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AN ABSTRACT OF THE THESIS OF Walter Edward Socha for the Master of
Science in Physics presented March 4 , 1976

Title: The Effect of an Applied Magnetic Field on the Leclanché Cell

APPROVED BY MEMBERS OF THE THESIS COMMITTEE:

Dr. John Dash, Chairman

Dr. Makoto Takeo

Dr. Pavel Smejtek

Dr. David Roe

The effect of a magnetic field on an electrochemical system, the Leclanché cell, was investigated. Experiments show that there is an increase in power output and charge passed when a cell is discharged in an applied magnetic field.

Possible explanations for the effect and descriptions of attempts to verify these explanations are presented.

THE EFFECT OF A MAGNETIC FIELD
ON THE LECLANCHÉ CELL

by

WALTER EDWARD SOCHA

A thesis submitted in partial fulfillment of the
requirements for the degree of

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in
PHYSICS

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TO THE OFFICE OF GRADUATE STUDIES AND RESEARCH

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INTRODUCTION

I. BULK HYDRODYNAMIC EFFECTS

A report by Dash and King (1) in 1972 shows that the electrochemical deposition and thinning of metals at constant current is more uniform if performed in a magnetic field. Also shown is that the resistance of an electrochemical cell may be reduced in a magnetic field.

This latter effect may be caused by the reduced thickness of the interface layer between the electrode and the bulk electrolyte. Fick's law states that the net drift J , expressed in carriers crossing a unit area per unit time is proportional to the concentration gradient.

$$J = -D(dn/dx) \quad (1)$$

where n is the number of molecules per unit vol. and x is the distance in the direction of drift (see Figure 1). The proportionality constant D is known as the diffusion constant and is proportional to the mobility of the carriers (2).

Figure 1. Pictorial diagram of electrothinning of zinc and the relationship between the concentration of $Zn^{++}(n)$ and the distance from the electrode (x). dn and dx are infinitesimals.

If at a constant current one obtains a lowering of impedance, then this may be due to a steeper concentration gradient. Also, this observation may be due to a mixing effect.

In electrochemical cells, the current is carried by moving ions. Therefore, on observing a mixing effect in a magnetic field, the assumption must be that the Lorentz force $q(\mathbf{B} \times \mathbf{v})$ is stirring the ions as they move. Drift vel. of the hydrogen ion is given as 22.5×10^{-4} cm/sec in a field of 1 volt/cm at 0°C (3). Using this value for the velocity in the Lorentz force and a value of 1 kilogauss (kG) for the magnetic field strength normal to the velocity, one gets a value of 36×10^{-26} newtons for the force deflecting the ion. Using $m = 1.68 \times 10^{-27}$ kilograms for the mass of the ion, a further simplistic calculation yields an acceleration of $a = F/m = 214$ meters/sec² perpendicular to the direction of motion. Note that the mobility was used for the velocity of the individual ion and no consideration was made for the mechanism of ionic conduction. However, even though arrived at with a naive calculation, the values of the force and acceleration of the ions are significant.

II. INHIBITION OF HYDROGEN EVOLUTION

Experiments performed by Tung in 1972 (4), and continued by Chen and Housen in 1975 (5), showed that the current efficiency for the deposition of chromium is greater when performed in an applied magnetic field. This means that a greater amount of chromium is deposited for the same amount of charge passed.

However, chromium co-deposits with hydrogen and Chen (5) found that a magnetic field inhibits hydrogen evolution. This inhibition of

hydrogen evolution could be caused by a decrease in mobility of the hydrogen ion due to a Hall effect in the electrolyte. The investigation by D. Laforgue-Kanzter (3) of the Hall effect in aqueous electrolytes supports the theory that the conductivity of aqueous solutions is partially due to the H_3O^+ ion and partially due to a dry proton, the latter having an extremely high mobility. A magnetic field could have a large effect on the movement of such a proton, reducing the mobility in the direction of the electrode (see Figure 2).

Figure 2. Pictorial diagram showing the effective path (dotted line) of the ion under the influence of a magnetic field.

III. SOLUTION-METAL INTERFACE PHENOMENA

Other possible interactions of a magnetic field with an electrochemical cell may take place at the sol'n-metal interface. One possible effect is a change in the activation overpotential. This overpotential is the difference between the decomposition potential of the cell and the reversible potential (the potential at which the forward and reverse rates at the electrode are equal). It is connected with the shift in the Fermi level in the metal electrode from the value which it

had when the electrode reactions were taking place at an equal speed. It is possible to change the Fermi level of the electrons in the metal by the use of an applied magnetic field. The magnitude of this change is, here, the product of the Bohr magneton (0.927×10^{-20} ergs/gauss) and the magnetic field strength. A field of 1 kG would then change the Fermi level by approximately 10^{-17} ergs.

Improved understanding of the magnetic interaction with electrolysis would then result from the elimination of one of the following:

1. bulk hydrodynamic effects (mixing)
2. inhibition of hydrogen evolution
3. sol'n-metal interface phenomena.

An electrochemical system with the electrolyte immobilized in the form of a paste or suspended in a fibrous material would decrease or eliminate the bulk mixing effect. For this reason, an investigation of the operation of the Leclanché cell in a magnetic field was started.

IV. THE LECLANCHÉ CELL (6)

The structure of a typical Leclanché cell is shown in Figure 3. The basic cell consists of the zinc can, separator, cathode mix, and carbon rod, with the electrolyte impregnating the cathode mix and separator.

The zinc can serves as the anode and to contain the cell. It is made by impact extrusion and a typical alloy consists of 1.0% lead, 0.05% cadmium, and the remainder zinc of 99.99% purity. The alloying elements improve the mechanical properties and decrease wasteful corrosion.

Figure 3. Modern Leclanché cell (6).

The cathode mix consists of an uniform mixture of manganese dioxide ($\approx 100\mu$), the actual cathode material, and carbon black (usually acetylene black). The latter serves the double purpose of increasing the conductivity of the MnO_2 and absorbing the electrolyte. The ratio of MnO_2 to carbon black may vary from 10:1 (transistor use) to 1:1 (photoflash batteries). The cathode mix also contains electrolyte amounting to about 25% of its total weight.

The electrolyte is made by dissolving ammonium chloride, zinc chloride, and a small amount of mercuric chloride in water. This latter converts to zinc chloride as the mercury plates out on the zinc on contact. In use, the pH of the paste (electrolyte and cathode mix) near the zinc may vary from roughly 6 to 4, while for the innermost portions of the mix, it may vary from 6 to 10.

The carbon rod serves as the conductor of electricity for the manganese dioxide electrode and also serves as a vent to allow hydrogen gas, which forms at the anode, to escape.

The separation of the two electrodes is accomplished by using

kraft paper (a strong paper made from sulfate pulp) coated on the zinc side with methyl cellulose containing mercurous(ic) chloride. The mercury coats the zinc (as with the mercury from the electrolyte) and inhibits its corrosion.

The basic anode reaction of the Leclanché cell is the oxidation of zinc,

while the cathode reaction is the reduction of manganese dioxide,

The standard reduction half-reactions and thermodynamic data for zinc and manganese dioxide are (7)...

The complete reduction of the MnO_2 is complicated and occurs in a series of steps. The Mn_2O_3 is first formed, then MnOOH , and finally Mn_3O_4 (8). The removal of the MnOOH is considered to be the rate determining step of the overall reaction (9). In acidic solutions, the removal is effected by

For neutral and alkaline solutions, protons and electrons diffuse into the interior of the MnO_2 particles, effectively removing the MnOOH . At pH 3 to 6, both processes occur. In either case, formation and the removal of MnOOH is itself limited by the diffusion of protons.

Corrosion at the zinc anode (see Figure 4) in the Leclanché cell is an important factor in its performance. Corrosion requires two

reactions, a reduction and an oxidation. The oxidation or anode reaction is zinc dissolution,

One possible reduction, which occurs at cathodic sites on the zinc anode, is that of hydrogen formation,

This necessitates venting, which allows a second reduction reaction, that of oxygen, which may occur anywhere in the cell,

Figure 4. Simplified illustration of corrosion. The oxidation of zinc frees two electrons which combine with hydrogen ions to form atomic hydrogen. The atomic hydrogen then recombine into molecular H_2 .

CELL DISCHARGE EXPERIMENTS

The investigation of the effects of a magnetic field on the Leclanché cell was begun by measuring the energy output and charge passed by cells discharged with and without an applied field.

I. EXPERIMENTAL

Leclanché cells of size N or D, chosen at random from commercial lots, were used. Either one cell or sets of several cells of the same kind were drained through a known constant resistor at a constant temperature. The voltage as a function of time was recorded using a double pen voltage-time recorder (Houston Instruments Omnigraphic 2-3000). Two similar sets of cells were tested at the same time. One set was drained in an applied magnetic field while the second set was drained without the field. The initial experiment had the hookup leads soldered to the size N cells. Subsequent experiments used copper tabs firmly taped to the cell ends or used non-magnetic alligator clips for contacts. With the size D cells, the steel contact plates at both ends were removed, since these would distort the applied magnetic field. The size N cells have their cans bare and have a copper contact pressed over the carbon post. In all cases, the hookup leads were kept the same length in the circuits of both sets.

Figure 5. Schematic electrical circuit for cell discharge experiments. The number of cells in series varied from one to six. In one case (Experiment 9), the cells in the field and those outside the field were in series across the resistance load (see Figure 7).

Temperature control was provided by bars of aluminum stock (at room temperature) or by ice-water baths. In the former case, the two cells or sets of cells were held in physical contact with an aluminum bar and were located at opposite ends of this bar. If the ice-water bath was used, the individual cells were sealed in plastic bags to prevent an electrical short circuit through the water.

Orientation of the cells was either parallel or perpendicular to the applied field.

Figure 6. Cell alignment in the applied magnetic field: (a) the applied field parallel to the axis of the cells, and (b) the applied field perpendicular to the axis of the cells.

The resulting strip chart graph of voltage versus time was integrated numerically in time interval segments to give the total amount of energy output from the cells,

$$E = \int P dt = \frac{1}{R} \int V^2 dt = \frac{\tau}{3R} \sum (V_f^2 + V_1 V_f + V_1^2) \quad (8)$$

where τ is the time interval used, R is the resistance load, V_1 is the initial voltage of the segment considered, and V_f is the final voltage of the same segment (see Appendix A for derivation). The summation is over all time segments.

The amount of charge passed was calculated (Appendix A) from the same strip chart graph according to,

$$Q = \frac{1}{R} \int V dt = \frac{\tau}{2R} \sum (V_1 + V_f) \quad (9)$$

One experiment was performed in a different manner. In Experiment 9, the two sets of cells were connected together in series (see Figure 7). In this manner, the current through both sets of cells is the same.

Figure 7. Schematic circuit of Experiment 9. The cells in the field and those outside the field were connected in series across a common resistance load. This load was made up of two known resistances, one of which (R) had its voltage drop (V_R) recorded. A two pen voltage-time recorder plotted the potential differences, V_B and V_A , versus time of the cells drained with and without an applied magnetic field, respectively.

The energy output and charge passed for the set of cells in Experiment 9 drained without the field was calculated according to,

$$E_A = \int P dt = \int IV dt = \frac{\tau}{6R} \sum (2V_{Ri} V_{Ai} + V_{Ri} V_{Af} + V_{Rf} V_{Ai} + 2V_{Rf} V_{Af}) \quad (10)$$

and for the charge passed,

$$Q_A = \int Idt = \frac{1}{R} \int V dt = \frac{\tau}{2R} \sum (V_{Ri} + V_{Rf}) \quad (11)$$

where V_{Ri} and V_{Rf} are the initial and final voltage drops across R for the time segment considered, V_{Ai} and V_{Af} are the initial and final potential differences of the cells for the same time segment, and τ is the length of the time segment (see Appendix B). The energy output and charge passed for the set drained with an applied magnetic field is calculated similarly.

II. RESULTS

The results of the experiments measuring the energy output and charge passed by the Leclanché cells with and without an applied magnetic field are given in Table I.

Experiments are labeled 1 through 26. The type of cells used were, for size N, Mallory M910F and Eveready 904, and, for size D, Burgess 210 and Eveready 950. The different types of magnets supplying the field are listed as I, II, III, IV, and V (see Appendix C for illustrations). The magnets are as follows:

I.....Varian Associates, electromagnet model V-4007 with six inch pole pieces

II.....Westinghouse, permanent horseshoe magnet

III.....Edmund Scientific, permanent ring magnet #30730.

TABLE I
RESULTS OF CELL DISCHARGE EXPERIMENTS

EXPERIMENT NUMBER	FIELD (kg)	MAGNET TYPE	NUMBER OF CELLS	CELL SIZE AND TYPE	RESISTANCE LOAD (ohms)	TIME (minutes)	ORIENTATION (of cells in field)	TEMPERATURE (°C)	ENERGY OUTPUT (joules)	ENERGY % INCREASE WITH FIELD	CHARGE PASSED (coulombs)	CHARGE % INCREASE WITH FIELD
1	4.5 0	I	6 6	N. M910F N. M911F	60 1½ 60 1½	600 600	parallel	0	2,900 2,590	+12%	1,060 1,010	+5.0%
2	4.5 0	I	1 1	D. 210 D. 210	4.6 1½ 4.6 1½	1080 1080	perpend.	22	12,900 12,090	+7.4%	12,400 12,300	+4.9%
3	4.5 0	I	1 1	D. 210 D. 210	4.6 1½ 4.6 1½	1020 1080	perpend.	22	10,470 11,500	-9.6%	11,290 12,000	-6.7%
4	4.5 0	I	1 1	D. 210 D. 210	4.6 1½ 4.6 1½	1030 1050	perpend.	22	12,300 11,600	+3.4%	12,300 12,100	+1.7%
5	3.3 0	I	6 6	D. 950 D. 950	4.6 1½ 4.6 1½	980 980	parallel	0	32,400 32,500	-0.3%	17,100 13,800	+24%
6	3.3 0	I	6 6	D. 950 D. 950	4.6 1½ 4.6 1½	1640 1640	parallel	0	35,500 28,000	+27%	20,300 17,500	+16%
7	3.3 0	I	6 6	D. 950 D. 950	1.05 2½ 1.05 2½	960 960	parallel	0	11,900 8,150	+46%	19,000 15,600	+19%
8	3.3 0	I	6 6	D. 950 D. 950	1.05 2½ 1.05 2½	620 620	parallel	0	11,900 9,600	+24%	17,400 14,900	+17%
9	3.3 0	I	6 6	D. 950 D. 950	15 1½ 15 1½	840 840	parallel	0	44,700 30,400	+47%	14,100 14,100	
10	1.5 0	II	3 3	N. 904 N. 904	30 1½ 30 1½	1030 1030	parallel	0	1,790 1,800	-0.6%	1,300 1,340	-3.0%
11	1.5 0	II	3 3	N. 904 N. 904	30 1½ 30 1½	670 600	parallel	0	1,730 1,930	-5.5%	1,190 1,170	+0.8%
12	1.0 0	III	3 3	N. 904 N. 904	30 1½ 30 1½	1030 1050	parallel	0	2,120 2,170	-2.2%	1,480 1,430	+3.5%
13	1.0 0	III	3 3	N. 904 N. 904	30 1½ 30 1½	1020 1120	parallel	0	1,720 1,790	-3.9%	1,320 1,360	-2.9%
14	1.0 0	IV	2 2	N. 904 N. 904	30 1½ 30 1½	1020 1020	parallel	0	1,640 1,630	+0.6%	1,360 1,340	+1.5%
15	1.5 0	II	3 3	N. 904 N. 904	1.052 1.045	1380 1030	parallel	0	174 195	-11%	1,660 1,580	+5.1%
16	1.0 0	I	6 6	N. 904 N. 904	59.6 60.0	220 220	parallel	0	2,320 2,160	+7.4%	612 586	+4.4%
17	1.1 0	V	6 6	N. 904 N. 904	59.6 60.0	1090 1070	parallel	22	4,750 4,630	+2.6%	1,550 1,570	-1.3%
18	1.1 0	V	6 6	N. 904 N. 904	59.6 60.0	720 720	parallel	22	4,620 4,700	-1.7%	1,460 1,460	0%
19	1.1 0	V	6 6	N. 904 N. 904	59.6 60.0	1000 1070	parallel	22	4,790 4,860	-1.4%	1,570 1,570	0%
20	2.5 0	V	3 3	N. 904 N. 904	30.2 30.1	1000 1000	perpend.	22	2,370 2,340	+1.3%	1,560 1,570	-0.7%
21	2.5 0	V	3 3	N. 904 N. 904	30.1 30.2	1000 1030	perpend.	22	2,400 2,370	+1.3%	1,560 1,540	+1.3%
22	2.5 0	V	3 3	N. 904 N. 904	30.1 30.2	1000 1000	perpend.	22	2,450 2,310	+6.1%	1,540 1,540	0%
23	2.5 0	V	3 3	N. 904 N. 904	9.13 9.14	1000 1000	perpend.	22	360 365	-1.4%	840 840	0%
24	2.5 0	V	3 3	N. 904 N. 904	59.6 60.0	1000 1000	perpend.	22	2,990 2,960	+4.5%	1,440 1,430	+2.9%
25	2.5 0	V	3 3	N. 904 N. 904	59.6 60.0	1000 1000	perpend.	22	2,860 2,980	-0.7%	1,400 1,390	+0.7%
26	2.5 0	V	3 3	N. 904 N. 904	59.6 60.0	1000 1000	perpend.	22	2,990 2,970	+4.2%	1,430 1,400	+2.1%

Resistors used in Experiments 1 through 14 are listed with their percentage error. For Experiments 15 through 26, the values listed are those measured with a Cenco Wheatstone bridge (#85295) accurate to the number of places given.

See Appendix E for error analysis.

IV.....Edmund Scientific, two permanent ring magnets #30730

V.....Laboratories For Science, permanent magnet model "Variflux"

For Experiment 1, a plot of the amount of charge passed versus time for the cells drained with and without an applied magnetic field is given in Figure 8. The energy output of these cells versus time is plotted in Figure 9.

Experiments 5, 6, 7, 8, and 9 were performed using the same field strength of 3.3 kG (kilogauss), but for various load resistances. For these experiments, the amount of charge passed and the energy output was recalculated for a common time of 620 minutes. These values are given in Table II. For these same experiments, graphs of charge passed and energy output per cell versus the resistance load per cell have been plotted (see Figures 10 and 11 respectively).

TABLE II

DATA COMPUTED FOR EXPERIMENTS
5 THROUGH 9. TIME IS
620 MINUTES

EXPERIMENT	FIELD (kG)	NUMBER OF CELLS	LOAD (ohms)	CHARGE PASSED (coulombs)	ENERGY OUTPUT (joules)
5	3.3	6	4.6	14,400	30,600
	0	6	4.6	10,600	19,100
6	3.3	6	4.6	14,700	32,600
	0	6	4.6	12,800	26,000
7	3.3	6	1.05	16,300	11,900
	0	6	1.05	13,300	8,580
8	3.3	6	1.05	17,400	12,300
	0	6	1.05	14,900	9,900
9	3.3	6	15	11,800	39,400
	0	6	15	11,800	29,700

Figure 8. The effect of a magnetic field on the amount of charge passed by Leclanché cells (Exp. 1).

Figure 9. The effect of a magnetic field on the energy output of Leclanché cells (Exp. 1).

CHARGE PASSED

Figure 10. Graph of charge passed versus the resistance load per cell for Experiments 5, 6, 7, 8, and 9. Time for each experiment was 620 minutes. Temperature was 0°C .

Figure 11. Graph of the energy output per cell versus the resistance load per cell for Experiments 5, 6, 7, 8, and 9. Time for each experiment was 620 minutes and the temperature was 0°C. The cells in the experiment at 1.25 ohms/cell were all in series (see page 10).

During the operation of Experiment 8, a power failure turned off the electromagnet and opened the Leclanché cell circuits. During this interruption, the cells were able to recover. The experiment was interrupted 346 minutes after its start and the length of the interruption was 534 minutes. The power was then reapplied and the experiment allowed to continue. In Table III, there is listed the values of the voltages across each set before and after the interruption of the experiment.

TABLE III

VOLTAGES ACROSS EACH SET OF CELLS IN EXPERIMENT 8 BEFORE AND AFTER A 534 MINUTE INTERRUPTION. EACH SET HAD BEEN CONNECTED TO A $1.05 \pm 2\%$ OHM LOAD FOR A PERIOD OF 346 MINUTES PRIOR TO THE RECOVERY PERIOD

	VOLTAGE BEFORE	VOLTAGE AFTER	% INCREASE
CELLS WITH FIELD	.322 volts	.810 volts	150%
CELLS WITHOUT FIELD	.275 volts	.570 volts	105%

Experiment 9 is unique in that it was the only experiment run with the two sets of cells in series (see Figure 7). The energy output and charge passed were calculated in this experiment only for the first 840 minutes. This was due to the voltage across the cells drained without an applied magnetic field dropping to zero at the end of this period (see Figure 12). The experiment was allowed to continue beyond this point and for a period of 130 minutes the potential across the cells outside the field was some unmeasured negative value. For the next 210 minutes, the potential across this set of cells was again positive. The experiment was then ended.

Figure 12. Rough plot of voltage versus elapsed time for Experiment 9. The two sets of six cells were wired in series with a 15 ohm resistance load. The field used was 3.3 kG. The dotted line indicates the section where no voltages were measured. During this period, the cells without an applied field were acting as an additional load for the set of cells positioned in the magnetic field.

It was stated in the Introduction that the removal of MnOOH by proton diffusion into the interior of the MnO_2 particle is considered to be the rate determining step in the Leclanché cell. Therefore, a crude determination of the diffusion distance (x) of the proton was calculated from the recovery time ($t = 130$ minutes) during which the potential across the cells in Experiment 9 without an applied magnetic field was negative. The diffusion constant (D) for protons is $1.2 \times 10^{-18} \text{ cm}^2/\text{sec}$ (10). Then the diffusion distance (11) is

$$x = \sqrt{2Dt} \quad (12)$$

$$= \sqrt{2(1.2 \times 10^{-18} \text{ cm}^2\text{sec}^{-1})(9.8 \times 10^3 \text{ sec})}$$

$$x = 1.5 \times 10^{-7} \text{ cm}$$

This value corresponds to several molecular layers.

These results indicate a apparent increase in energy output and in the amount of charge passed when the cells are drained in an applied magnetic field. The total energy output of the Leclanché cells in Experiments 1 through 26 is 217 kilojoules for those drained in a field and 188 kilojoules for those without. This is a 15% difference in energy output. The percentage increase in the amount of charge passed was 9.0% with a total of 149,000 coulombs passed by those cells in the field and 136,000 coulombs for those without. The total number of Leclanche cells used in the 26 experiments was 202, with 101 being drained in an applied magnetic field and 101 without.

A marked difference is noted between the increased output of the size D and size N cells (see Table IV). The latter have a relatively small increase in energy output and in the amount of charge passed with the applied magnetic field. Another difference between the two cell sizes lies in the ratios of the volume of the cathodic material (V) to the surface area of the zinc (A) with which it is in contact. For the size N cells, the approximate ratio is

$$V/A = (2000 \text{ mm}^3)/(800 \text{ mm}^2) = 2.5$$

while for the size D cells,

$$V/A = (30,000 \text{ mm}^3)/(5,000 \text{ mm}^2) = 6$$

If the bulk hydrodynamic mixing effects are negligible in the Leclanché cell, then one possible contribution to the greater efficiency of the cell is the inhibition by the magnetic field of hydrogen evolution at the zinc anode. This might be expected if proton motion to cathodic

TABLE IV
ENERGY OUTPUT AND CHARGE PASSED FOR
SIZE N AND SIZE D CELLS SUMMED
OVER ALL EXPERIMENTS

SIZE	NUMBER OF EXPERIMENTS	NUMBER OF CELLS	ENERGY (J)		CHARGE (C)		% INCREASE	
			FIELD	NO FIELD	FIELD	NO FIELD	ENERGY	CHARGE
N	18	136	45,000	44,300	24,300	24,100	1.6%	0.8%
D	8	66	172,000	144,000	124,000	112,000	19%	11%
all cells	26	202	217,000	188,000	149,000	136,000	15%	9.0%

sites on the anode is impeded by the field. The zinc-oxidation/hydrogen-reduction mechanism does not directly influence the zinc-oxidation/manganese dioxide-reduction couple, but it does indirectly by increasing the amount of zinc ions being produced. This last increases the zinc ion concentration gradient, reducing its effective mobility and increasing the resistance of the cell.

FURTHER INVESTIGATION OF THE LECLANCHÉ CELL

The positive relationship between an applied magnetic field and an increase in the energy output and in the amount of charge passed has been shown. However, the reasons for this effect are still uncertain. Assuming that the bulk hydrodynamic effect of mixing has been eliminated or reduced, investigations of corrosion in Leclanché cells with and without the presence of a magnetic field were attempted.

I. HYDROGEN EVOLUTION

As seen in Table I, an applied magnetic field of several kilogauss can increase the amount of charge passed by Leclanché cell through various resistance loads. If this is at least partly a result of the inhibition of hydrogen evolution, then discharging cells in a field should have measurably less hydrogen gas being discharged than cells discharging under the same conditions outside the field.

Using the results of Experiment 1, a difference of about 50 coulombs passed was calculated for two sets of six cells being drained into 60 ohms. This corresponds to

...several cubic centimeters of hydrogen gas, assuming that the greater amount of charge being passed in the cells inside the field is

a result of the inhibition of hydrogen evolution. So if one were to seal the cells in a container, with a method of measuring volume or pressure change as the cells were drained, it should be possible to test the theory.

The basic approach was to seal the cells in a glass tube with wire leads entering by way of a water filled tube (see Figure 13) and to detect a change of volume by a column of water or mercury. A nitrogen atmosphere was used to suppress the accompanying reaction

Alternately, the load resistor itself could be sealed in with the cells. No consistent results were obtained due to either leakage or lack of sensitivity, and this approach was abandoned.

Figure 13. Basic approaches to the detection of hydrogen evolution.

II. MASS CHANGE

The reduction of oxygen (which enters the cell through the carbon rod) also increases the amount of zinc corroded.

Another possible explanation of the increased charge passed may lie in less cell resistance due to an inhibition of the above reduction.

To investigate this possibility, size D cells were stripped of their paper jackets and metal contact caps, and cleaned. Cells were placed in ice-water baths as in the cell discharge experiments and drained into constant resistance loads. Mass measurements were made of the cells before and after being drained but no consistent data was obtained. Data is given in Table V. Differences in the number of cells drained with and without an applied magnetic field resulted from the discarding of cells that leaked electrolyte.

TABLE V

MASS CHANGE OF SIZE D CELLS (BURGESS 210)
DURING DISCHARGE AT 0°C. TIME
WAS 108 MINUTES

FIELD	LOAD	INCREASE IN MASS
4.5 kG	5 ohms	+0.0067 grams
0	5	-0.0134
0	5	-0.0306
0	5	+0.0067
3.3	10	+0.0075
3.3	10	-0.0047
3.3	10	+0.0096
3.3	10	+0.0060
0	10	+0.0108
0	10	+0.0082
0	10	+0.0038

III. EXTENT OF CORROSION

Hydrogen evolution is part of the corrosion process for zinc in the Leclanché cell (9). Therefore, a crude measurement of the extent of corrosion of cells drained with and without an applied field was made.

Thirty-six Eveready 950 size D cells (see Table I, experiments 6, 7, and 8) had been drained until the cell walls were pitted with holes. After discharging, the cells were cut apart and the cells flattened out. The bottom ends were discarded as they were protected from extensive corrosion by a cupped kraft washer (see Figure 3).

The flattened cell walls were then used to obtain a photographic contact print from which the open area of the zinc anodes was estimated. This was done by using a plastic sheet which had a grid network photographically laid on it. The individual squares on this grid had an unit area of 0.011 cm^2 . The 18 cells drained without the field had a total area of 11.9 cm^2 eaten away compared to 25.8 cm^2 for the cells without the field (see Table VI).

The increased area of corrosion of the cells in the magnetic field correlates qualitatively with the increased charge passed (see Tables I and VI). However, there is no way presently to quantitatively connect the amount of open area corroded to the amount of charge passed. This last is necessary to determine if there was an inhibition of corrosion due to the magnetic field or if the amount of open area is just a result of the amount of charge passed.

TABLE VI
OPEN AREA OF LECLANCHÉ CELL CANS
CORRODED DUE TO DISCHARGE

EXPERIMENT NUMBER	FIELD (kG)	NUMBER OF CELLS	LOAD (ohms)	TIME (minutes)	CHARGE PASSED (coulombs)	AREA (cm ²)	% INCREASE WITH FIELD
6	3.3	6	4.6	1640	20,300	14.11	76%
	0	6	4.6	1640	17,500	6.10	
7	3.3	6	1.05	960	19,000	5.01	7%
	0	6	1.05	960	15,600	4.38	
8	3.3	6	1.05	620	17,400	6.75	280%
	0	6	1.05	620	14,900	1.48	

INVESTIGATIONS OF THE CORROSION OF ZINC

I. CORROSION EXPERIMENTS

In an electrochemical cell, interaction of the magnetic field with processes at both anode and cathode are possible. Further work, therefore, was concentrated on only one process, that of corrosion at the zinc anode, due to time limitations.

Specimens of zinc were allowed to corrode with and without an applied magnetic field in an electrolyte made up of ammonia chloride and zinc chloride. These two chemicals are contained in the electrolyte used in the Leclanché cell. Change in mass of the specimens was measured to determine the effect of the magnetic field on the corrosion process.

The electrolyte was made up with one mole of each of the above chemicals plus enough de-ionized water to make one liter of solution.

In all cases, the zinc specimens for each experiment were cleaned and weighed in an identical manner. Four different experiments were performed.

Experiment A

Fifteen zinc discs (99.9% pure with respect to metallic impurities) were allowed to corrode in the $\text{NH}_4\text{Cl-ZnCl}_2$ solution. The discs were 0.03 cm thick and 1.94 cm in diameter. They were washed with Labtone (Van Waters & Rogers, Cat. No. 21850-003), rinsed with water, and then placed in an ultrasonic cleaner with distilled water for 5

minutes. The specimens were then dried with a hot air gun. Nine of the discs were placed horizontally in a 15 ml beaker (Kimax #14000) with one layer of Kimwipes material (Kimberly-Clark Corp., Stock No. 34150) between each disc. The beakers were filled to the 10 ml mark with the electrolyte. The second group of nine discs were prepared in the same way. One group was left in a field of approximately 2 kilogauss, while the second group of nine discs was allowed to corrode without a magnetic field. The magnet used was a Varian Associates model V-4004 electro-magnet with 2 inch pole pieces.

Figure 14. Equipment and positioning of Experiment A.

The mass of the specimens was measured before and after the experiment. Table VII gives the results of this experiment. The total change in mass is given with a positive amount indicating an increase in mass. Time for the experiment was $98\frac{1}{2}$ hours.

Experiment B

Twenty-four rectangular zinc strips (99.9% pure with respect to metallic impurities) of various dimensions were allowed to corrode in the electrolytic solution. The strips were arranged in three groups,

TABLE VII

MASS CHANGE OF THE ZINC SPECIMENS DUE TO CORROSION

EXPERIMENT	FIELD (kg)	SPECIMENS (type)	NUMBER OF SPECIMENS	TOTAL MASS CHANGE (grams)	TIME	TEMPERATURE (°C)
A	2	discs	9	-0.01276	98½ hours	22
	0	discs	9	-0.01133	98½ hours	22
B	2 top	rectangles	8	-0.02518	7 days	22
	2 bottom	rectangles	8	-0.02337	7 days	22
	0	rectangles	8	-0.02573	7 days	22
C	4.5	cans	10	+0.0063	7 days	22
	0	cans	11	+0.0076	7 days	22
D	1.5 top	rectangles	4	-0.0151	7 days	22
	0	rectangles	4	-0.0076	7 days	22

each of which contained the following zinc strips:

- 2 strips: 15.2 cm x 1.27 cm x 0.7 cm
- 2 strips: 15.2 cm x 1.27 cm x 0.3 cm
- 4 strips: 15.2 cm x 0.91 cm x 0.3 cm

Each group made up of the above strips were cleaned as in Experiment A and placed in a 25 ml graduated cylinder (Pyrex #3075) with a strip of Kimwipes material between each strip. The cylinders were filled with the electrolyte to one inch above the top of the specimens. One group was left to corrode with a field centered at the bottom edge of the strips, one with the field at the top edge of the strips, and the remaining group with no applied magnetic field.

As mentioned before, the corrosion of zinc involves an oxidation and a reduction reaction. Two possible reductions are that of H^+ and of O_2 . The latter would be influenced by the depth in the solution at which the corrosion occurred. The field was applied at two regions of the zinc strip to determine if there exists an interaction between the field and O_2 reduction. A difference in depth should, therefore, vary the strength of such an interaction, if all other factors are unchanged.

Time was one week. The magnet used was a Varian Associates model V-4004 electromagnet with 2 inch pole pieces. Field was approximately 2 kG. Results are given in Table VII and the experimental equipment is diagramed in Figure 15.

Experiment C.

In this experiment, the zinc containers from Eveready 904 cells were filled with 1 ml of the NH_4Cl_2 - $ZnCl_2$ solution and tested for the effect of a magnetic field on corrosion.

Figure 15. Equipment and position of magnetic field in Experiment B.

The cells used were cut open at the top and the inside materials removed. The cans were then cleaned with Labtone, rinsed, and then placed in a zinc cleaning solution for one minute. This cleaning solution was made up of 100 grams of chromic acid, $7\frac{1}{2}$ grams of sodium sulphate, 25 ml of nitric acid and 475 ml of distilled water. The zinc cans were then re-rinsed and placed in an ultrasonic cleaner with distilled water and finally rinsed again in distilled water. The cans were then each dried with a hot air gun for 10 seconds.

The can size was $\frac{7}{16}$ inches in diameter and $\frac{3}{4}$ inches high. An aluminum bar was drilled with two sets of holes, one at either end, to serve as a heat sink and holder for the cans. Once divided into two groups and placed in either end of the aluminum bar, the cans were filled with one ml of the electrolyte (using a 1 ml calibrated pipette). One ml of electrolyte filled the zinc cans to a depth of approximately 1.0 cm. A magnetic field was centered on the zinc cans at one end of

the aluminum bar while the other set of cans was left to corrode without an applied field. The magnet used was a Varian Associates model V-4007 with 6 inch pole pieces. The field strength was 4.5 kG.

Figure 16. Position of apparatus in Experiment C.

After a period of one week, the cans were removed, rinsed, placed in an ultrasonic cleaner for 5 minutes, and re-rinsed, all with distilled water. Then each can was dried with a hot air gun for 10 seconds and re-weighed. In Table VIII are listed the individual mass changes, together with the mean, average deviation, and standard deviation of each group of cans.

At the completion of the experiment, the cans were cut open (see Figure 17) and inspected. A dividing line of variable clarity was observed, separating the inside surface of the zinc cans into two regions, one which was in contact with the electrolyte and the other which was exposed only to air. In both groups, the liquid-air line on the flattened cans show a visual increase in width with an increase in

TABLE VIII
INDIVIDUAL DATA FOR ZINC CANS
IN EXPERIMENT C

	FIELD	NO FIELD
INDIVIDUAL MASS CHANGES (grams)	-0.0051	-0.0031
	-0.0040	-0.0023
	-0.0024	-0.0007
	+0.0003	-0.0007
	+0.0008	+0.0009
	+0.0017	+0.0010
	+0.0018	+0.0011
	+0.0021	+0.0012
	+0.0025	+0.0013
	+0.0042	+0.0019
	+0.0044	
MEAN VALUE	+0.0006	+0.0001
AVERAGE DEVIATION	+0.0025	+0.0014
STANDARD DEVIATION	+0.0030	+0.0016
TOTAL MASS CHANGE	+0.0063	+0.0006

FIGURE 17. INTERIOR SURFACE OF ZINC CANS AT END OF EXPERIMENT C. MASS CHANGE IS IN MILLIGRAMS.

mass.

Experiment D

This experiment is identical with Experiment B except that none of the rectangular specimens were allowed to corrode with a magnetic field applied at the bottom edge (see Figure 15). Data is given in Table VII.

II. DISCUSSION OF RESULTS

Experiments A, B, C, and D were performed by allowing zinc metal to corrode in an electrolytic solution. For Experiments A, B, and D, the mass of the specimens decreased, but the results are conflicting. In A and D, the zinc specimens which were allowed to corrode in a magnetic field have a greater mass loss than the specimens corroding with no applied field. But in Experiment B, the specimens outside the field have the greater mass loss.

Also, in Experiment B, there is a definite difference in mass loss between the two groups of zinc strips which were allowed to corrode with a magnetic field centered on different ends which were at different depths in the electrolyte. The strips with the field centered on the edge near the surface had the greater mass loss. Both of these groups did, however have a smaller mass loss than the third group of zinc strips which were allowed to corrode without the applied magnetic field.

So while the results indicate that the magnetic field reduces the corrosion of zinc in Experiment B, it does so to a greater extent when it acts further from the surface of the electrolyte. Differential aeration (see Figure 18) would cause the lower part of the zinc strip

(which is aerated to a lesser degree) to corrode at a greater rate. It would then appear that the magnetic field inhibits the zinc oxidation reaction, having a lesser effect near the surface where the cathodic reaction dominates. However, this theory conflicts with Experiments A and D, where the field appears to promote corrosion.

Figure 18. Schematic picture of differential aeration. The availability of oxygen causes the upper part of the zinc strip to be cathodic with respect to the bottom.

In Experiment C, the corroding zinc cans actually gained mass, and it is assumed that zinc compounds (formed as the zinc oxidized) adhered to the metal. The cans that corroded within the applied field gained significantly more mass than the cans outside the field (see Table VIII). The standard deviation for the values of mass change of the individual cans in the field was almost twice that of the cans outside the field. No explanation was developed for this or for the change in width of the electrolyte-air line on the interior surface of the zinc cans. This liquid-air line could possibly be caused by dif-

ferential aeration, although this has not been investigated (see Figure 19).

Figure 19. Possible explanation for the liquid-air line on the interior surface of the zinc cans used in Experiment C. Corrosion initiated at a weak point of the metal surface might lead to the formation, along the meniscus where the renewal of oxygen is easy, of a membrane of oxidized zinc products. This might then shield the zinc surface underneath from access of oxygen, making it anodic with respect to areas with aerated passive regions.

CONCLUSIONS

An applied magnetic field apparently can affect the energy output of a Leclanché cell in two ways, depending on the strength of the field. Below 2 kG, the data suggests a decrease in energy output for the cells drained with an applied field (see Appendix F). This could be caused by an increase in cell impedance due to a Hall effect (page 3).

At field strengths of 2.5 kG or larger, an increase in energy output is indicated (Appendix F). No well-grounded explanation has yet been developed and more work is necessary. Possibly, for large enough field strengths, the decrease in mobility of H^+ would permit a more active role for a secondary charge carrier.

The original problem of magnetic effects at a solution-metal interface is still unsolved. More work must be done in this area. The action at the zinc-electrolyte interface in the Leclanché cell was masked by the rate-determining step at the cathode.

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APPENDIX A

THE CALCULATION OF THE ENERGY OUTPUT AND THE AMOUNT OF CHARGE PASSED BY A LECLANCHÉ CELL

The energy output of the Leclanché cells in the cell discharge experiments is given by

$$E = \int P dt = \frac{1}{R} \int V^2 dt = \frac{1}{R} \sum_{k=1}^n \int_0^{\tau} V_k^2 dt \quad (12)$$

where the voltage-time plot of the experiment has been divided into n segments of width τ . R is the resistance load of the cell drainage experiments, V_k is the voltage as a function of time for segment k , and τ is the width of the segment.

Figure 20. In the calculation of energy output and charge passed, the voltage of the cell sets as a function of time is assumed to be in linear segments. Segment k is labeled.

If V_k is assumed to be equal to a linear function for each segment and V_i , V_f to be the initial and final voltages of those segments, then

$$E = \frac{1}{R} \sum_{k=1}^n \int_0^{\tau} V_k^2 dt \approx \frac{1}{R} \sum_{\text{all segments}} \int_0^{\tau} (V_i + (V_f - V_i)t/\tau)^2 dt \quad (13)$$

where...

$$V_k = V_1 + (\text{slope})(\text{time}) = V_1 + (V_f - V_1)t/\tau \quad (14)$$

Simple integration yields

$$E = \frac{\tau}{3R} \sum (V_f^2 + V_1 V_f + V_1^2) \quad (8)$$

summed over all segments. The charge passed is given by

$$Q = \frac{1}{R} \int V dt = \frac{1}{R} \sum_{k=1}^n \int_0^{\tau} V_k dt \quad (15)$$

$$Q = \frac{\tau}{2R} \sum (V_1 + V_f) \quad (9)$$

summed over all segments.

APPENDIX B

THE CALCULATION OF THE ENERGY OUTPUT AND THE AMOUNT OF CHARGE PASSED IN EXPERIMENT 9

In experiment 9, both sets of cells were wired in series with a common resistance load (see Figure 7). For this case, the energy output for the set of cells without the field is given by

$$\begin{aligned} E_A &= \int P dt = \int I V_A dt \\ E_A &= \frac{1}{R} \int V_R V_A dt \end{aligned} \quad (16)$$

where, at any time t , V_A is the potential difference across the cells, V_R is the voltage drop across R , and $I = V_R/R$ is the current.

As in Appendix A, the voltage-time plot has been divided into equal segments of width τ , and for each segment, the voltage is assumed to be a linear function of time. Therefore, we have for V_A and V_R ,

$$\begin{aligned} V_R &= V_{Ri} + (V_{Rf} - V_{Ri})t/\tau \\ V_A &= V_{Ai} + (V_{Af} - V_{Ai})t/\tau \end{aligned} \quad (17)$$

where for each segment, V_{Ri} and V_{Rf} are the initial and final voltages of the resistance load, and, V_{Ai} and V_{Af} are the initial and final potential differences of the cells drained without an applied magnetic field.

The energy output is then given by

$$E_A = \frac{\tau}{6R} \sum (2V_{Ri}V_{Ai} + V_{Ri}V_{Af} + V_{Rf}V_{Ai} + 2V_{Rf}V_{Af}) \quad (10)$$

where the summation is over all segments.

The expression for the charge passed by the same set of cells is given by

$$Q_A = \int I dt = \frac{1}{R} \int V_R dt \quad (18)$$

$$Q_A = \frac{\tau}{2R} \sum (V_{Ri} + V_{Rf}) \quad (11)$$

where the summation is over all segments.

The equations for the energy output and charge passed for the cells drained in an applied magnetic field are identical.

APPENDIX C

MAGNETS USED IN EXPERIMENTS

Magnet, Experiment D

Magnet II

Magnet III, IV
Edmund Scientific #30,730

Magnet I

- A...Varian model V-4007 electromagnet, with the pole pieces (six inch diameter) turned to provide a vertical magnetic field
- B...Polystyrene container in which the cells were placed, along with a mixture of water and ice to maintain constant temperature

APPENDIX D

INITIAL CALCULATIONS OF ENERGY OUTPUT AND CHARGE PASSED FOR THE FIRST 100 MINUTES OF EXPERIMENTS 5, 6, 7, 8, AND 9

Experiment 5

TIME (minutes)	ENERGY OUTPUT (joules)		CHARGE PASSED (coulombs)	
	FIELD	NO FIELD	FIELD	NO FIELD
0	0	0	0	0
1	407	270	72.8	59.7
2	756	508	140	115
3	1080	730	205	169
4	1390	939	269	221
5	1690	1140	331	272
6	1970	1330	392	322
7	2250	1520	452	372
8	2520	1700	512	420
9	2790	1876	571	468
10	3040	2050	629	516
20	5350	3600	1180	965
30	7160	4860	1660	1370
40	8570	5870	2090	1730
50	9700	6700	2480	2060
60	10700	7420	2830	2370
70	11600	8060	3170	2660
80	12400	8620	3500	2930
90	13100	9130	3800	3190
100	13800	9590	3970	3430

Experiment 6

TIME (minutes)	ENERGY OUTPUT (joules)		CHARGE PASSED (coulombs)	
	FIELD	NO FIELD	FIELD	NO FIELD
0	0	0	0	0
1	425	407	74.4	72.8
2	791	750	143	140
3	1130	1080	210	204
4	1450	1380	275	268
5	1760	1670	338	329
6	2060	1950	401	390
7	2350	2230	436	450
8	2630	2490	470	509
9	2910	2750	531	567
10	3180	3010	590	625
20	5640	5350	1160	1170
30	7680	7160	1670	1660
40	9340	8600	2140	2100
50	10700	9690	2560	2490
60	11900	10900	2950	2860
70	13000	11800	3330	3220
80	13900	12700	3680	3560
90	14800	13500	4020	3880
1000	15600	14300	4340	4200

Experiment 7

TIME (minutes)	ENERGY OUTPUT (joules)		CHARGE PASSED (coulombs)	
	FIELD	NO FIELD	FIELD	NO FIELD
0	0	0	0	0
1	428	373	157	146
2	743	649	290	271
3	1030	896	417	390
4	1290	1130	540	505
5	1540	1340	660	616
6	1780	1550	777	724
7	2000	1740	890	829
8	2220	1920	1000	932
9	2430	2100	1110	1030
10	2620	2260	1220	1130
20	4200	3560	2160	1990
30	5290	4440	2950	2690
40	6120	5090	3640	3310
50	6810	5590	4270	3840
60	7380	5950	4840	4290
70	7870	6220	5370	4690
80	8280	6410	5850	5020
90	8620	6550	6290	5290
100	8900	6650	6690	5530

Experiment 8

TIME (minutes)	ENERGY OUTPUT (joules)		CHARGE PASSED (coulombs)	
	FIELD	NO FIELD	FIELD	NO FIELD
0	0	0	0	0
1	362	324	143	136
2	628	562	267	252
3	870	779	384	364
4	1100	982	498	471
5	1310	1170	609	575
6	1520	1350	718	676
7	1720	1520	824	774
8	1900	1670	928	869
9	2090	1830	1030	962
10	2260	1970	1130	1050
20	3650	3130	2020	1870
30	4620	3950	2760	2550
40	5360	4600	3410	3160
50	5970	5150	4000	3720
60	6470	5620	4540	4240
70	6900	6020	5030	4720
80	7260	6380	5490	5170
90	7580	6700	5910	5590
100	7860	6970	6310	5990

Experiment 9

TIME (minutes)	ENERGY OUTPUT (joules)		CHARGE PASSED (coulombs)
	FIELD	NO FIELD	
0	0	0	0
1	360	359	54.3
2	684	681	105
3	992	985	155
4	1290	1280	204
5	1570	1550	252
6	1840	1830	300
7	2100	2090	345
8	2360	2310	391
9	2620	2560	436
10	2870	2810	482
20	5170	5090	916
30	7190	7060	1320
40	8980	8770	1700
50	10520	10200	2050
60	11820	11400	2380
70	13020	12500	1680
80	14120	13500	2970
90	15120	14400	3250
100	16020	15200	3520

APPENDIX E

ERROR ANALYSIS

Error in the calculation of the energy passed and in the amount of charge passed by the Leclanché cells in Experiments 1 through 26 may arise from 3 sources:

1. The value of the resistance load of the cells
2. The accuracy of the strip chart recorder in recording voltage and time passed
3. The substitution of a summation for an integral in the calculation of the energy output and of the amount of charge passed.

The resistance loads were known to within 1% except for experiments 7 and 8, where the values were given to 2%.

The strip chart recorder used (Houston Instruments Omnigraphic 2-3000) was accurate to $\pm 0.2\%$ for the voltage (full scale) and $\pm 0.1\%$ for the time.

The estimation of the extent of error due to the substitution of a summation for an integration (equations 8 and 9) was not straightforward. The summations were usually taken over time intervals of 10 minutes. To illustrate the possible inaccuracy, sample calculations were made of energy output for the cells drained without an applied magnetic field in Experiment 7. This experiment was chosen because it has a large initial voltage drop in the first few minutes of the experiment due to a low resistance load (1.05 ohms $\pm 2\%$). The energy output was calculated for the first 100 minutes according to equation 8,

$$E = \frac{\tau}{3R} \sum (V_f^2 + V_i V_f + V_i^2)$$

where τ is the size of the time interval. A comparison was made between the values obtained with $\tau = 10$ minutes and $\tau = 1$ minute. This will provide a rough estimate of the expected error in using a summation over intervals of 10 minutes instead of integration (the limit as $\tau \rightarrow 0$) in equation 8. Values of energy output were calculated for 10 minute portions of the experiment.

Portion of Experiment	ENERGY (joules)		
	minutes	minute	Percentage Difference
first 10 minute portion	2970	2280	30%
second	1300	1390	6.5%
third	873	970	1.0%
fourth	655	651	0.6%
fifth	447	449	0.5%
sixth	370	370	-
seventh	268	268	-
eighth	193	191	1.0%
ninth	135	133	1.5%
tenth	98	98	-

Except for the first 10 minutes of the experiment, the difference between the values for the energy using $\tau = 1$ minute and $\tau = 10$ minutes is less than 1% over the entire experiment. Because of the large difference in the first few minutes, experiments using low resistances loads (around 1 ohm) had the energy output and charge passed for the

first 10 minutes calculated with $\tau = 1$ minute. The error involved in calculating the charge passed is much less since it is proportional to only the first power of the voltage (see equation 9). All experimental calculations are therefore rated at 1%.

The magnitudes given for the field strengths used are accurate to a tenth of a kilogauss except for the ring magnets (III and IV in Table I). The field strengths for these last vary greatly but are approximately one kilogauss at their centers, increasing to about 2 kilogauss next to the inner surface of the magnets.

The temperature given for cells drained in an ice-water bath is 0°C and any variation due to atmospheric pressure or Joule heating is considered minimal. Experiments performed at room temperature are listed as 22°C and may vary within a degree. However, in all cases, the experiments were performed in pairs with one group of cells drained in a magnetic field and with the second group drained in an identical manner but without the applied magnetic field.

APPENDIX F
STATISTICAL ANALYSIS

In Table I are listed the results of 26 experiments. The experimental conditions of these, however, are widely varied.

In order to investigate the reproducibility of these results, those experiments performed under similar conditions were arranged in groups. The mean and standard deviations of the energy outputs of these similar experiments were then calculated.

Group 1 (as given in Table I)

Experiment No.	Field (kG)	Energy (joules)
2	4.5	12,900
	0	12,000
3	4.5	10,400
	0	11,500
4	4.5	12,000
	0	11,600

With field: mean E = 11,770 joules
 standard deviation σ = 1,270

Without field: mean E = 11,700 joules
 standard deviation σ = 265

Group 2 (data recalculated for only the initial 100 minutes)

Experiment No.	Field (kG)	Energy (joules)
10	1.5	1,240
	0	1,110
11	1.5	1,130
	0	1,320
12	1.0	1,430
	0	1,520
13	1.0	1,110
	0	1,120

With field: mean $E = 1,230$ joules
 standard deviation $\sigma = 147$

Without field: mean $E = 1,270$ joules
 standard deviation $\sigma = 194$

Group 3 (as given in Table I)

Experiment No.	Field (kG)	Energy (joules)
17	1.1	4,750
	0	4,630
18	1.1	4,620
	0	4,700
19	1.1	4,790
	0	4,860

With field: mean $E = 4,720$
 standard deviation $\sigma = 89$

Without field: mean $E = 4,730$
 standard deviation $\sigma = 118$

Group 4 (as given in Table I)

Experiment No.	Field (kG)	Energy (joules)
20	2.5	2,370
	0	2,340
21	2.5	2,400
	0	2,370
22	2.5	2,450
	0	2,310

With field: mean E = 2,410 joules
standard deviation σ = 40

Without field: mean E = 2,340 joules
standard deviation σ = 30

Group 5 (as given in Table I)

Experiment No.	Field (kG)	Energy (joules)
24	2.5	2,990
	0	2,860
25	2.5	2,860
	0	2,880
26	2.5	2,990
	0	2,870

With field: mean E = 2,925 joules
standard deviation σ = 92

Without field: mean E = 2,870 joules
standard deviation σ = 10

In all the above groups, the mean values have deviations that overlap. This is interpreted as a result of the variability of the individual cells. However, the data still strongly suggests an influence of the energy output due to the presence of an applied magnetic field. This is more clearly seen by considering those experiments in which the field used is less than 2 kG. For these experiments, 70%

(7 out of 10) show a negative effect on the energy output. For the experiments with $B \geq 2.5$ kG, 75% (12 out of 16) show a increase in energy output.

EXPERIMENTS PERFORMED WITH $B < 2.5$ kG
(from Table I, page 12)

Experiment No.	Number of cells in each set	Percentage increase in energy output
10	3	-0.6%
11	3	-5.5%
12	3	-2.2%
13	3	-3.9%
14	2	+0.6%
15	3	-11%
16	6	+7.4%
17	6	+2.6%
18	6	-1.7%
19	6	-1.4%

EXPERIMENTS PERFORMED WITH $B \geq 2.5$ kG
(from Table I, page 12)

Experiment No.	Number of cells in each set	Percentage increase in energy output
1	6	+12%
2	1	+7.4%
3	1	-9.6%
4	1	+3.4%
5	6	-0.3%
6	6	+27%
7	6	+46%
8	6	+24%
9	6	+47%
20	3	+1.3%
21	3	+1.3%
22	3	+6.1%
23	3	-1.4%
24	3	+4.5%
25	3	-0.7%
26	3	+4.2%