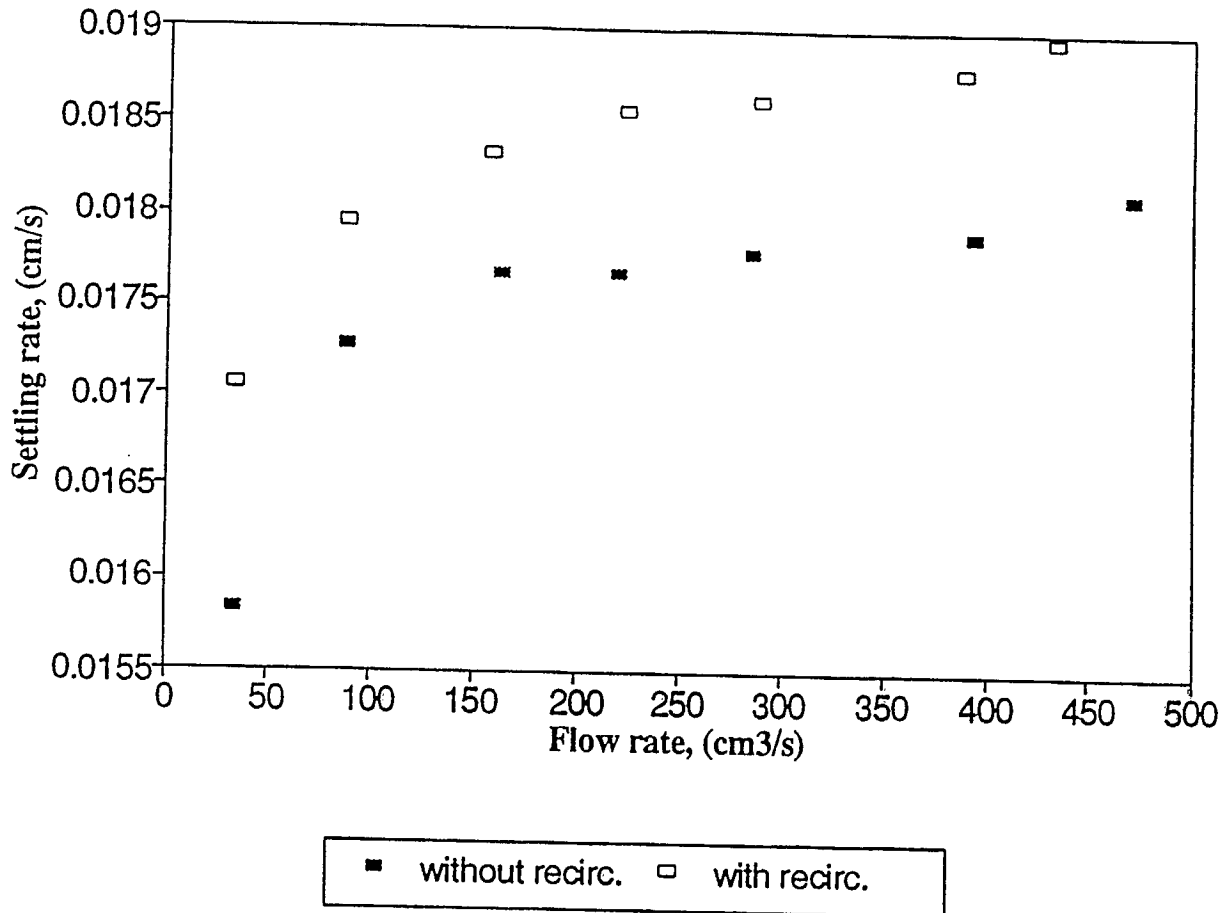


Fig. 17 - Effect of flow rate on setting rate

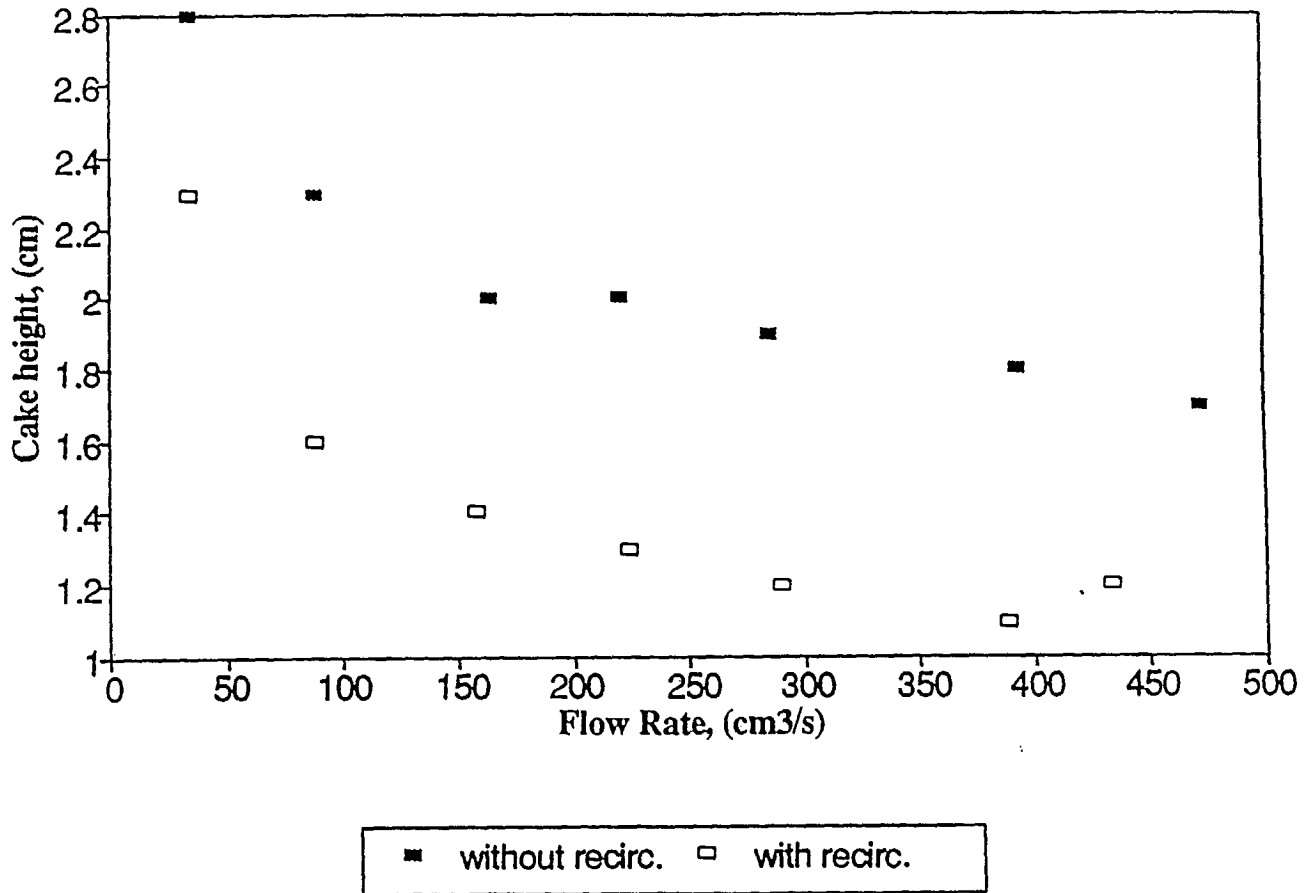


Fig. 18 - Effect of flow rate on cake height

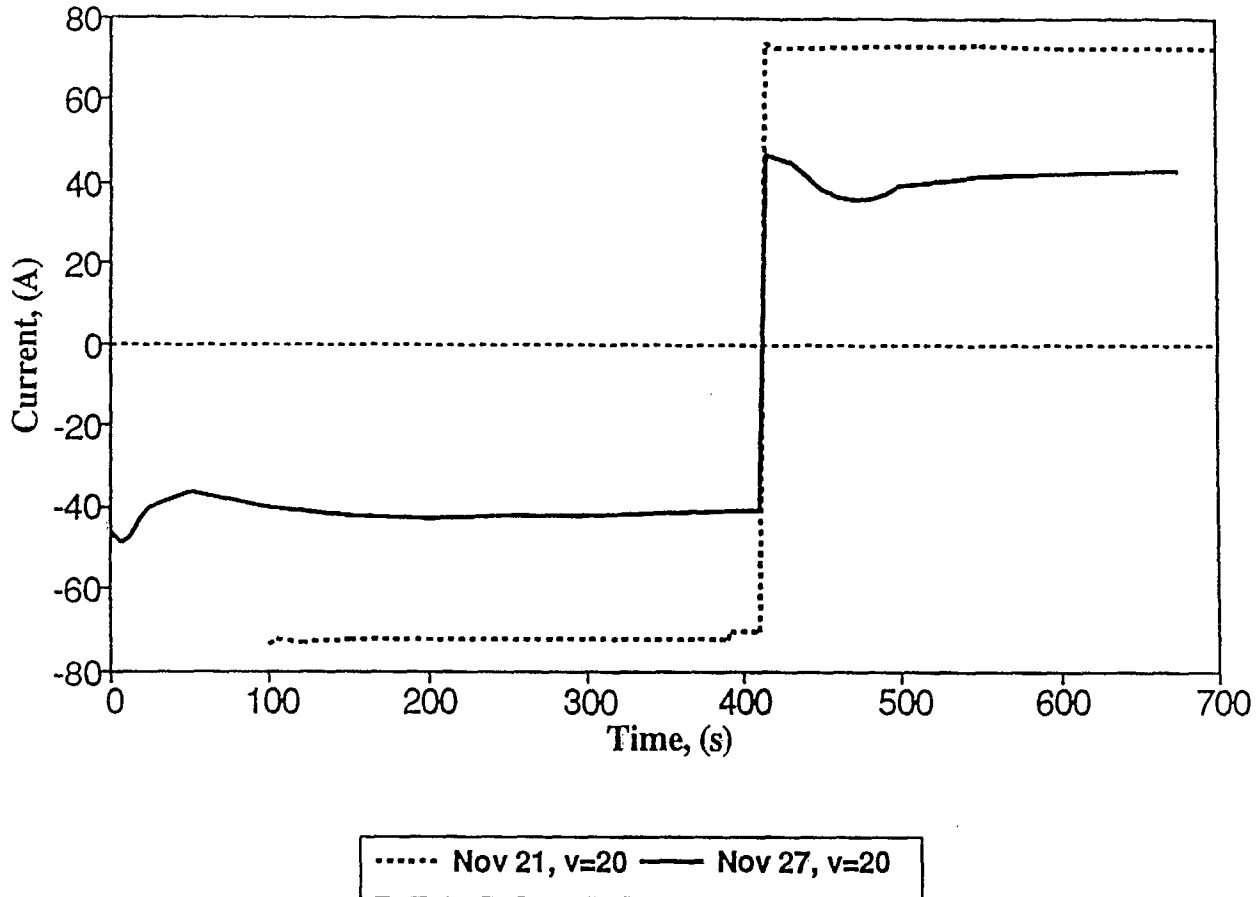


Fig. 19 - Current waveform on November 21 and November 27

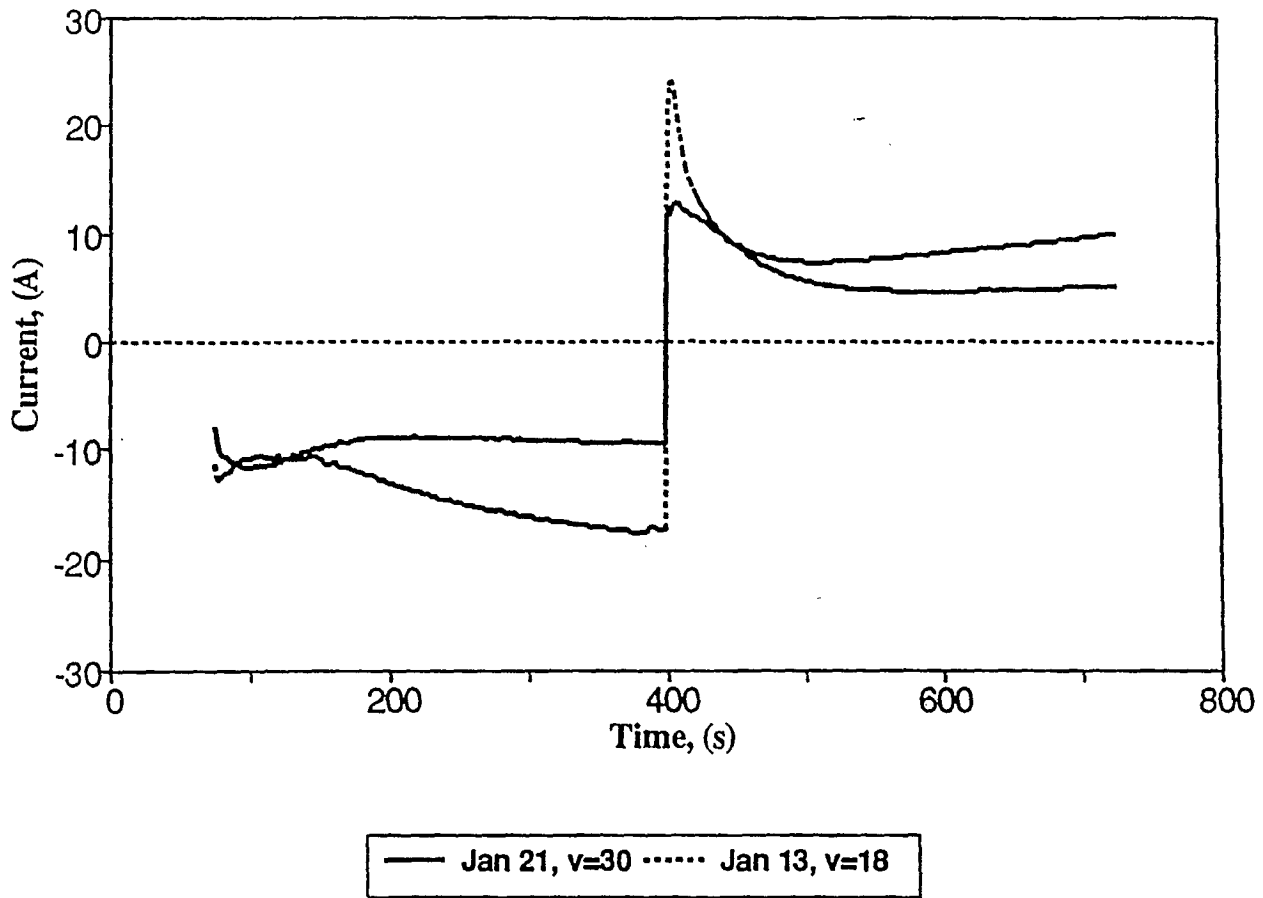


Fig. 20 - Current waveform on January 13 and January 21

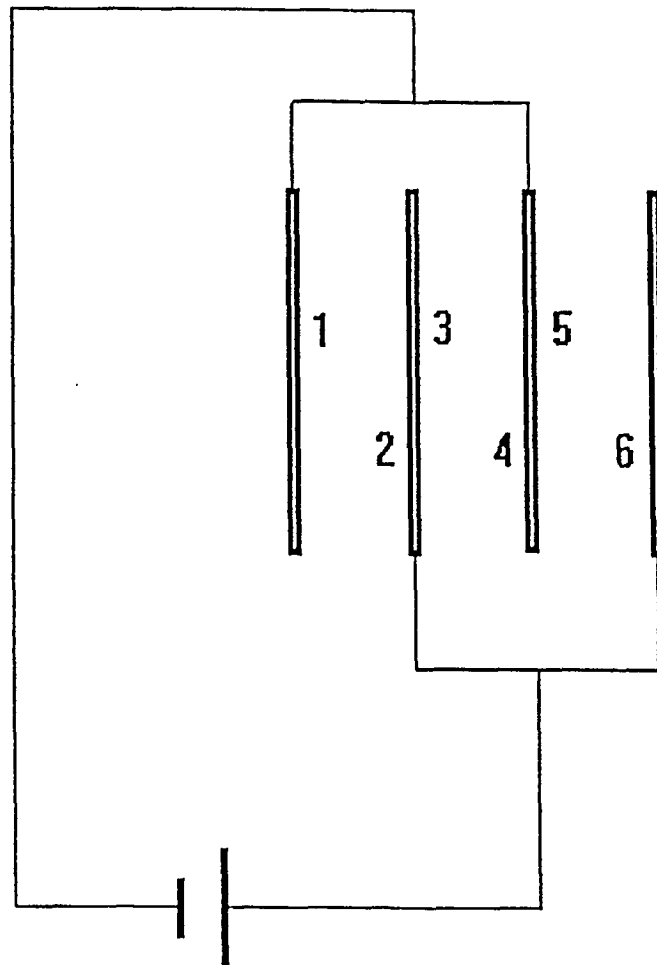


Fig. 21 - Schematic diagram of electric circuit of the cell

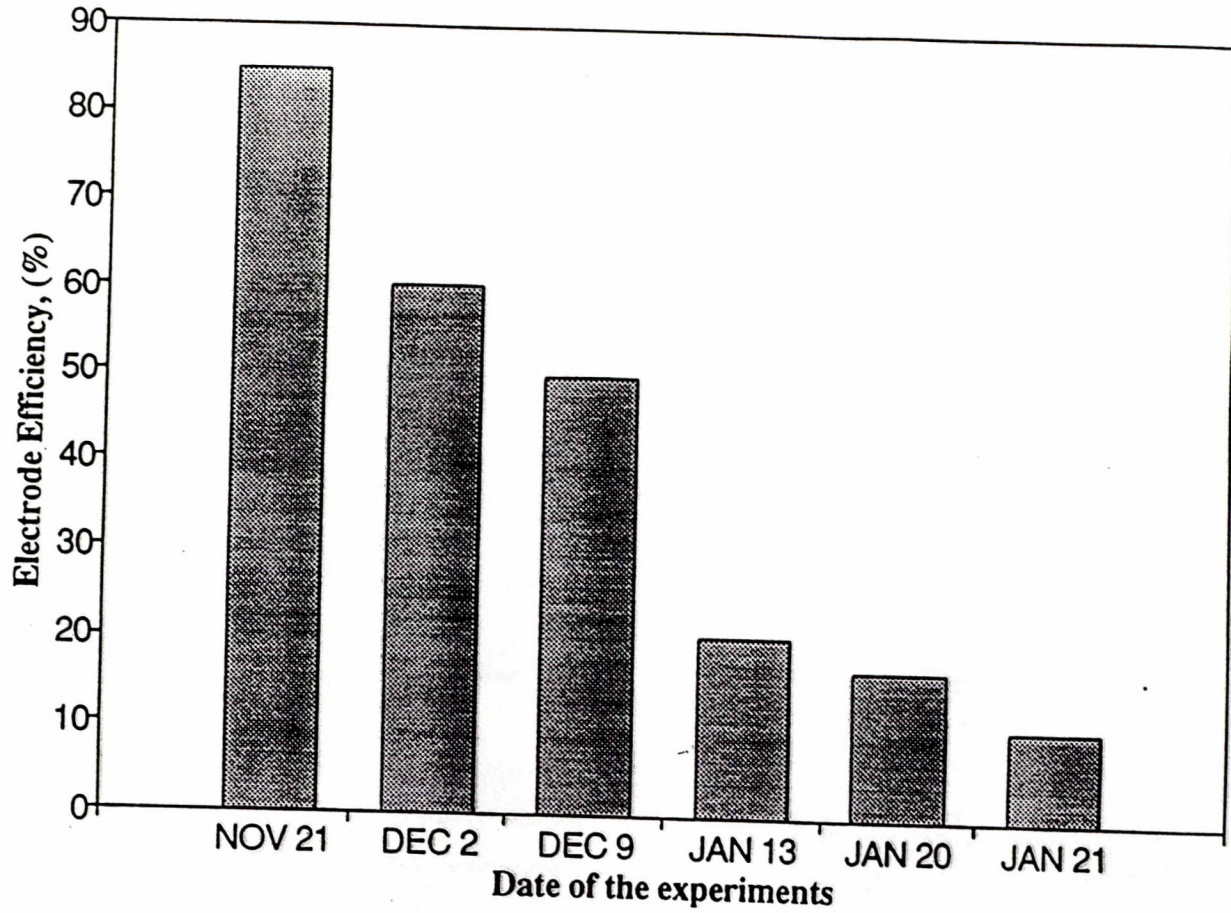


Fig. 22 - Effect of time on electrode efficiency

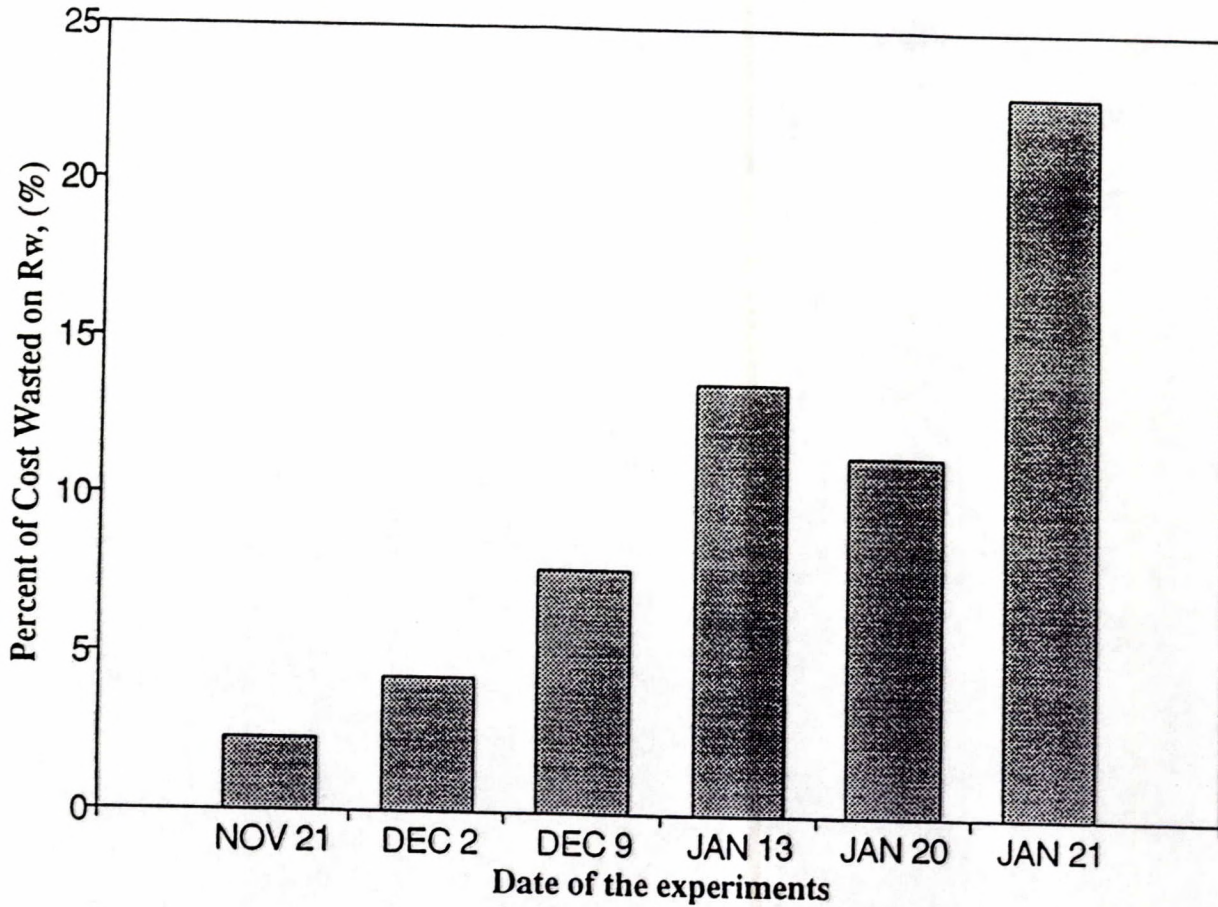
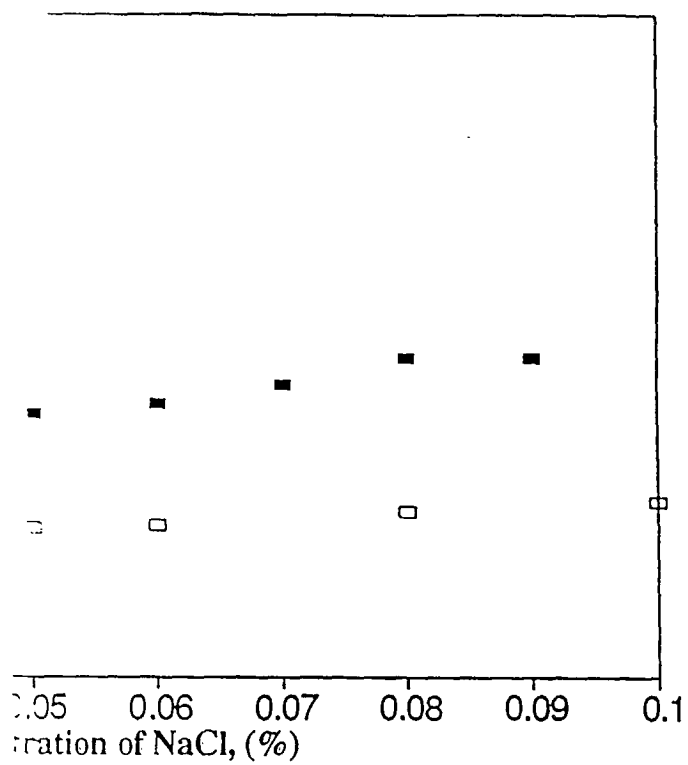


Fig. 23 - Effect of time on percentage of cost wasted on the passivation layers



13 □ JAN 21

electrode efficiency

(concentration of sodium chloride)

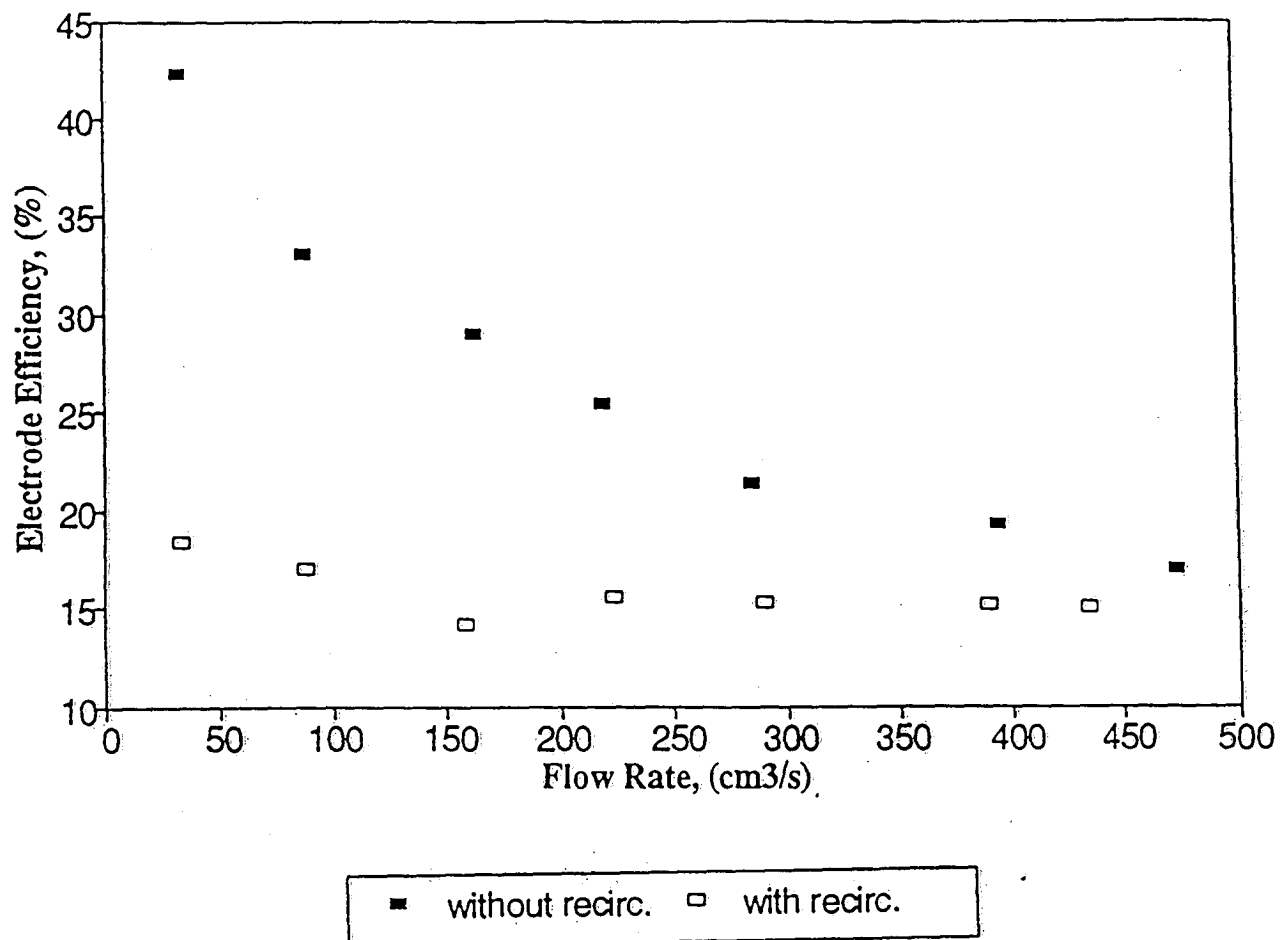
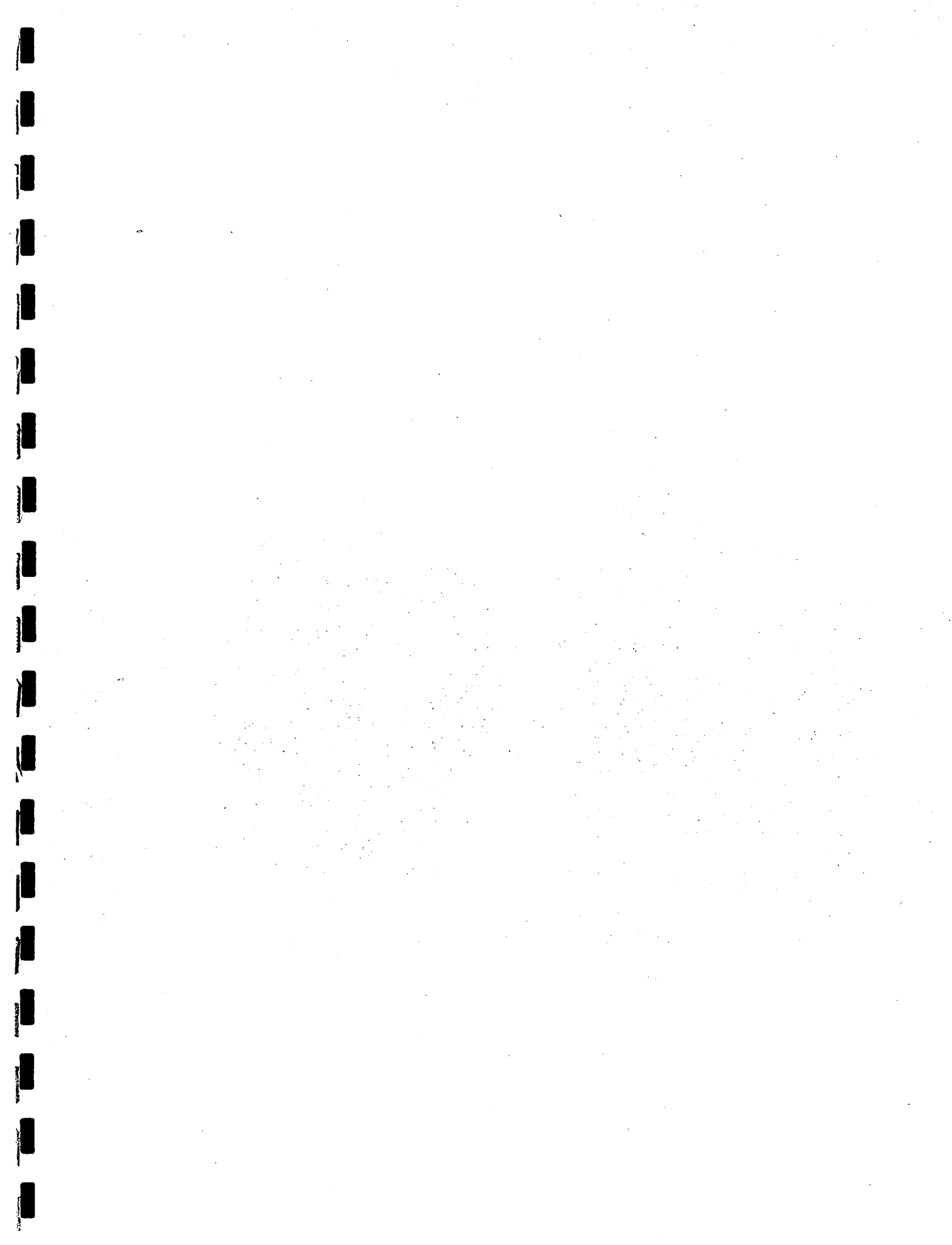


Fig. 25 - Effect of time on electrode efficiency
(changing flow rate)



APPENDIX A

THE CALCULATION OF RESIDENCE TIME WITH AND WITHOUT
Recirculation

In the case where there is no recirculation, residence time can be calculated as:

$$\Delta T_1 = U / Q_M \quad \text{Eq A1}$$

where: ΔT_1 is the residence time without recirculation

U is the volume of the cell

Q_M is the flow rate of the main pump.

In the case where there is recirculation, residence time is the weighted sum of each time period needed for the corresponding remaining portion to pass the cell. The time period needed is:

$$\Delta t = U / (Q_M + Q_C) \quad \text{Eq A2}$$

where : $Q_T = Q_M + Q_C$, is the total flow rate flowing through the cell.

Q_C is the flow rate of recirculation.

Let

$$r = Q_M / Q_T \quad \text{Eq A3}$$

Each time a unit of material passes through the cell a



$$\Delta T_2 = \Delta t * [1 + (1-r) + (1-r)^2 + \dots + (1-r)^n + \dots]$$

where ΔT_2 is the residence time with recirculation.

When there is recirculation, $0 < r < 1$.

Hence:

$$[1 + (1-r) + (1-r)^2 + \dots + (1-r)^n + \dots] = 1 / (1 - (1-r))$$

$$\Delta T_2 = \Delta t * 1 / (1 - (1-r)) = \Delta t / r \quad \text{Eq A4}$$

Substitute Eq A1, A2, A3 into Eq A4 :

$$\Delta T_2 = (U / Q_T) * (Q_T / Q_M) = U / Q_m = \Delta T_1$$

That is, the residence time with recirculation is exactly the same as that without recirculation.

