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ELECTROLYSIS OF ALUMINUM SOLUTIONS
IN A MAGNETIC FIELD

THESIS

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CHAPTER I

INTRODUCTION

The rectification or valve action of aluminum has been known for many years and it is well known that aluminum electrodes in solutions of borates, phosphates, oxalates, citrates, tartrates and carbonates conduct well as a cathode, but when an aluminum anode is used, the conduction is very poor if the voltage is applied slowly to about 100 volts.^{1,2,3} This action is due to a film of oxide that forms on the aluminum which allows anions to pass and causes the film to increase in thickness.⁴ This valve action has been found in tantalum, niobium, antimony, bismuth, silver, copper, magnesium, zinc, and cadmium, although with the latter three metals the conditions must be carefully controlled. This property has been used in commercial aluminum electrolytic

¹S. Glasstone, The Electrochemistry of Solutions, Methuen and Co., LTD., (1930), p. 434-5.

²V. A. Suydam, Electricity and Electromagnetism, D. Van Nostrand, (1940), p. 264-5.

³W. E. Holland, "A Commercial Aluminum Electrolytic Rectifier", Transactions of the American Electrochemical Society, Vol. LIII, (1928), p. 195-201.

⁴Glasstone, op. cit. p. 434.

rectifiers and was used in the advent of radio for charging of wet batteries. This same effect is also used in aluminum electrolytic condensers.⁵

The effect that a magnetic field would have on the rectification action of aluminum in an aluminum sulfate solution has been investigated by George Antonoff and Anne Rowley, Ferdham University, in an article "Anodic Behavior of Aluminum in a Magnetic Field" which is reproduced in its entirety in the Appendix. This article was printed in Acta Physica Austriaca, July, 1948, and also in Journal of Physical and Colloid Chemistry, June, 1948. This article claims that the forming of an oxide film on aluminum and its disappearance must take time, and that the current will not flow in one direction, but immediately upon changing the connections the current would flow in the opposite direction. They maintain that this indicates some special electronic structure, such that an electron under an electric field can move in one direction and not in the other. This being the case, a magnetic field should produce an effect. Antonoff and Rowley set up a test electrolytic cell with an aluminum cathode in a magnetic field of about 2000 gauss. The cell contained a saturated solution of aluminum sulfate with a platinum wire as the anode and this was connected to a 45 volt battery. There was no current in the circuit without the magnetic field, but as the field was established the potential fell

⁵Ibid.

to 10 volts and passage of current was evident. At the same time it was observed that the aluminum strip was covered with a deposit having the appearance of a molten mass, and the shape of a disc of the same diameter as the iron rod facing it. Palumbo et al.⁶ have investigated cells containing two electrodes of the same metal immersed in an electrolyte consisting of a salt of the metal. The action of a magnetic field in generating an electromotive force was investigated with negative results.

The present investigation is an attempt to verify the original work done by Antonoff and Rowley⁷ and to contribute specific data on the action of a magnetic field on aluminum cells. Experiments of the type they described have been performed and an extensive set of data has been collected. It was thought that if the results of Antonoff and Rowley could be duplicated, further investigation would be warranted. However, the experiments have produced negative results. Various conditions have been tried with an especial attempt to get the molten mass-like deposit, to no avail. These condition and results are described in detail in subsequent chapters.

⁶D. Palumbo and G. Riccobone, Ricerca Scientifica, Vol. 18, (July, 1948), p. 821-3.

⁷Antonoff and Rowley, op. cit. p. 1105.

CHAPTER II

DESCRIPTION OF EQUIPMENT

The equipment used had to be of a type that could produce a strong concentrated magnetic field that could be varied easily and constructed so that an electrolytic cell could be placed between the poles of the magnet with a strip of the metal in the solution. One such electromagnet was constructed which used high current and few turns of wire, but it was found by checking with a General Electric Light Beam Type Fluxmeter, Catalog No. 32C247 Gr. 7, Reg. Dal91087, that the strongest field that could be produced with this magnet was 4000 gauss, and this only for short periods due to the tremendous current of 700 amperes required, which caused the brushes of the motor-generator to arc. This source was fed directly into the magnetic field coils of the electromagnet which were two coils taken from a similar arc welder motor-generator. These coils were connected in series aiding with a core of iron bolted together to form a single yoke with 1.19 centimeters diameter pole faces. The gap could be controlled by the bolted connection of the top pole face. Some tests were run with this equipment but they were of no significance.

The data reported in this thesis were obtained with a double yoke, army surplus, magnetron electromagnet with the

original pole faces removed. The bottom adjustable core served as one pole face. The top core was removed and replaced by another core of approximately the same type material as the original. This core was 15 cm. in length and 3 cm. in diameter. The increased length allowed smaller gaps. The magnet is shown in Fig. 1. The power furnished to coils was from a variable power supply of 0-1000 volts, 300 millamperes, direct current. The Flux density in the gap of the electromagnet is shown in Table 1¹ and Fig. 2. These readings are for a gap of 0.71 centimeters which was used throughout this experimental work.

The magnetic flux reading were made with a General Electric Light Beam Type Fluxmeter, Catalog No. 32C247, Gr. 7, Req Dal 91087, using a search coil that had a deflection factor of 60.7 gauss per millimeter of deflection. It can be seen by Fig. 2 that with a voltage of 1000 volts and current of 300 milliamperes the core was running close to saturation. Higher voltages caused internal heating of the coils and were not used.

The electrolytic cell was a 150 milliliter pyrex beaker with a 50 milliliter pyrex beaker tied to the inside pole with rubber bands to protect the pole face and to keep from contaminating the electrolyte with the iron pole. For the test in the magnetic field the aluminum electrode was placed in the bottom of the large beaker so that its plane was

¹All tables are in the appendix.

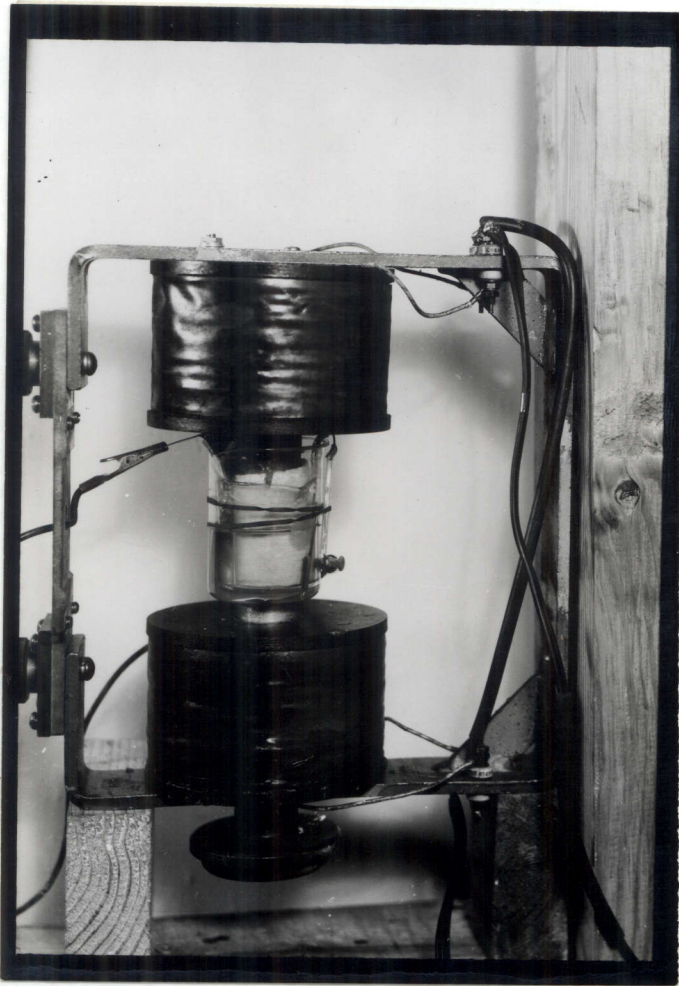


Fig. 1.--Photograph of electromagnet
with cell in place.

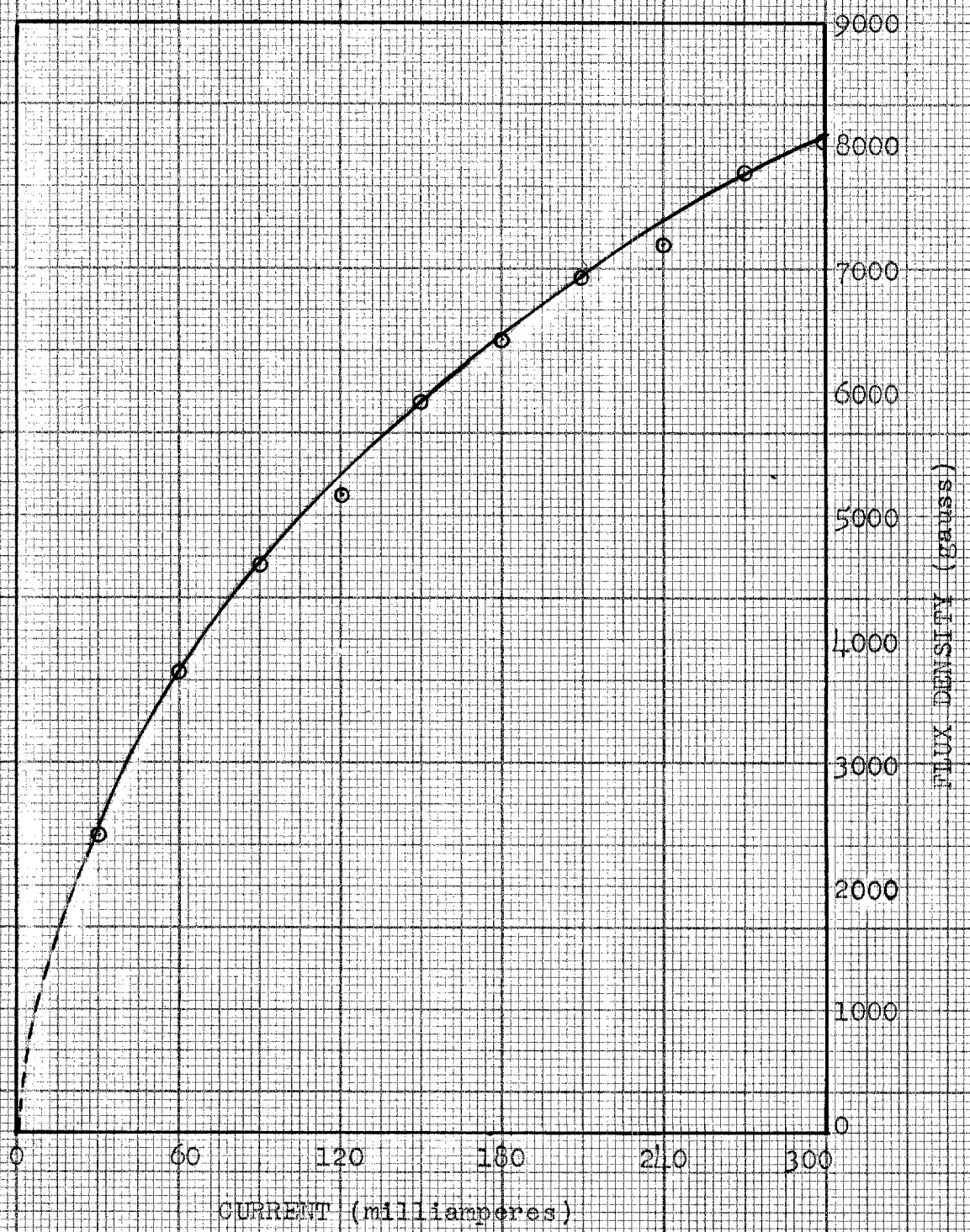


Fig. 2--Magnetic characteristics of the electromagnet.

perpendicular to the magnetic field. The other electrode of platinum was placed in the solution to the side and not in the magnetic field. For the electrolysis tests these electrodes were connected to a 45 volt "B" battery through a double pole, double throw reversing switch. An ammeter was used to read electrode current and a voltmeter to read the potential difference applied to the electrolysis cell. For the electromotive force test a Leeds and Northrup Co. No. 7552, Serial No. 63037, potentiometer was used. This potentiometer was checked against an Eppley standard cell No. 436337 which has an emf. of 1.01930 absolute volts at 23° C.

CHAPTER III

EXPERIMENTAL DATA AND RESULTS

Two Aluminum Electrodes in Aluminum Sulfate

Three tests were made using two electrodes of aluminum in a concentrated solution consisting of 300 grams of $\text{Al}_2(\text{SO}_4)_3 \cdot 18 \text{H}_2\text{O}$ in 300 milliliters of distilled water. In the first test the electrodes were 8 millimeters wide and of aluminum metal, light sheet 1/64 inch thick, Lot No. 62448, J. T. Baker Chemical Co.. All of the aluminum used in this work except one strip was of this type. These electrodes were placed in a test tube in such a way that both electrodes ran the complete length of the tube parallel to each other, and the electrolyte was poured in the tube until it was three-fourths full. The electrodes were connected to a 45 volt battery and the current read 2 amperes with a voltage drop to 20 volts. It was observed that the anode gassed vigorously while no apparent reaction was evident at the cathode. The magnetic field was then applied and observed for a period of five minutes and there was no change in the gassing at the anode. The cathode showed no change from the magnetic field. There was no change in current except a momentary flicker when the field was applied. The current density was 0.143 amperes per square centimeter at the electrode surfaces.

In the second test the two aluminum strips of 6 millimeters width were mounted in such a way that the bottoms of the strips were just above the pole face and the electrolyte level was just below the top of the pole face so that the region of electrolysis was completely in the magnetic field. The electrode current read a minimum of 40 milliamperes after it stabilized. The voltage was 39 volts and there was no change in reaction with the magnetic field. This test was run for ten minutes and the current density was 0.0179 amperes per square centimeter.

The third test was like the second except that the width was reduced to 2 millimeters and as soon as the cell was connected the magnetic field was applied. The results were the same as the first except that the current started out at 0.35 amperes and steadily dropped to 0.080 amperes, the same as if the magnetic field were not present. It was found that every time a potential was applied, the electrodes current started off high and slowly receded to a minimum value. The current density of this test was 0.432 to 0.10 amperes per square centimeter and this test was run for 20 minutes.

It is conclusive that these tests do not agree with a similar one reported by Antonoff and Rowley.¹

The potential difference of the third cell was measured with an RCA Ultra-sensitive Microammeter, Model WV-84A,

¹Antonoff and Rowley, op. cit.

before the cell was used in the current test. The potential difference was 0.05 volt and did not change immediately upon applying a magnetic field of about 6000 gauss. Changes smaller than 0.001 volt could not have been observed with the instrument.

Electromotive Force of a Cell with Aluminum Electrodes

A cell was constructed with the aluminum electrode between the pole faces of the electromagnet, and the magnetic field was applied at various times to see if there would be any change in the electromotive force of the cell. The other electrode was platinum. The data in Table 2 were taken with the aluminum electrode in place in the cell, but without a magnetic field. The electromotive force was measured with a Leeds and Northrup Type K Potentiometer. There was a pulsating effect with the electromotive force, which was probably due to polarization and the giving off of gas bubbles. The electrolyte had a concentration of 135 grams of $\text{Al}_2(\text{SO}_4)_3 \cdot 18 \text{H}_2\text{O}$ in 200 milliliters of distilled H_2O .

The second emf. test was made using this same concentration for a total of 39 minutes by varying the voltage applied to the electromagnet coil in 100 volt steps every two minutes. By looking at the data from this test in Table 3 one would be led at first to think that the emf. increased with the magnetic field, but the same rate of change of emf. continued even after the magnetic field was removed. The cell was heated by heat conduction from the pole faces

and the solution became quite warm every time the magnetic field was applied for this reason.

Another test was run 58 minutes using this same electrode and a fresh solution of the same concentration as shown in Table 4. The results of this test show that the emf. steadily increased up to the 33rd minute, when it started down for no apparent reason and continued to decrease at about the same rate as the previous increase. The variation of emf. with and without the magnetic field forces the conclusion that any possible magnetic effect is small compared with polarization and other effects which tend to change the emf..

In the test that is shown in Table 5, the concentration was 50 grams of $\text{Al}_2(\text{SO}_4)_3 \cdot 18 \text{H}_2\text{O}$ to 400 milliliters of distilled water. The magnetic field was changed every two minutes. There was only one change in the emf. during this test and that was at the beginning of the 6th minute when the electromagnet voltage was changed to 300 volts. This change could have been due to the magnetic field, but it is doubtful as on the other test there were no extreme changes at this point.

The last emf. test was run for a period of 35 minutes. The magnetic coil voltage was varied in steps of 100 volts at two minute intervals, as is shown in Table 6. In this test the emf. of the cell appeared to be increasing because of its own internal action and the application of and changes in the applied field apparently had little if any effect.

Electrode Current of a Cell with Various Concentrations of Electrolyte

This series of experiments was made with various concentrations of solutions to try to determine the effect which the concentration of electrolyte would have upon the reaction in a field. The cell was set up with a strip of aluminum between the pole faces of the electromagnet. The other electrode was of platinum and these two electrodes were connected to a 45 volt battery through a double pole, double throw reversing switch in order that the polarity could be changed quickly. On all of these tests the switch was in position to make the aluminum electrode the anode and the platinum the cathode. The reversing of the switch simply changed this connection to make the aluminum the cathode and the platinum the anode.

The first test was with a concentration of 25 grams of $\text{Al}_2(\text{SO}_4)_3 \cdot 18 \text{H}_2\text{O}$ and 200 milliliters of distilled H_2O . The voltage was varied in steps of 100 volts each minute for a period of 10 minutes until maximum field strength was reached. This test was run for 12 minutes and with no significant results as is shown in Table 7.

The next test was run for a period of 46 minutes with alternately no field and maximum field at three minute intervals. The voltage was increased by 5 volts immediately after the field was removed each time. The voltage was raised to the maximum for the batteries, and then the

polarity was reversed and decreased in steps of 5 volts at one minute intervals. The concentration of this solution was 300 grams $\text{Al}_2(\text{SO}_4)_3 \cdot 18 \text{H}_2\text{O}$ and 400 milliliters of distilled H_2O , and was used as a standard for the two following tests. In this test as is shown in Table 8 there was no apparent magnetic effect.

The standard solution was diluted with equal parts of distilled H_2O and the test just described was run on this solution with the exception that when polarity was reversed the readings were made instantaneously to see if there was an appreciable change. The tests show no visible effect due to the magnetic field, as is shown by Table 9. This same test was repeated with exception that the standard solution was diluted with two parts distilled H_2O to one part solution. The results were the same as all of the above and are shown in Table 10.

These four tests show that there is not any change in the reaction caused by the concentration of the solution. The only change noticeable is that the internal resistance of the cell is changed and it draws less current as the concentration decreases. These tests do show the rectification property of aluminum but also show that aluminum sulfate has a tendency to inhibit the property.

Deposits on the Aluminum Electrode

Throughout this experimental work particular attention was paid to any deposits that might appear on the aluminum

electrode. There were only four electrodes that showed any significant deposits, and these were of a minor nature and could not be duplicated. Approximately fifty tests of various kinds were run and these four showed a few minor spots which could be due to contamination of the electrolyte as duplication was attempted and could not be accomplished. Impurities in the electrode and surface conditions could also explain the occasional deposits obtained.

The first of these deposits is shown in Figures 3 and 4. These tests show that on the top side, which was next to the north magnetic pole, strip A was corroded and had a slight amount of pitting. This pitting showed up in cases where the current density was high but no constructive data is available on this as it turned up in the beginning of this experiments and it could not be duplicated. A' shows the bottom of this same electrode, which was next to the south pole. It shows more corrosion but is of no consequence. B showed some definite deposits in about four spots the size of pin points located on the periphery of a corroded spot that is about the size of a match head. This particular experiment was also made in the beginning and no actual data is available and could not be repeated. B', the bottom of B, showed a little corrosion around the edges and nothing more. All of the photographs are approximately eight tenths normal size.

Figures 5 and 6 show two other tests on which the data is available, but could not be duplicated. C is the test

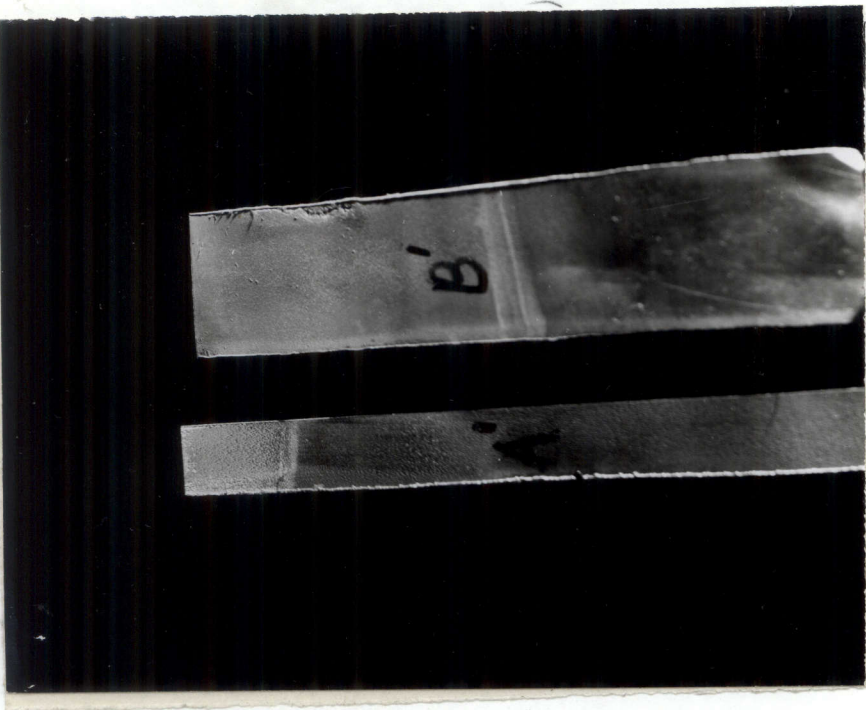


Fig. 4.--Bottom view of electrodes (A and B).

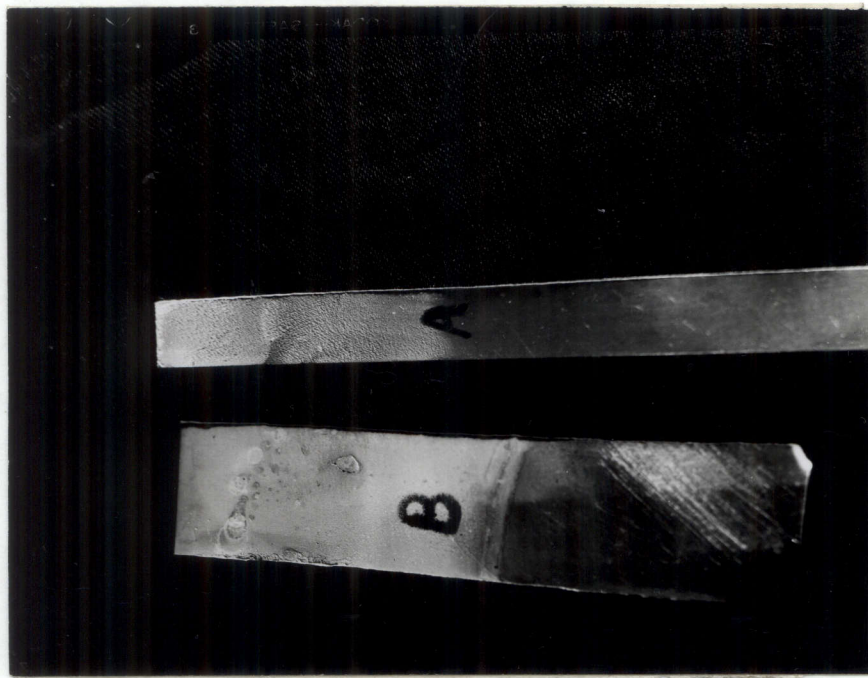


Fig. 3.--Top view of electrodes (A and B)

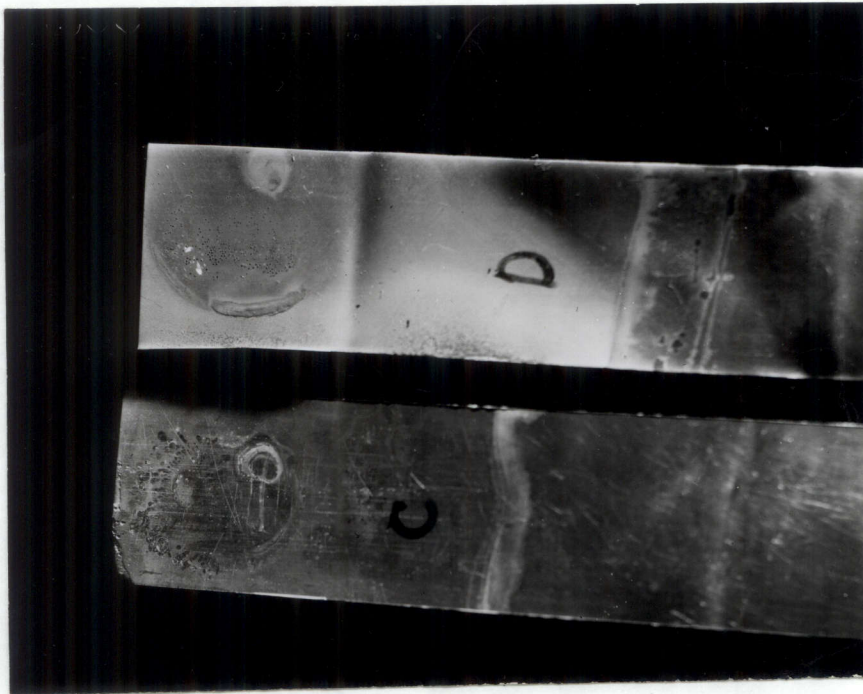
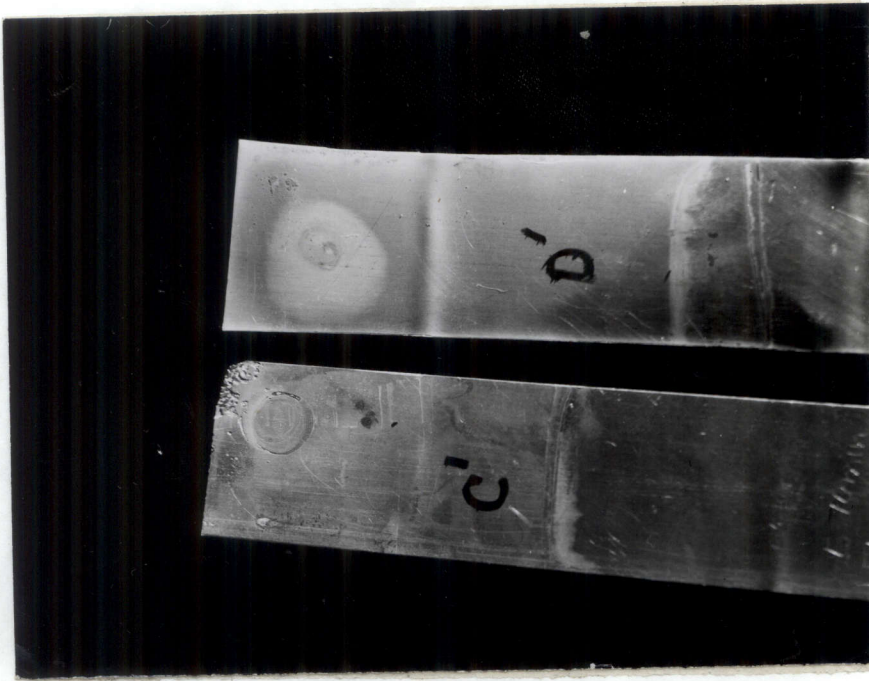


Fig. 6.--Bottom view of electrodes (C and D).

Fig. 5.--Top view of electrodes (C and D)

strip of a 10 minute test with a magnetic field of 8040 gauss and a current of 0.8 amperes in the cell. It is believed that the large circle was caused by the top pole face glass protector lying against the strip. This strip shows quite a lot of corrosion, but it is believed that the circles in it and in C' were caused by the container or by the circular motion of the solution that was always present when the magnetic field was applied, due to the rotation of the charged gas bubbles in the magnetic field.

In Figure 5, D shows the side of a strip against the north pole of the magnet. There were approximately 50 black spots which might contain some deposits, but on close examination they appear to be principally corrosion spots. The electrolyte in this test was 25 grams of $\text{Al}_2(\text{SO}_4)_3 \cdot 18 \text{H}_2\text{O}$ and 200 milliliters of distilled H_2O . This test was run for approximately 3 minutes and when the maximum magnetic field was applied the current was fair, constant at 0.020 amperes and slowly increased to about 1.5 amperes in about three minutes. This result of the test is believed to have been due to a slight amount of Cu SO_4 from a copper wire inside a broken glass support for the platinum pole. The Cu SO_4 came from an electrolytic action of copper wire and aluminum sulfate. The black deposits are probably cupric oxide.² D' is the bottom of this strip, and does not show anything.

²Holland, op. cit., pp. 198-199.

This experimental work failed to show any molten like masses on the aluminum as was mentioned by Antonoff and Rowley.³

³Antonoff and Rowley, op. cit.

CHAPTER IV

SIGNIFICANCE OF RESULTS AND SUGGESTIONS FOR FURTHER WORK

The results obtained in the investigation reported here do not support the work of Antonoff and Rowley.¹ On the basis of these results, it seems probable that either (a) Antonoff and Rowley misinterpreted their own results, or (b) the results they got, in particular the formation of the molten like mass on the aluminum electrode during electrolysis in a magnetic field, were due to some factor or factors unknown by them. In only one case, discussed in Chapter III, was a deposit obtained in the present investigation which remotely resembled the one described by Antonoff and Rowley, and this result could not be duplicated in an exhaustive series of tests. Therefore if one does an experiment of this type with a magnetic field, and then tries to repeat it with the same conditions except for the absence of the field, the results are likely to be inconclusive because the successive performance of two experiments identical in all respects, including the presence of the field, failed to produce consistent results.

Therefore, if the effect described by Antonoff and Rowley exists, it exists only under a very special set of conditions

¹Antonoff and Rowley, op. cit.

which were not duplicated in the numerous tests conducted in the present research. It can be said that the effect is not pronounced or far-reaching.

It was thought that impurities in the aluminum electrode might be responsible for Antonoff and Rowley's results. Antonoff² has said that this is probably a factor. A series of tests with Aluminum Company of America alloy 24-ST³ failed to produce results any different from those obtained with pure Sargent aluminum used in the other tests. It is possible that a particular combination or concentration of impurities is necessary, of course, but the means were not available for extending the investigation along these lines, so that the main effort was concentrated on pure aluminum with the thought that the effect, if it exists with pure aluminum, might be more readily explained theoretically. The negative results obtained precluded the necessity of investigating various aspects of the effect, which had been contemplated in the initial stages of the investigation.

The electromotive force test, of the type described in Chapter III, is probably a more sensitive indicator of the effect of magnetic fields on electrolytic properties of metals than the deposition test. The main effort in the present work was not put into emf. tests, however, and although it can be stated that under the various conditions

²George Antonoff, personal communication.

³The composition of 24-ST alloy is as follows: copper, 4.5 per cent by weight; manganese, 0.6; magnesium, 1.5; rest, aluminum. This information was obtained from Stock List No. 15, New York, Whitehead Metal Products, Inc., 1947.

prevailing in the tests there is no pronounced effect due to the magnetic field, more refined tests under carefully controlled conditions would be necessary to define the extent of the effect, if it exists. In fact, the work of Palumbo and Riccobono⁴ has established that the change in emf. of a cell with like electrodes changes by less than 0.001 volt upon application of the magnetic field, and that this result can be explained as a thermal effect. Their work is closely related to the present investigation, and the one substantiates the other.

Suggestions for Further Work

It is possible that the magnetic effect on aluminum electrodes during electrolysis, under special conditions of impurities and surface properties, is very pronounced. It appears that an attempt to find the exact conditions under which the deposition of the molten-like mass described by Antonoff and Rowley⁵ is deposited reproducibly would constitute a worthwhile investigation. It might even have commercial applications. Many different types of electrolytes and electrodes, with controlled amounts of impurities in both the electrolytes and the electrodes, could be tried. It is probable that the magnetic effect is closely related to the rectification property of the electrode. Therefore the

⁴Palumbo and Riccobono, op. cit.

⁵Antonoff and Rowley, op. cit.

effect might exist with tantalum, columbium, antimony, bismuth, and other metals which exhibit the rectification property.⁶

No reference has been found in the literature to a possible magnetic effect with ferromagnetic electrodes, such as iron, nickel, or cobalt, in electrolytic cells, but such an effect might exist and its investigation would be worthwhile.

⁶Glasstone, op. cit., p. 434.

APPENDIX

TABLE 1

MAGNETIC CHARACTERISTICS OF ELECTROMAGNET

Coil Voltage (Volts)	Current (Milliamperes)	Deflection (Millimeters)	Magnetic Flux Density (Gauss)
100	30	40	2430
200	60	61.5	3730
300	90	76	4620
400	120	86	5220
500	150	97	5890
600	180	108	6480
700	210	115	6900
800	240	120	7200
900	270	130	7800
1000	300	136	8160

TABLE 2

ELECTROMOTIVE FORCE WITH TIME ONLY
(EMF. TEST NO. 1)

Time (Min.)	Electromotive Force (Absolute Volts)	Time (Min.)	Electromotive Force (Absolute Volts)
0	1.1352	8	1.1691
1	1.1509	9	1.1707
2	1.1578	10	1.1690
3	1.1628	11	1.1639
4	1.1658	12	1.1618
5	1.1741	13	1.1600
6	1.1688	14	1.1587
7	1.1688		

TABLE 3

ELECTROMOTIVE FORCE WITH FLUX DENSITY
(EMF. TEST NO. 2)

Time (Min.)	Coil Voltage (Volts)	Coil Current (Ma.)	Flux Density (Gauss)	Electromotive Force (Absolute Volts)
0	0	0	0	0.89722
1	100	30	2430	.89722
2	100	30	2430	.89510
3	100	30	2430	.90205
4	200	60	3730	.94508
5	200	60	3730	.94508
6	200	60	3730	.94508
7	300	90	4620	.94508
8	300	90	4620	.94536
9	300	90	4620	.94536
10	400	120	5220	.94636
11	400	120	5220	.94717
12	400	120	5220	.94979
13	500	150	5890	.95506
14	500	150	5890	.95580
15	500	150	5890	.95580
16	600	180	6480	.95838
17	600	180	6480	.96705
18	600	180	6480	.97031
19	700	200	6800	.97904
20	700	200	6800	.97153
21	700	200	6800	.97625
22	800	230	7300	.98630
23	800	230	7300	.98630
24	800	230	7300	.98910
25	900	250	7600	.99329
26	900	250	7600	.99520
27	900	250	7600	.99616
28	1000	260	7700	1.00513
29	1000	260	7700	1.01169
30	1000	260	7700	1.01588
31	1000	260	7700	1.01610
32	1000	260	7700	1.01771
33	0	0	0	1.01979
34	0	0	0	1.02856
35	0	0	0	1.03173
36	0	0	0	1.03960
37	0	0	0	1.04366
38	0	0	0	1.04640
39	0	0	0	1.05458

TABLE 4
ELECTROMOTIVE FORCE WITH FLUX DENSITY
(EMF. TEST NO. 3)

Time (Min.)	Coil Voltage (Volts)	Coil Current (Ma.)	Flux Density (Gauss)	Electromotive Force (Absolute Volts)
0	0	0	0	1.05585
1	0	0	0	1.05712
2	0	0	0	1.05840
3	0	0	0	1.06012
4	0	0	0	1.06073
5	0	0	0	1.06062
6	0	0	0	1.06041
7	0	0	0	1.06050
8	0	0	0	1.06041
9	0	0	0	1.06041
10	0	0	0	1.06394
11	0	0	0	1.06369
12	0	0	0	1.06244
13	0	0	0	1.06220
14	0	0	0	1.06220
15	100	30	2430	1.06233
16	100	30	2430	1.06198
17	200	60	3730	1.06198
18	200	60	3730	1.06231
19	300	90	4620	1.06377
20	300	90	4620	1.06158
21	400	110	5000	1.06122
22	400	110	5000	1.06097
23	500	140	5800	1.06116
24	500	140	5800	1.06098
25	600	175	6350	1.06204
26	600	175	6350	1.06169
27	700	200	6800	1.06401
28	700	200	6800	1.06486
29	800	220	7100	1.06612
30	800	220	7100	1.06618
31	900	240	7200	1.07004
32	900	240	7200	1.06843
33	1000	265	7750	1.10059
34	1000	265	7750	1.09283
35	1000	265	7750	1.08150
36	1000	265	7750	1.08018
37	1000	265	7750	1.07872

TABLE 4---Continued

Time (Min.)	Coil Voltage (Volts)	Coil Current (Ma.)	Flux Density (Gauss)	Electromotive Force (Absolute Volts)
38	1000	265	7750	1.06743
39	1000	265	7750	1.05836
40	1000	265	7750	1.05511
41	1000	265	7750	1.05318
42	1000	265	7750	1.05124
43	0	0	0	1.05124
44	0	0	0	1.05124
45	0	0	0	1.05065
46	0	0	0	1.05051
47	0	0	0	1.05097
48	0	0	0	1.05442
49	0	0	0	1.05078
50	0	0	0	1.04725
51	0	0	0	1.04725
52	0	0	0	1.04725
53	0	0	0	1.04681
54	0	0	0	1.04524
55	0	0	0	1.04524
56	0	0	0	1.04585
57	0	0	0	1.04718
58	0	0	0	1.04387

TABLE 5
ELECTROMOTIVE FORCE WITH FLUX DENSITY
(EMF. TEST NO. 4)

Time (Min.)	Coil Voltage (Volts)	Coil Current (Ma.)	Flux Density (Gauss)	Electromotive Force (Absolute Volts)
0	0	0	0	0.95044
1	0	0	0	.95044
2	100	30	2430	.95044
3	100	30	2430	.95044
4	200	60	3730	.95044
5	200	60	3730	.95044
6	300	90	4620	.95654
7	300	90	4620	.94654
8	400	120	5220	.94654
9	400	120	5220	.94654
10	500	150	5980	.94654
11	500	150	5980	.94654
12	600	180	6480	.94654
13	600	180	6480	.94654
14	700	210	6900	.94654
15	700	210	6900	.94654
16	800	240	7200	.94654
17	800	240	7200	.94654
18	900	270	7800	.94654
19	900	270	7800	.94654
20	1000	295	8100	.94654
21	1000	295	8100	.94654
22	0	0	0	0.94654

TABLE 6
ELECTROMOTIVE FORCE WITH FLUX DENSITY
(EMF. TEST NO. 5)

Time (Min.)	Coil Voltage (Volts)	Coil Current (Ma.)	Flux Density (Gauss)	Electromotive Force (Absolute Volts)
0	0	0	0	1.06750
1	100	30	2430	1.06750
2	100	30	2430	1.06750
3	200	60	3730	1.06750
4	200	60	3730	1.06750
5	300	90	4620	1.06983
6	300	90	4620	1.07089
7	400	110	5000	1.07230
8	400	110	5000	1.07230
9	500	140	5800	1.07230
10	500	140	5800	1.07297
11	600	170	6300	1.07297
12	600	170	6300	1.07297
13	700	200	6800	1.07297
14	700	200	6800	1.07569
15	800	210	6900	1.07706
16	800	210	6900	1.07706
17	900	240	7200	1.07706
18	900	240	7200	1.07706
19	1000	270	7800	1.08142
20	1000	270	7800	1.08142
21	1000	270	7800	1.08142
22	500	120	5300	1.08142
23	0	0	0	1.08142
24	0	0	0	1.08142
34	0	0	0	1.08142

TABLE 7

ELECTRODE CURRENT WITH FLUX DENSITY
(CURRENT TEST NO. 1)

Time (Min.)	Electrode Current (Amp.)	Electrode Voltage (Volts)	Coil Voltage (Volts)	Coil Current (Ma.)	Flux Density (Gauss)
0	0.5	36	0	0	0
1	.45	36	100	2600	2430
2	.42	36	200	4300	3730
3	.40	36	300	4800	4620
4	.42	36	400	5300	5220
5	.38	36	500	5900	5890
6	.38	36	600	6480	6480
7	.38	36	700	6800	6900
8	.34	36	800	7300	7200
9	.35	36	900	7700	7800
10	.34	36	1000	8100	8160
Reversed polarity					
11	1.25	30	1000	8100	8160
12	.64	31.5	1000	8100	8160

TABLE 8
ELECTRODE CURRENT WITH FLUX DENSITY
(CURRENT TEST NO. 2)

Time (Min.)	Electrode Current (Amp.)	Electrode Voltage (Volts)	Coil Voltage (Volts)	Coil Current (Ma.)	Flux Density (Gauss)	Temperature (°C.)
0	0.021	5	0	0	0	31
1	.006	5	1000	300	8160	31
2	.006	5	1000	300	8160	31
3	.006	5	1000	300	8160	31
4	.014	5	0	0	0	31
5	.060	10	0	0	0	31
6	.010	10	0	0	0	31
7	.018	10	1000	300	8160	32
8	.020	10	1000	300	8160	32
9	.030	10	1000	300	8160	33
10	.043	10	0	0	0	34
11	.067	15	0	0	0	35
12	.067	15	0	0	0	35
13	.086	15	1000	300	8160	35
14	.086	15	1000	300	8160	35
15	.094	15	1000	300	8160	36
16	.160	20	0	0	0	37
17	.180	20	0	0	0	37
18	.200	20	1000	290	8050	38
19	.240	20	1000	290	8050	39
20	.240	20	1000	290	8050	39
21	.240	20	0	0	0	40
22	.400	25	0	0	0	40
23	.480	25	0	0	0	41
24	.440	25	1000	280	8000	42
25	.460	25	1000	280	8000	43
26	.460	25	1000	280	8000	47
27	.460	25	0	0	0	49
28	1.200	30	0	0	0	53
29	1.280	30	0	0	0	55

TABLE 8---Continued

Time (Min.)	Electrode Current (Amp.)	Electrode Voltage (Volts)	Coil Voltage (Volts)	Coil Current (Ma.)	Flux Density (Gauss)	Temperature (°C.)
30	1.200	30	1000	280	8000	58
31	1.260	30	1000	280	8000	61
32	1.260	30	1000	280	8000	64
33	1.260	30	0	0	0	67
34	.940	30	0	0	0	71
35	.9900	30	0	0	0	72
Reversed polarity						
41	2.000	30	0	0	0	66
42	2.000	25	0	0	0	66
43	1.500	20	0	0	0	66
44	1.200	15	0	0	0	66
45	.650	10	0	0	0	66
46	0.28	5	0	0	0	65

TABLE 9
ELECTRODE CURRENT WITH FLUX DENSITY
(CURRENT TEST NO. 3)

Time (Min.)	Electrode Current (Amp.)	Electrode Voltage (Volts)	Coil Voltage (Volts)	Coil Current (Ma.)	Flux Density (Gauss)	Temperature (°C)
0	0.018	5	0	0	0	26
1	.003	5	0	0	0	26
2	.003	5	0	0	0	26
3	.004	5	1000	300	8160	26
4	.004	5	1000	300	8160	26
5	.004	5	1000	300	8160	26
6	.003	5	0	0	0	26
7	.015	10	0	0	0	26
8	.018	10	0	0	0	26
9	.018	10	0	0	0	27
10	.018	10	1000	300	8160	27
11	.018	10	1000	300	8160	27
12	.018	10	1000	300	8160	27
13	.032	15	0	0	0	27
14	.042	15	0	0	0	27
15	.048	15	0	0	0	28
16	.058	15	1000	290	8050	28
17	.058	15	1000	290	8050	28
18	.058	15	1000	290	8050	28
19	.010	20	0	0	0	28
20	.010	20	0	0	0	28
21	.012	20	0	0	0	28
22	.012	20	1000	290	8050	28
23	.012	20	1000	280	8000	29
24	.012	20	1000	280	8000	29
25	.020	25	0	0	0	29
26	.023	25	0	0	0	30
27	.030	25	0	0	0	31
28	.030	25	1000	280	8000	31
29	.028	25	1000	280	8000	32

TABLE 9---Continued

Time (Min.)	Electrode Current (Amp.)	Electrode Voltage (Volts)	Coil Voltage (Volts)	Coil Current (Ma.)	Flux Density (Gauss)	Temperature (°C.)
30	0.028	25	1000	280	8000	33
31	.052	30	0	0	0	34
32	.059	30	0	0	0	35
33	.064	30	0	0	0	36
34	.050	30	1000	280	8000	37
35	.050	30	1000	280	8000	38
36	.050	30	1000	280	8000	39
37	.054	30	0	0	0	40
38	.058	30	0	0	0	41
39	.060	30	0	0	0	42
40	.060	30	0	0	0	43
41	.060	30	0	0	0	44
Reversed polarity						
Time instantaneous						
	.900	30	0	0	0	45
	.950	25	0	0	0	45
	.700	20	0	0	0	45
	.480	15	0	0	0	45
	.300	10	0	0	0	45
	0.102	5	0	0	0	45

TABLE 10
ELECTRODE CURRENT WITH FLUX DENSITY
(CURRENT TEST NO. 4)

Time (Min.)	Electrode Current (Amp.)	Electrode Voltage (Volts)	Coil Voltage (Volts)	Coil Current (Ma.)	Flux Density (Gauss)	Temperature (°C.)
0	0.090	5	0	0	0	28
1	.002	5	0	0	0	28
2	.002	5	0	0	0	28
3	.002	5	0	0	0	28
4	.002	5	1000	300	8160	28
5	.002	5	1000	300	8160	28
6	.003	5	1000	300	8160	28
7	.022	10	0	0	0	28
8	.014	10	0	0	0	28
9	.024	10	0	0	0	28
10	.024	10	1000	300	8160	28
11	.024	10	1000	300	8160	29
12	.024	10	1000	300	8160	29
13	.036	15	0	0	0	29
14	.036	15	0	0	0	29
15	.036	15	0	0	0	29
16	.036	15	1000	280	8000	29
17	.036	15	1000	280	8000	29
18	.036	15	1000	280	8000	30
19	.066	20	0	0	0	30
20	.088	20	0	0	0	30
21	.088	20	0	0	0	30
22	.078	20	1000	280	8000	30
23	.078	20	1000	280	8000	30
24	.078	20	1000	280	8000	30
25	.140	25	0	0	0	30
26	.150	25	0	0	0	30
27	.170	25	00	0	0	31
28	.131	25	1000	280	8000	31
29	0.136	25	1000	280	8000	32

TABLE 10---Continued

Time (Min.)	Electrode Current (Amp.)	Electrode Voltage (Volts)	Coil Voltage (Volts)	Coil Current (Ma.)	Flux Density (Gauss)	Temperature (°C.)
30	0.140	25	1000	280	8000	32
31	.300	30	0	0	0	32
32	.430	30	0	0	0	33
33	.450	30	0	0	0	33
34	.450	30	1000	280	8000	33
34	.450	30	1000	280	8000	34
35	.450	30	1000	280	8000	35
36	.450	30	0	0	0	36
Reversed polarity Time instantaneous						
	1.080	27	0	0	0	36
	.760	20	0	0	0	36
	.580	15	0	0	0	36
	.300	10	0	0	0	36
	0.066	5	0	0	0	36

10 volts and passage of the current became evident. At the same time it was observed that the aluminum strip was covered with a deposit having the appearance of a molten mass and the shape of a disc of the same diameter as the iron rod facing it (figure 3A). The disc appeared on the upper surface; on the other surface there could be observed small amounts of the same matter deposited here and there.

A similar experiment was performed with a permanent alnico magnet. In this case the two iron rods need not be screwed into the body of the magnet, because they are held by the magnetic force itself. The permanent magnet did not have the strength of the electromagnet, but the effect observed was of the same nature. The same substance was deposited in a circle which was, however, not completely covered with the deposit, as in the case with the electromagnet (figure 3B). It was found afterwards that even with a very weak magnetic field a deposit of the same kind is formed in a circle.

Without the magnetic field, especially if one uses pure aluminum, one observes deposits in small quantities of the same matter here and there, and not in a circle. This matter is not easily detachable from the metal itself, so that a way of collecting it for analysis has not yet been found.

A number of photographs were taken under a microscope. Figure 4 shows figures 3A and 3B magnified twenty times.

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January 26, 1948

ANODIC BEHAVIOR OF ALUMINUM IN A MAGNETIC FIELD

It is well known that aluminum immersed in a solution of certain aluminum salts does not conduct anodically, or does so very poorly. This property is taken advantage of for rectifying the current, and the usual explanation given for this phenomenon is that the passage of the current is prevented by the formation of a film of oxide.

Certain facts have come to my attention which indicate that there are other factors which may be responsible for this peculiarity of aluminum and of other metals.

In electrolyzing an aluminum sulfate solution with a platinum anode, an aluminum strip was inserted into the anode compartment. The solution was hot, and the strip of aluminum dissolved with energetic evolution of gas. The strip of aluminum was then connected to the platinum anode and the evolution of gas stopped, or very nearly so. On breaking the connection with the platinum anode the evolution of gas reappeared instantaneously. The fact that these effects are observed at once does not seem to support the theory of an oxide film, because its formation and disappearance must take time. The film of oxide can be a contributing factor, but it cannot be solely responsible for the destruction of the current.

The idea came to mind that it may be due to some special electronic structure, such that electrons under the electrical field can move only in one direction and not in the other.

If there is any justification for this view, a magnetic field should produce an effect; to test this the following experiments have been performed.

A test tube of such a size that it just fitted into the gap between the two poles of a powerful alnico magnet was filled with a solution of aluminum sulfate and

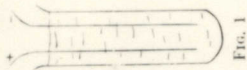


FIG. 1

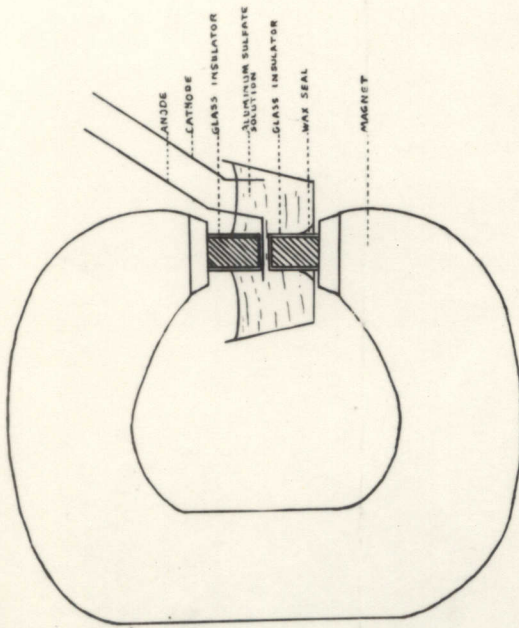


FIG. 2

two aluminum electrodes were inserted (figure 1). This cell was connected to a 45-volt battery, with no visible effects of the passage of current. But when it was placed between the poles of the magnet, the anode began to produce gas, a result which indicated some increase in conductivity of the solution.

Next an experiment was carried out with a powerful electromagnet of about 2000 Gauss. Two iron rods were screwed into its body as in figure 2. They

were insulated with thin glass caps having a wall thickness of 0.3 mm. These caps were 8 mm. in diameter and 3 mm. apart. On the lower rod a container capable of holding a solution of aluminum sulfate was fixed. It was thus possible

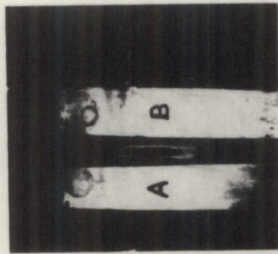


FIG. 3

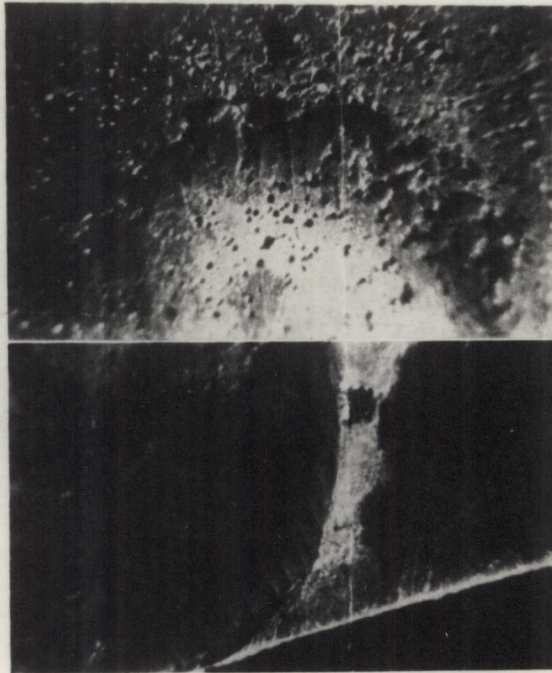


FIG. 4

to place a strip of aluminum anode between two poles of the magnet. A platinum wire served as cathode. With the 45-volt battery connected to the electrodes in a saturated solution of aluminum sulfate there was no drop of potential observed. However, when a magnetic field was established the potential fell to

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