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Report on

Heat Balance Studies on Submarine Storage Cells.

for

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
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by

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ABSTRACT

Heat balance studies have been made on a WLH-29 Ironclad cell to determine the magnitudes of all heating and cooling effects and to determine the effect of these magnitudes on cell temperature both in the free electrolyte above the elements and at various other locations in the cell. The studies include a complete survey of the cooling effects associated with cell ventilation.

It has been found that the main sources of heat in the early stages of the charge are the reversible heat effect of the charging reaction and the irreversible heat due to the I^2R drop in the cell. During the latter stages of the charge when gassing is pronounced, the main source of heat is due to the heat of formation of molecular hydrogen and oxygen from the atomic gas produced from the current. Ventilating air is not an important factor in reducing cell temperatures, either from the standpoint of evaporation or direct conductance. The reversible heat effect of the gassing reaction is an important cooling effect during the gassing phase of the charge.

There is little temperature change from place to place in the cell during charge. The small temperature difference found in the early stages of the charge disappears when gassing sets in. This equalization in temperature parallels the equalization of gravity. Highest temperatures found are in the center of the cell. Maximum differences average about 8° Fahrenheit.

SECTION 4 - INTRODUCTION

4-a. AUTHORIZATION

1. This problem was authorized by Bureau of Engineering letter SS/S62 (2-20-D1) dated 21 February 1934.

4-b. STATEMENT OF PROBLEM

2. The purpose of the problem was to determine the heat balance relationships in a lead-acid storage cell during charge. The complete solution of this problem should give the magnitudes of all heating and cooling effects. It should therefore explain temperature phenomena encountered in battery charging on shipboard in submarine installations. It should give proper insight into temperature effects within the cell and should determine the value of temperature readings as normally obtained from the cell top during the charging cycle.

3. The work was carried on by the author at the Naval Research Laboratory during the periods: June 1 to 10 and July 20 to September 20, 1934. Certain of the calculations were made between these periods and after the completion of the experimental work.

4-c. EXPLANATION OF REPORT

4. In submitting this report, it is desired to point out certain factors in connection with its general form. The Theory of the Lead-Acid Cell, Section 5-a, was included only for the purpose of bringing out certain things directly bearing on this report rather than a discussion in full of the theory of the cell reaction. A complete discussion was not thought pertinent to the report. The same remarks apply to Sections 5-a and 5-c, Theory of the Gassing Phase of Charge, and Practical Considerations in Cell operation.

5. Table 1 gives the conversion units used in the calculations and the mathematical formulas used for the calculations. Section 6-c discusses the manner in which the calculations were made. These are included to enable the reader to check certain of the data if he so wishes. Not all intermediate data are included as these would make the report entirely too bulky.

6. Considerably repetition exists in certain sections of the report, for example in Sections 8 and 9, Discussion of Results and Conclusions. While this adds to the length of the report, it was thought advisable to follow the plan employed in order properly to clarify the sections.

7. As far as possible, data were taken from the Chemical Engineers' Handbook.

SECTION 5 - THEORETICAL AND PRACTICAL CONSIDERATIONS

5-a. THEORY OF THE LEAD-ACID STORAGE CELL.

8. While there is some question as to the actual mechanism of the ionic changes in the lead-acid storage cell, the potential relationships have been completely worked out by Harned and Hamer at Yale University (N.R.L. Report No. P-1071 dated 14 September 1934). It does not seem necessary in this report to discuss the cell reaction or the potential magnitudes. However, in the work undertaken, the energy relationships are most important. This discussion is included, therefore, to bring out the heat changes accompanying cell charge and discharge.

9. A storage cell stores electrical energy by reason of the chemical reactions taking place at the electrodes. On charge the electrical energy is converted to chemical energy and on discharge the chemical energy is changed back to electrical energy. However, the chemical energy is not equal to the electrical energy in exact magnitude. This can be demonstrated experimentally by charging and discharging a storage cell in a calorimeter so that exact temperature and heat effects can be noted. It is found that the cell cools on discharge and heats on charge. This means that the cell delivers on discharge more electrical energy than that furnished by the heat of the reaction. This extra energy is absorbed from the surroundings. Conversely on charge less chemical energy is stored than electrical energy put in, and therefore energy is lost in the form of heat to the surroundings. It is this last magnitude in which we are interested in this work, inasmuch as it is a contributing factor to the increase in cell temperature during charge. This heating effect is referred to as the reversible heat effect as opposed to the irreversible heat effect due to the resistance drop in the cell. With both charge and discharge, the irreversible heat effect is positive, that is, the cell is heated because of it. On the other hand, the reversible heat effect is positive on charge but negative on discharge.

10. The relationship between the various magnitudes discussed above is given by the thermodynamic equation known as the Gibbs-Helmholtz relationship. This is derived from the First Law of Thermodynamics which may be written in one form as follows:

$$Q = W + q \qquad (1)$$

In this equation Q is the change in the total energy of the cell or the heat of the reaction; it is usually expressed in calories. W is the available work produced. In the discharge it is the electrical energy produced. q is the heat change; it may be either negative or positive. For cell charge it is negative. That is to say, part of the electrical energy put into the cell goes into chemical energy and part is evolved as heat. By means of thermodynamic relationships which will not be discussed here, there is derived the Gibbs-Helmholtz equation, which is very useful in connection with considerations of the storage cell. One form of this relation is:

$$\frac{Q}{23{,}070\ n} = E - T\ \left(\frac{dE}{dT}\right) \qquad (2)$$

In this expression, Q is the heat of the reaction in calories, E is the electromotive force of the cell, T is the absolute temperature, n = 2 for the lead-acid cell, and dE/dT is the change of electromotive force per degree Absolute. The term 23,070 is a constant for all electrolytic cells.

11. Now either equation can be used to calculate the reversible heat effect. In (1) it is necessary to know the heat of the reaction Q and the electrical energy associated with the reaction:

$$Pb + PbO_2 + 2H_2SO_4 = 2PbSO_4 + 2H_2O$$

at the particular gravity of acid used in the cell. Such a calculation is made by Vinal on page 166 of his textbook on Storage Batteries. A value of 5,595 calories is obtained.

12. Or if (2) is employed, it is necessary only to evaluate the last term and then to multiply by 23,070 x 2. This involves only a knowledge of dE/dT, the rate of change of the potential at the temperature T. Vinal does not employ this method to calculate q, but he does use the value of q obtained above the calculate dE/dT. The value obtained is approximately equal to the average value of dE/dT given in the table on page 170 of his book. However, it is pointed out that while the average agrees very well with the calculated value, it does not agree with the average value obtained for temperatures from 0-25°C. Nor does the calculated value agree with the dE/dT values of Harned and Hamer which agree substantially with those of the table of Vinal. If, then, the dE/dT average value obtained from measurements from -70 to +25°C be used, the value calculated would agree with the value obtained from (1). But if values of dE/dT be used for the range 0-25°C, the value of q so obtained would be only about one-half the above magnitude.

13. It is impossible to say which is the more correct value. It is to be remembered that thermodynamic calculations apply to systems operating reversibly, a condition never found in actual practice. This subject might well be checked experimentally to throw further light on the calculations. In this work we have used the value of 5,595 calories. The use of this value gave results which agree on the whole with the results of the tests. It should be pointed out that this magnitude of heat is evolved on charge when two mols (a mol being the molecular weight in grams) of lead sulphate is changed to the active material. It is important only with large charging currents and becomes small in value as the charging current is reduced in magnitude and the gassing current increases.

5-b. THEORY OF THE GASSING PHASE OF CELL CHARGE

14. While the theory of the fundamental cell reaction and the operation of the cell while charging normally is fairly well understood and fully discussed in books on storage batteries, the theory of the gassing phase of cell charge is barely mentioned. It is, of course, recognized that gassing takes place even on open circuit, but no explanations have been advanced as to the evolution of the gas nor are any thermodynamic discussions bearing directly on the problem to be found.

15. It can be computed thermodynamically that at 25°C the electrolysis of water should produce hydrogen and oxygen gas at 1.23 volts when inert electrodes are used. By inert electrodes is meant electrodes that do not react with the ions when they are discharged. We speak of

this voltage of 1.23 as the reversible decomposition potential of water or the equilibrium reaction potential. Now, if more than one electrochemical reaction is possible in an electrolysis, the one with the lowest potential should predominate over the others. If this be true, the charging of a storage cell might be expected to result in the electrolysis of water with the production of hydrogen and oxygen gas rather than in the destruction of the lead sulphate. This, of course, is because the potential of the lead cell is approximately 2 volts (depending on acid gravity, temperature, etc.). However, such does not prove to be the case at ordinary temperatures with the usual gravities of acid in the absence of impurities. It will be well to consider the reasons why the expected water electrolysis does not take place. Let us consider the lead plate and the reaction which may take place on its surface. If hydrogen be produced, the electrode reaction may be written as follows:

$$H^+ + \text{Electron} = H$$

$$H + H = H_2$$

The hydrogen gas as evolved has the formula H_2. It is to be noted that it is not formed simultaneously with the discharge of the hydrogen ion. The above are written in two steps to emphasize the fact that monatomic hydrogen is first formed and then this form reacts to form molecular hydrogen. That these two steps are actually separated in the case of a number of electrode materials has been amply demonstrated by chemical experiments. Now the velocity of the second reaction is affected greatly by the nature of the electrode material. In general, the softer the metal the slower is the reaction, and with such metals there is an accumulation of monatomic gas on the electrode. The accumulation of monatomic gas increases the potential necessary to discharge the hydrogen ion. This increase of potential is spoken of as the overvoltage. It must be added to the equilibrium reaction potential in order to compute the actual potential necessary to evolve the gas.

16. The same general considerations apply to the evolution of oxygen from the peroxide plate. However, we do not know just what electrode reaction takes place to produce the oxygen. In fact, we do not know whether the oxygen is produced from the lead grid or the peroxide plate. Whatever takes place, the fact remains that there is an oxygen overvoltage factor that must be added to the equilibrium reaction potential just as in the case of the hydrogen gas at the lead electrode.

17. The addition of the oxygen hydrogen overvoltages, as discussed above, to the 1.23 volts gives a potential sufficiently high to be above the reaction potential for the normal or fundamental cell reaction. In fact, the magnitudes as given in the texts give a potential above that at which gassing actually takes place. The explanation, of course, is that the values as given for hydrogen and oxygen overvoltages are for sheet electrodes and not the finely-divided material found in cell plates. With the finely-divided material, the olvervoltage values are undoubtedly much below the values for sheet or plate electrodes.

18. During the latter stages of the charge, the gassing process supplants to a great extent the normal reaction. In fact, then, the cell actually becomes a hydrogen oxygen cell. When the circuit is broke, the

gas passes from the plates and the potential then falls back to that of the lead and lead peroxide magnitudes. Of course, gassing takes place at all stages of the charge to some extent. In fact, gassing takes place on open circuit. This is due partly to local action and partly to different potentials from place to place on the plates. Undoubtedly other factors come into play which are not at all understood.

19. If the mechanism of gas production as outlined above is true, then any heat effect characteristic of the formation of the molecular gas from the monatomic gas (second stage of gas evolution) should, if large enough in magnitude, have an effect on cell temperatures. The heat effect is very large indeed, as is shown in the section on the explanation of the calculations, and this must be computed in the heat changes properly to explain the large heat evolution accompanying the gassing phase of the cell charge.

20. It should, of course, be mentioned in this connection that the amounts of hydrogen and oxygen do not necessarily have to be the same, as the positive and negative plates may be in different states of charge.

21. Just as we have a reversible heat effect with the normal reaction, as explained in Section 5-a, so we have a similar effect with the gassing reaction (water electrolysis). Unfortunately we have only very meager data for calculating this magnitude. The potential of the cell is, of course, the sum of the potentials of the two electrodes, the hydrogen on lead, and the oxygen on lead or lead peroxide. We have sufficient data to calculate the manner in which the hydrogen electrode changes with temperature in solutions of various concentrations of hydrogen ions. However, we have practically no data for the oxygen electrode. Lewis and Randall, in their book on Thermodynamics (see bibliography),give free energy equations for calculating this magnitude. However, the calculations are much involved and the wrter would not care to put too much confidence in the calculated value. In Section 5-d there is discussed a series of experiments conducted at the New York Navy Yard which indicate that the potential decreases with increasing temperature. It will be recalled that the reverse is true of the normal reaction at ordinary concentrations and temperatures. Consequently, the effect for the water electrolysis will be a cooling one. The magnitudes, as shown in the report from the New York Navy Yard experiments, were used in the calculations of this report, as discussed more in detail in later sections.

22. Of course, pronounced gas evolution produces a rapid equalization of gravity and also serves to equalize temperatures at various parts of the cell.

23. One other point should be mentioned in this Section. The evolution of hydrogen and oxygen gas produces water loss in the electrolyte. Since we do not know just how the ionic action takes place, we do not know just where the water loss takes place. If this loss should be more or less localized, it would produce gravity differences in the electrolyte. Such differences would result in diffusion effects, which in turn would produce heating effects. It is not thought that such effects can be of very large magnitude, even if they exist.

5-c. PRACTICAL CONSIDERATIONS IN CELL OPERATION

24. Besides the theoretical considerations discussed in (a) and (b) of this Section, it seems advisable to consider briefly certain matters of a practical nature connected with cell operation which are pertinent to the proper interpretation of the results given in this report.

(a) Temperature Effects. In charging operations, a certain maximum temperature is permitted. As is seen from an inspection of charging data from shipboard operation, there is a large rise in temperature at the beginning of a charge. This rise falls off as the charging current is decreased, but increases rapidly again when gas evolution becomes pronounced. This same phenomenon was found in the work reported and an explanation of the effect is given. It should be noted that this rise during the gassing phase has been thought due to mixing of hot electrolyte from the interior of the cell with the cooler electrolyte at the top. Later in this report this point is discussed and it is brought out that this explanation cannot be correct.

(b) Cooling Effects from Ventilation. It has been generally considered in charging operations on submarines that ventilation is a very effective means of keeping cell temperatures from being excessive. Its effect is due, of course, to evaporation of water from the electrolyte and to direct thermal flow to the cooler ventilating air. This report shows that ventilation can not be an important factor in cell cooling.

(c) Hydrogen Evolution. In operations in tropical waters, hydrogen evolution is much more pronounced than in colder waters when a low gravity acid is employed. This is due to the effect of temperature on the decomposition potential of water, as explained in 5-b. This report does not throw any light on the temperature-gassing-gravity-voltage relationships, but one of the major cooling effects in the later stages of the charge, when gassing is pronounced, is due to the reversible heat of water decomposition. That gassing is important from the standpoint of temperature rise has been discussed in (a) above.

(d) Heat Loss by Interchange with Surroundings. As far as the author is aware, no information is available that throws light on the heat loss from a cell by interchange with the cell surroundings: air space around cells, loss through sides of ship, etc. It is thought that this loss cannot be very great, although the question cannot be properly answered without experimental work on shipboard. Heat loss to ventilating air has been mentioned in (c) above.

(e) Gravity Considerations. It is known that the gravity of the electrolyte varies with its height within the cell. It is logical to assume that the gravity within the active material is different from that in the main body of the electrolyte. Certainly, then, the mixing of the electrolyte from diffusion, convection, or by mixing from gas evolution must result in some heat generation. Just what this magnitude would be is hard to estimate. Until more is known as to how the gravity varies within the cell, this problem cannot be solved. This is discussed further in a later section of the report.

5-d. PRIOR WORK ON PROBLEM

25. No prior work exists bearing directly on the problem of heat balance studies in storage cells. Theoretical discussions are, of course, found in all texts on storage batteries concerning the reversible and irreversible heat effects due to the normal reaction (see bibliography). However, no work is available on the reversible heat effect due to the gassing reaction. Vinal and Blum, in a paper before the Electrochemical Society in October, 1934, discussed the magnitudes of the polarization effects in lead-acid cells, but, as stated by Mr. Vinal to the author, the purpose of the paper was to define terms and not to present data. Dr. Vinal stated that the data given should be considered as only qualitative in nature. This paper is recommended to anyone who wishes a detailed discussion of the terms used in electrolysis phenomena associated with cells and electrolytic baths. (For reference see bibliography.)

26. Submarine charging data, of course, furnish figures which show in general how temperatures change during a charge. These data show that the gassing phase is characterized by rapidly increasing temperatures.

27. There has been conducted at the New York Navy Yard a series of tests to determine the best charging voltages for Tudor Submarine cells. The results of these tests were presented in a report entitled: Report of Test on Charging Methods on Tudor Type 20-POR-820 Submarine Storage Cells, Test No. 2527A, 2 July 1934. These tests have brought out certain points which are of interest in connection with heat balance studies. In that work cell temperatures were maintained as near as possible to 60, 80, 100 and 120°F. This was done by immersing the cells in tanks of water heated electrically. It was found that with both 1210 and 1280 acid the gassing voltage decreased .05 volts per twenty degree Fahrenheit interval. For the two gravities, the gassing potentials were the same and had the following values: 60°-2.40 volts, 80°-2.35 volts, 100°-2.30 volts, 120°-2.25 volts. Of course, the current magnitude has some effect on these gassing voltages. It is also to be observed that the temperature-current data show that when gassing is pronounced, the temperature of the cell begins to rise rapidly. Of course, it was impossible to keep the temperatures of the cells exactly constant. Furthermore, the tests were not conducted specifically to determine temperature data. The values for the gassing voltages from these tests were used in this report for calculating the reversible heat effect for water electrolysis.

28. No tests have been conducted heretofore to determine temperatures at various parts of the charging cell. However, the Electric Storage Battery Company has conducted tests to show the gravity relationships at various parts of the electrolyte during charge and discharge. For reference see bibliography.

SECTION 6 - EXPERIMENTAL PROCEDURE

6-a. APPARATUS

29. The tests reported in this report were made on an Exide WLH-29 Ironclad cell furnished by the Electric Storage Battery Company. The specifications are given in Table 2, together with the data and computations involved with the calculation of the heat capacity of the cell. The cell was

enclosed in two Celotex boxes so construction that the first, or inner, box fitted snugly around the cell. The second, or outer, box was so constructed as to give an air space approximately 4-1/2 inches in depth between the inner and outer box. The cell was placed on a platform approximately 8 inches above the floor of the laboratory. The inner box was painted with black paint and the outer box was painted with aluminum paint in order to cut down radiation heat losses. Within the air space were located four strip heaters so wired that heating currents equal to the expenditure of 125, 500, 750, and 1000 watts could be used. Equalization of temperature within the air space was effected by means of two small electric fans. These fans gave an energy expenditure of 44 watts each. Tests proved that temperature equalization was maintained and regulated in the air space with perfect efficiency. By means of the heating system, temperatures within the air space could be maintained at any desired value. This permitted the charge to be carried out adiabatically, that is, without heat loss due to radiation, or not, as desired. Suitable openings were placed in the top of the boxes for the terminal leads, air inlet, ventilation outlet, thermocouple openings, etc. On the side,at the top and bottom were placed rubber stopcocks held in place by means of Bakelite plates which connected to similar stopcocks in the side of the cell. These were used for the tubes for the NRL Battmeter. The stopcocks in the cell jar and the Celotex outer box were connected by rubber tubing. The outside dimensions of the outer box were 60" x 36" x 36".

30. Ventilation was by means of a motor-operated blower connected to the cell top by means of a duct averaging something over two inches in inside diameter. Most of this duct consisted of hard rubber tubing, but two lengths of glass were included, in addition to a section of glass tubing constructed for holding wet and dry bulb thermometers. Since readings were not made with these, the details of this part of the apparatus will not be included. One section of the glass tubing merely served as a connection with the outlet on the gooseneck of the cell top and the remainder of the ventilation duct. The other contained three sealed-in glass stopcocks which were employed to draw off samples of the duct air for purposes of analysis for moisture.

31. Air flow was measured by means of a differential pressure membrane indicator operating from outlets on either side of an orifice plate in the ventilation duct. The air flow meter was calibrated by means of a Sargent Wet Test Meter.

32. The moisture content of the air at the induction and in the ventilation duct after passage over the cell top was obtained by an absolute method, namely by chemical analysis. Liter samples were used. Two-liter Erlenmeyer flasks were connected at their tops to the U-tubes which held the absorbent for the moisture. These U-tubes were in turn either left open to the air or connected to the stopcocks mentioned in the preceding paragraphs, depending, of course, upon whether it was desired to obtain the moisture content of the air before or after passing over the electrolyte. The Erlenmeyer flask was filled with water and the desired volume of air was drawn through the U-tube by allowing water to run by gravity from the bottom of the flasks through glass stopcocks into graduated cylinders. Proper precautions were, of course, taken to prevent absorption in the tubes of water from the Erlenmeyer flasks. The absorbent used was magnesium perchlorate, which is marketed under the trade name of Anhydrone. All weighings were

made on an analytical balance with properly calibrated weights. The alternate method, that of using wet and dry bulb thermometer readings for determining moisture content in the duct, proved very unsatisfactory.

33. The current was measured on a Leeds and Northrup Micromax Recording Ammeter. Voltages were determined on a Leeds and Northrup Recording Voltmeter. These instruments were supplemented by a properly calibrated precision ammeter and voltmeter.

34. Gravities were obtained by means of an NRL Battmeter through stopcocks in the cell jar, as discussed above. Hydrometer readings were also taken on samples withdrawn from the top and bottom of the electrolyte through the stopcocks used for the Battmeter connections. For this purpose, the tubes to the Battmeter were temporarily disconnected.

35. Hydrogen percentage in the duct air was obtained from readings with a properly calibrated NRL Hydrogen Detector.

36. Temperature readings of the air at the induction and in the ventilating duct were obtained by means of mercury thermometers. Thermometers were also used for measuring the temperature of the acid samples withdrawn from the stopcocks in the side of the cell. Thermocouples were used for temperature measurements in the electrolyte and at various places in the air space between the insulating Celotex boxes around the cell. These couples were constructed of insulated constantan wire and bare copper wire. These wires were threaded through small rubber tubing, and the ends connected for the couple were plated with Vultex rubber cement to protect the wire from the corrosive action of the electrolyte. The other ends of the couple wires were connected to the distributor bar of a rotary Leeds and Northrup Thermocouple Switch. An ice-water mixture was used as the cold junction. The EMFs of the couples were measured with a Leeds and Northrup Pyrometer Potentiometer and the temperature then obtained from a potential-temperature chart. This chart was obtained by calibrating the couples at several temperatures.

37. The charging current was furnished by a motor generator set.

6-b. METHODS OF TEST

38. Tests were conducted both according to the Bureau and the Manufacturer's charging procedure. Certain tests were conducted adiabatically, some non-adiabatically, and some with partial heating of the air space between the insulating boxes. In some of the charges data were collected at fifteen minute intervals, in others at 30 minute intervals. In this report, only data for thirty-minute intervals are given, except in certain cases where the use of more frequency data was advisable. This condensing of data was done in order to keep the report from becoming too bulky.

39. The anlytical data for moisture content of ventilating air are given for thirty-minute intervals, although much more frequenct values were determined, but again it was not thought their inclusion would add to the value of the report.

40. In most tests, data were obtained for: current, voltage (both on open circuit and closed circuit), hydrogen percentage, air flow, room temper-

ature, moisture content of air both before and after passage over electrolyte, gravity readings both with NRL Battmeter and by hydrometer readings in acid samples withdrawn from the Battmeter stopcocks in the side of the cell, temperature readings at various points in the electrolyte, and temperature readings at various phases in the insulating boxes. Potential readings at different charging currents and on both open and closed circuit permitted the calculation of the I_R drop in the cell.

41. Tests were also conducted on certain of the discharges. Certain of these data are included. Tests were also made to determine heat losses due to radiation from the cell system to the surrounding air. This loss could thus be corrected for in the non-adiabatic charges.

6-c. EXPLANATION OF CALCULATIONS

42. In the presentation of the data and the calculation of the various heat effects, it has been decided to compute heat effects on the basis of the minute as the unit of time. The figures are given in calories per minute only, except in the case of charges Nos. 9 and 10, in which the figures are given in wattage as well as calories.

43. In all calculations involving gases the perfect gas law:

$$PV = NRT$$

is assumed to hold. In this formula P = pressure, V = volume, N = number mols. (total grams divided by molecular weight), T = absolute temperature, and R is a constant expressure in proper units depending on the units for P and V. The methods used in making the individual calculations follow.

(a) Irreversible Heat Effect (IR drop). This magnitude was obtained in two ways. For certain of the tests the current was broken and the difference between the voltages on open and closed circuit was multiplied by the current. For other tests, the two voltage values for two different values of current were used to compute the resistance of the cell. The product of I^2R gave the desired heat effect. Of course, this term so obtained would be in electrical units and would have to be corrected to calories. Table 7 gives the values used. The resistance of the cell would, of course, vary with the state of the charge and from charge to charge, but the variation was not great and the magnitude of the I^2R effect is not great enough for small currents to permit the use of average values of R. Table 1 gives the conversion units used.

(b) Reversible Heat Effect for Normal Reaction. This magnitude was obtained by determining the number of mols of lead sulphate destroyed per minute and multiplying by 2,800 calories. This is half the magnitude of the reversible heat effect for the complete reaction in which two mols of lead sulphate are destroyed. The number of mols of lead sulphate destroyed is determined by converting the ampere-seconds for one minute to Faradays and subtracting the amount of this current which goes to gassing. This is calculated from the air flow and the hydrogen percentage. As is seen in Table 1, one Faraday destroys half a mol of lead sulphate at each electrode.

(c) Calculation of Moisture Content of Air. The formulas for this calculation are given in Table 1. It is to be noted that the moisture increase, that is, the amount of water evaporating from the electrolyte, cannot be determined directly by subtraction of the water content for a given volume of air at induction and in the duct. This is because the volume undergoes expansion when it becomes heated in passing over the electrolyte. A correction must be made for this expansion, as shown in the formula.

(d) Calculation of Heat Loss to Ventilation Air by Direct Interchange. To compute this magnitude it is only necessary to multiply the cubic feet of air in a given time by the heat capacity per cubic feet and by the temperature rise. The heat capacity for air is given in Table 2. It is to be noted that the moisture content of the air affects the heat capacity to only a negligible amount. In the calculations it was therefore assumed to be constant and an average value was used. It is also to be noted that it is little affected by temperature change.

(e) Calculation of Heat Loss by Evaporation. This was calculated by determining the loss per minute in grams from the electrolyte and multiplying by 577 calories, the latent heat of evaporation of one gram of water. See Table 6 for this magnitude. It is noted that its value changes slightly with change in gravity of acid.

(f) Calculation of Heat of Formation of Molecular Hydrogen and Oxygen. The heats of formation of molecular hydrogen and oxygen are approximately 105,000 and 131,000 calories per mol. For the gas from the destruction of 1 mol of water this would give a combined value of 170,000 calories. This is accurate to only about 5 per cent. The value for the heat from the heats of formation was obtained by calculations the mols of hydrogen evolved per minute, and multiplying by 170,000 calories. It is to be remembered that there is one mol of water electrolyzed for every mol of hydrogen evolved.

(g) Reversible Heat Effect for Water Electrolysis. From the hydrogen percentage was calculated the number of mols of water electrolyzed per minute. The reversible heat for water electrolysis was obtained from the dE/dT value from the New York Navy Yard experiments as discussed in 5-d. Table 1 gives the formula for making the calculation. The calculation, of course, involves the evaluation of the third term of the Gibbs-Helmholtz equation. The value per mol of water was taken as 34,000 calories. Its sign is such as to produce cooling on charge.

(h) Calculation of Heat Capacity of Cell. This was made by taking the total weights of each component making up the cell and multiplying these weights by the heat capacities of the individual substances. These computations are given in Table 3. It should be noted that the heat capacity changes with the state of charge, since lead sulphate has a different heat capacity from lead and lead peroxide. This factor will make the heat capacity of the WL-29 cell used approximately 1200 calories greater at the beginning than at the end of the charge. Moreover, the heat capacity of the electrolyte is different in the low gravity acid at the beginning of the charge than it is in the 1280 acid at the end. This factor will make the heat capacity greater at the beginning of the charge. Unlike the effect of the lead sulphate, it is not easy to calculate the amount of this difference. At the beginning, the gravity varies from place to place in the cell and is probably quite different in the active material. Rough calculations from thermodynamic data lead to the conclusion that as much as 10,000 calories difference may exist. This is based on considerations of the difference in heat capacity as calculated from thermodynamic magnitudes and the difference in weight of electrolyte at the beginning and end of the charge due to gravity differences. In all calculations in this report the value 52,110 calories per degree Fahrenheit corresponding to 93,800 calories per degree Centigrade was used as the heat capacity. This is justified because the acid gravity within an hour of the start of the charge takes a value which gives a heat capacity close to that used. Also, by the end of the second hour one-half the lead sulphate has been converted to active material. Therefore, any error introduced is mainly in the first and second hours. The error is about ten percent for this period.

The calculations of the heat capacity is rendered difficult because of the cell jar. Rubber has a high heat capacity, but the heat capacity of the hard rubber used in the jar is not known. Moreover, the jar temperature on the whole is below that of the cell, except when the charge is carried out adiabatically. In that case, the jar is just as likely to heat from the outside as from the inside. It was therefore decided to compute the heat capacity at one third the value for pure para rubber. This introduces an element of uncertainty of some magnitude.

The only accurate method of determining the heat capacity is to make calorimetric tests with the cell. However, this would involve considerable experimental detail and time was not available for the determination.

7-a. DATA OBTAINED

44. Data were obtained from ten charges. In addition, certain discharge tests were made and certain other experiments were carried out to determine radiation losses, to test efficiency of procedures, etc. The data for these ten charges and for certain of the discharges are given in this Section. In most cases complete gravity, temperature, and evaporation data are included. However, in connection with temperature only group values are reported, except for the last three charges, for the thermocouple values in the cell. These group values are representative and accurate. Charges 1, 2, 3, 4, 7, 7B and 8 are non-adiabatic. The remainder are adiabatic. However, the heating current in the cell box was not sufficient to completely prevent radiation from the cell through the box in charges 5 and 6. Charges 7, 8, 9 and 10 are considered superior to the others from the standpoint of the accuracy of the data. It is to be noted that in all charges the ventilating fans contribute 88 watts heating effect to the cell box.

45. All energy values are given in calories per minute. In charge No. 9 the values are also given in watts per second.

46. Moisture data are given in terms of grams of water per liter and in grams of water per 100 cubic feet. This last value enables one to note the approximate humidity of the air by referring to Table 5.

47. Plate I gives the grouping of the thermocouples.

48. The actual rise in the cell temperature is not always easy to determine exactly. This is due to the fact that quite often the temperatures at the start of the charge vary with the different locations of the couples. The estimated rise can be exactly computed by plotting the heat effect per minute against the time and graphically integrating the area under the curve. In most of the charges an approximate estimate of the rise was made. Plate IV gives the plotting method for charge 9.

49. Further discussion of data obtained is given in Section 8, "Discussion of Results".

7-b. STATEMENT OF ERRORS

50. (a) Temperatures. All temperatures, whether expressed in degrees Centigrade or Fahrenheit, are accurate to 1°. Readings were made with thermometers and thermocouples to fractions of degrees, but in the data submitted in this report there are expressed in even figures. All thermometers were properly checked.

(b) Current and Voltage Readings. Current and voltage readings were made on the recording instruments and checked on precision instruments. An accuracy of .02 volts was easily attained. Current values are accurate to 10 amperes. The above make the calculation of the irreversible heat very accurate. Of course, average values for the cell resistance or the voltage drop in the cell were used. These values change quite rapidly near the end of the charge when the gassing becomes heavy, as can be seen from the open and closed voltage values in charges 8 and 9, but the total value of the irreversible heat is so small in comparison to other effects in the latter stages of the charge that no appreciable error is introduced by the use of average values.

(c) Moisture Loss to Ventilating Air. The moisture analysis was quite accurate. The water content of one liter of air in grams could be checked to .0003 grams. This, combined with the accuracy in measuring temperatures, makes the evaporation loss data almost exact. The radiation loss to the ventilating air is accurate to 14 calories, the heat capacity of 1.92 cu.ft.; in other words, the accuracy is that of the temperature measurement, namely 10°F. The value of the heat capacity of air changes with moisture content, but the change is very small, as can be seen from Table 2. Also, the heat of vaporization changes with acid gravity, but, as is seen from Table 6, the value changes by only .2% for a ten percent change in acid concentration.

(d) Reversible Heat. Normal Reaction. The calculation of the total mols of lead sulphate from the current and the hydrogen percentage is limited in accuracy to the hydrogen calculation. The total number of mols (lead sulphate changed and water electrolyzed) is as accurate as the measurement of the current. However, the hydrogen percentage is not accurate as determined by the hydrogen detector in most cases. In the data submitted, the hydrogen percentage in the earlier charges is probably in error to a considerable extent. This error is no doubt positive in value, the hydrogen evolution probably being less than recorded. This makes the reversible heat too low. But the total amount of the reversible heat is small when hydrogen percentage is large, that is, when charging currents are small near the end of the charge. It is therefore thought that the reversible heat due to the normal reaction is very accurate. In the last four charges the hydrogen percentages recorded are quite accurate. In these charges the reversible heat and heat of formation of gas are quite accurate.

(e) Reversible Heat. Electrolysis of Water. The statements above in regard to hydrogen percentage apply here also. In addition, it is recalled that the magnitude of the reversible heat for water electrolysis is not available. As discussed in Section 6-c, "Explanation of Calculations", the value used was obtained from the data of the experiments at the New York Navy Yard. The values given in the data are very much in question.

(f) Heat of Formation of Gases. The statements concerning the hydrogen percentage apply in this case. The value for the heat of formation of molecular hydrogen and oxygen from the monatomic gases is thought to be accurate to five percent. This value becomes quite large in magnitude towards the end of the charge so that a considerable error may be introduced.

(g) Calculation of Heat Capacity of Cell. The calculation of this magnitude with possible errors was discussed fully in Section 6-c, "Explanation of Calculations". The value of 52,110 calories per degree Fahrenheit is probably quite accurate for adiabatic charges. However, as explained in 6-C, it is probably in error when used for non-adiabatic procedures. This results in a greater estimated rise due to the smaller value of the heat capacity.

(h) Gravity Readings. These are very accurate, but as they play no part in the heat calculations, they will not be discussed.

8. DISCUSSION OF RESULTS

General Temperature Characteristics

51. An inspection of the data for the charges conducted brings out certain general points. The calculated rise is from 30-35° Fahrenheit in magnitude for a regular charge. There is little difference in the calculated rise for the Bureau and manufactuer's charging procedures. The rise as actually found varies from approximately half this magnitude to the calculated amount depending, of course, on how completely adiabatic the charge is made. Charges 9 and 10 are completely adiabatic and the actual increase is found to be almost exactly equal to the rise as calculated. It is to be noted that on the whole the manufacturer's procedure gives an actual rise nearer the estimated rise than is the case with the Bureau procedure. This is probably due to the fact that gassing is slightly more pronounced in the former type of procedure and small positive errors in heat effects involved with gassing would introduce a positive error.

52. As can be seen from temperature data taken after the end of certain of the charges, a drop of approximately 1° per hour is found in the cell temperature when the temperature difference between the cell and the air is approximately 18°. It seems reasonable, therefore, to conclude that when such a temperature gradient exists the cell will lose 52,110 calories, its heat capacity, by radiation through the cell box per hour.

53. It is therefore to be expected that when a charge is started in which the initial cell temperature is above the room temperature by 15-20°, immediate loss of heat through radiation takes place. If the temperatures of the cell, cell box, and air are approximately equal, heat loss from this cause will not take place until a sufficient temperature gradient is established. In such cases the estimated rise and actual rise should be of approximately the same magnitude in the early stages of the charge. Such, in general, proves to be the case if the data are inspected from the standpoint of cell, cell box, and air temperatures. Calculated rise is greater than actual in the later stages of the charge. This is due to the above in most cases.

Temperature Effects at Various Points in Cell

54. An inspection of the data shows that temperature values vary from place to place in the cell. However, the greatest difference is usually

about 8°F. The greatest differences exist in the early stages of the charge. As the charge proceeds the temperatures equalize. This equalization is probably due to two causes. Gassing will serve to mix the electrolyte and hence produce temperature equalization. This effect should accompany the equalization of gravity as found from hydrometer readings on electrolyte samples drawn from the stopcocks in the side of the cell. Such proves to be the case. Also when charging current is decreased, heating effect falls off rapidly. This gives a chance for temperature equalization to take place by heat flow from the hotter to the colder portions of the cell. It is to be noted that in the middle stages of the charges, in some cases, temperatures actually fell in the central portion of the cell as they rose elsewhere. The maximum heating effects in the early stages of the charge are found in the center of the cell. Smallest rises in the early stages are found on the outer portions of the electrolyte. Cooling effects on the surface (radiation to air and evaporation) serve to keep the surface cooler than the remainder of the electrolyte. Too much value should not be given to temperature readings taken by means of a thermometer in the electrolyte samples drawn from stopcocks in the side of the cell. In the installation used these stopcocks were about seven inches from the stopcocks on the outside of the cell box. Hence, the samples drawn would tend to take the temperature of the tube connecting the two cocks. On the whole, however, they follow fairly closely the temperatures within the cell as determined with the thermocouples.

General Shape of Temperature-Time Curve

55. Plates II, III and IV show in general how cell temperatures vary with time and charging current. It is noted that the most rapid increase is in the early stages of the charge. The latter stages, when gassing is pronounced, are also characterized by rapidly increasing temperatures. The middle stages are characterized by more or less constant temperatures. The early heating effects are easily explained from the standpoint of the irreversible and reversible heat effects. The heating effects during the gassing phase must be accounted for by other means.

Heating Effects

56. The various heating effects will be discussed under separate subheads.

(a) Irreversible Heat. Little need be said of this factor. Its value can be calculated from open and closed circuit potentials or from resistance measurements of the cell. Table 7 shows approximate values of voltage and resistance for various charging currents. The heating value falls off rapidly with decreasing current, for it must be remembered that this heat is given by the I^2R product, so that the resistance would have to change several fold to make up for decreasing current. As a heating factor it becomes insignificant in the latter stages of the charge.

(b) Reversible Heat. Normal Reaction. This factor has been discussed in full in Section 5-a, "Theory of the Lead-Acid Storage Cell". An examination of the data shows that it decreases almost in proportion to decreasing current. Of course, hydrogen evolution affects its magnitude as less current is used for the normal reaction when gassing is heavy.

(c) Heat of Formation of Molecular Gas. As was found in this study and as is shown in the report of the work at the New York Navy Yard (see bibliography), temperatures rise rapidly with gassing. This is shown in data for charges 7B and 10 on Plates V, VI and VII. This rise was originally thought to be due to the hot electrolyte from the center of the cell being brought to the surface by gas evolution in the gassing phase. Two arguments may be used to disprove this. In the first place, our temperature values in the center of the cell differ but little from those elsewhere. In the second place, if such be the cause, it should disappear as soon as the electrolyte is thoroughly mixed. As seen in charges 7B and 10, it continues even after gravity equalization and long after the start of heavy gassing.

The heat of formation of molecular gases is therefore proposed as a theory to explain this heat effect. This theory is discussed in 5-b, "Theory of the Gassing Phase of Cell Charge", and the arguments in its favor need not be repeated. It is seen from an inspection of the data that this effect is the largest of all the heating effects and, of course, is most pronounced during the latter stages of the charge. Errors in the reading of the hydrogen percentage would therefore introduce large errors in the estimated heat rise. It is thought that in certain of the early charges the hydrogen percentage data are high and this no doubt has something to do with the greater differences found in estimated and actual heat changes in the earlier charges. This effect would be most evident with the higher percentages at the end of the charge in some of the first tests.

(d) Heat of Mixing Electrolyte. This effect is not considered of appreciable magnitude. This mixing can be due to several causes. Convection currents can be produced due to temperature differences in the electrolyte. If such is the cause, it should disappear with the equalization of temperatures. Mixing may be produced by gas evolution and if the acid gravity varies from place to place in the cell, heat of mixing will be produced. However, as is seen from hydrometer readings from the side of the cell and from the data of the report of the gravity tests made by the Electric Storage Battery Company (see bibliography), gravity equalization is reached before gassing takes place to any extent. Gravity differences may exist between the free electrolyte between the plates and the electrolyte within the active material on the grids. If such differences exist, continuous mixing may take place throughout the charge, even during the gassing phase. In both the normal charge and the gassing phase, water is removed from the electrolyte. Therefore, if a heat effect is produced from the mixing from this cause, it should be distributed more or less evenly throughout the charge. Thus it is thought that heat of mixing cannot be the cause of any appreciable heat effect and most certainly it can hardly be the cause of the rapid rise at the end of the charge if our present ideas of the charge mechanism are correct.

Cooling Effects

57. These will be discussed separately.

(a) Reversible Heat. Water Electrolysis. The cause and magnitude of this effect have been discussed in Section 5-b, "Theory of the Gassing Phase", and 6-c, "Explanation of Calculations". It is found to be one-fifth the value of the heat effect due to the formation of molecular gas from the electrolysis of water. It is the principal cooling effect. As seen from the data and Plates V, VI and VII, its magnitude is small in the early stages of the charge and increases with gas evolution.

(b) Radiation (and Convection) to Ventilating Air. The effect due to the direct passage of heat from the cell to the ventilating air is seen to be quite small in magnitude. An examination of Tabe 2 shows that the heat capacity of air is approximately 7.5 calories per cu.ft. At a rate of 2 cu.ft. of air per minute, only 15 calories of heat would be removed when the ventilating air temperature increased by one degree. If 100 cu.ft. of air pass over the cell top and if the temperature increases 20°C, only 7,500 calories will be removed. This would lower the cell temperature but 1/7°. This is on the basis of a heat capacity of the cell of 52,110 calories. With cells larger than the WLH-29 a smaller temperature effect would of course result. It is thus seen that in the normal rate of ventilation little cooling can result from this effect. However, one point must be recognized; whatever cooling takes place is at the surface of the electrolyte. Therefore, if this surface temperature is used as a measure of the entire cell temperature, erroneous conclusions may be drawn. In certain of the charges in these tests surface temperatures lower than other portions of the cell were found. It can readily be seen that if large radiation takes place, temperatures at the top may fall one or more degrees. This last discussion applies equally well to the loss due to evaporation.

(c) Evaporation Losses. Evaporation losses are much more important than convection and radiation losses to the ventilating air, as discussed above. Table 6 shows that the heat of vaporization per gram of water is approximately 576 calories. Hence, to lower the cell temperature 1°F would require the evaporation of approximately 100 grams of water. Table 5 shows how many cubic feet of air would be required for this evaporation under various conditions of temperature and moisture content. Approximately 100 cu.ft. of perfectly dry air would be needed at 90°F to effect this evaporation, assuming the air became saturated over pure water. Or twice this much would be needed if the air is half saturated before leaving the electrolyte.

58. Now, as a matter of fact, the vapor pressures of sulphuric acid solutions are much less than the vapor pressures of pure water at the same temperatures. This is brought out in Table 6. On the whole, it may be concluded that air over 1280 acid is saturated at a value roughly of 70% moisture content of the air over pure water. Therefore, the estimated volume of air to effect a degree change in temperature as estimated above must be correspondingly increased.

59. A cell must therefore be highly ventilated to produce any appreciable cooling effect as regards the whole cell. As noted in the concluding paragraph under (b) immediately above, excess cooling may be produced on the surface due to rapid evaporation. But the effect may be entirely local in nature. Moreover, to effect any appreciable cooling over a long period of time, much water would have to be evaporated, which, of course, is not desirable from the standpoint of the watering of cells.

60. An examination of the actual moisture data secured in the charges made supplements nicely the speculations given above. It is seen from an inspection of the data and by reference to Table 5 that on the whole the moisture pickup represents an increase of about 15% in the relative humidity. If the relative humidity is around 50 percent, the increase produces a humidity of 65 percent. This is nearly a state of saturation for air over 1280 acid. If the

percentage is less than 50 percent in the air at the intake, the value in the duct will probably be less than 65 percent. In other words, complete saturation does not always result. Of course, this is to a certain extent desirable, for if the air became saturated at the higher temperatures over the cell top, condensation might take place when the air is cooled in the duct. This would result in moisture accumulation.

61. The state of the weather affects to some extent the amount of the moisture pickup in the air as it passes over the electrolyte. This is shown in the tabulated data of charge 3 which was made with variable atmospheric conditions prevailing. The day was marked by alternate periods of rain and semi-clearing. It is seen that the moisture data are erratic.

62. The moisture pickup tends to increase as the charge progresses. This is to be expected, for as gassing increases better contact is made between the air and the electrolyte due to the splashing of the acid as the gas bubbles leave the surface.

(d) Radiation and Other Heat Losses to Surroundings. In the non-adiabatic and semi-adiabatic charges heat loss took place by reason of heat loss from the outside of the insulating box. As stated in Section 8, "General Temperature Characteristics", this loss seemed to amount to about 1^{o} per hour with a temperature gradient of around 18^{o}. This loss is hardly sufficient to account for the difference between the estimated temperature rise and the rise found. The explanation for this is given later in this Section. Tests with the heating elements in the insulating box served to substantiate the magnitude of this loss. It is therefore a major cooling effect in certain of the charges conducted. Whether it is a factor on shipboard can only be determined by actual tests on the submarine installations. It would certainly indicate that artificial cooling around the cell jars would be an effective way of keeping cell temperatures from becomming excessive.

63. It was stated above that the 1^{o} leak per hour was not sufficient to account for the difference between the calculated rise and the rise as found in the non-adiabatic procedures. It will be recalled that the heat capacity of the cell was estimated on the basis of one-third of the actual heat capacity of the rubber jar. "s is seen from Plate I, the heat capacity of this jar is quite high. If the charge is not carried out adiabatically, the cell jar temperature rise must come entirely from the heat generated within the cell. This would make the heat capacity much higher. In an adiabatic charge the heat for the cell jar may come equally well from within the cell or from the air around the jar. The rate of heat absorption by the jar will be determined by the temperature within the cell and outside the jar, and by the rate of heat transfer in the jar itself.

Comparative Value of Data from Various Charges

64. In general, it may be concluded that the data for charges 7 to 10 are most accurate and it is thought that they give an accurate picture of the heat effects in cell charge. It is therefore recommended that these charges be used for study of the various effects involved. Various data for these charges have been plotted on Plates II to VIII.

Discharge Data

65. The discharge data on the whole is self-explanatory. It is noted

that the maximum heating is near the upper part of the elements in the early stages of the discharge and that temperatures do not become uniform, as is the case with the charge.

9. CONCLUSIONS

Heating Effects

66. The heating effects in a normal charging procedure are as follows:

(a) Irreversible Heat. This is large at the start of the charge, but diminishes as the charging current is reduced. It is one of the two main heating effects in the early stages of the charge.

(b) Reversible Heat. Normal Reaction. This is the second of the two main heating effects in the early stages of the charge. Like the irreversible heat, it diminishes in value as the charging current is reduced.

(c) Heat of Formation of Gases. This source of heat is small in the early stages of the charge, but increases as hydrogen percentage increases. It is the main source of heat in the latter stages of the charge. It must be remembered that this explanation of the source of the heat near the end of the charge may not be correct.

Cooling Effects

67. The cooling effects in a normal charging procedure are as follows:

(a) Radiation (and Convection) to Ventilating Air. This effect is quite small in magnitude, as is seen from an inspection of the data. It is never a major factor in the reduction of cell temperatures.

(b) Evaporation Losses. The cooling due to water evaporation from the electrolyte is, in a normal charging procedure, not a major factor in the control of cell temperatures. See Section 8, "Discussion of Results".

(c) Reversible Heat. Water Electrolysis. This seems to be the chief cooling effect. Its magnitude is one fifth the magnitude of the heat of formation of the gases.

Temperature Characteristics of Cell Charge.

68. (a) The principal rise in temperature takes place during the early stages of the charge when the reversible heat and irreversible heat effects are at a maximum. The temperature again rises rapidly near the end of the charge when gassing becomes pronounced. Very little rise is found in the intermediate stages of the charge, that is, after the initial high charging rate has been reduced and before the start of the gassing phase.

(b) The temperatures within the cell are somewhat higher than those at the top and on the sides of the cell during the early stages of the charge. As gassing sets in the temperatures equalize. This equalization of temperature parallels the equalization of gravity and is no doubt due to the effect of the gas in mixing the electrolyte. However, the temperature difference is never over 8°F.

(c) According to calculations made, the temperature of a MLH-29 Ironclad cell should rise about 30° if no cooling effects other than those listed above come into play. This is based on a heat capacity of 52,110 calories for this cell. The cooling effects mentioned are not sufficiently large to carry off more than a minor part of the heat generated. Consequently, if radiation to the surroundings is restricted, the heat generated to a large extent is used in raising the cell temperature.

Control of Cell Temperatures

69. It can be concluded that cell temperatures can be prevented from becoming excessive by either preventing excess gassing or by artificial cooling. This artificial cooling can be effected by circulating cold air or water around the cells. As stated above, evaporation cannot become a major factor in cell cooling unless excess ventilation is employed.

10. RECOMMENDATIONS

70. In view of the results obtained in the tests conducted in the study reported in this communication, the following recommendations are made for further study on projects connected with the general subject matter under investigation.

Studies Concerning the Gassing Phase of the Charge

71. Practically nothing is known of the phenomena associated with the gassing phase of the charge. It is therefore recommended that a series of investigations be undertaken in an attempt to throw further light on gassing phenomena. These investigations may be further divided as follows:

(a) Origin of Gas. It is not known just where the gas originates. That hydrogen evolves from the lead is of course certain; but does it come from the grid, from the surface of the active material, or from the interior of the active mass? This is perhaps important; for if our conclusions as to the heat of formation of molecular hydrogen are correct, the knowledge of the exact location of the combination may be of value in the construction of grids and plates and in the proper understanding of the phenomena of cell charge. This question may be answered by visual observation or perhaps by the proper placing of thermocouples for the observation of possible centers of high local heating. What applies to hydrogen evolution at the lead plate applies equally well to oxygen evolution at the peroxide plate. At present the exact mechanism of oxygen evolution is not known; study of whether the gas arises from the lead grid or the lead peroxide would help decide this.

(b) Single Electrode Potential Studies. Measurements of the single electrode potentials should be made at all stages of the charge, with various acid gravities, and at various temperatures. This would throw light on the point at which hydrogen and oxygen evolution supplants the normal electrode reactions; it would enable one to calculate the decomposition potentials of water in various acid concentrations at various temperatures with lead and lead peroxide electrodes; and would furnish the data necessary properly to calculate the reversible heat effect associated with water electrolysis. It will be recalled that these data were lacking for the proper calculation of this effect in this report. These studies would also give the overvoltage values of hydrogen on lead and oxygen on lead or lead peroxide, as the case may be. The solution of this particular phase of the problem would undoubtedly clear up entirely the voltage-temperature-gravity-gassing relationships so important in the operation of a storage cell, particularly in tropical waters.

Gravity Equalization Studies

72. It is thought that it would be well worth while to study further the gravity equalization phenomena associated with cell charge. This study would probably have to be done on a cell constructed especially for the purpose with the electrodes much farther apart than in the regular cell. By the proper location of thermocouples one should be able to tell by temperature effects the heating phenomena due to diffusion or to mixing due to gas evolution. It might be advisable to effect for purposes of study what might be termed artificial diffusion phenomena. At present we do not know the gravity of acid within the active material and without this knowledge we cannot properly calculate the theoretical voltage for comparison with the actual. Experiments might be devised for checking up on diffusion from within the active material. Morse (see bibliography) discusses this matter to some extent in his text on storage cells.

Further Practical Tests of General Nature

73. It seems advisable with the data as secured from the work of this report to carry the studies to shipboard installations, particularly under operating conditions. Without these studies it will be impossible to calculate heat losses due to radiation from the cells in the battery space. Temperature phenomena may prove different from those encountered in the experimental set-up employed in this problem. The further checking of the high heat evolution characteristic of the gassing phase should be made on a regular installation. If possible, tests should be made on a bad cell, one which starts gassing at the start of the charge, during which period the charging currents are high. If our theory of the source of this heat is correct, the cell should heat very rapidly unless radiation losses are high. It would be well to check thoroughly temperatures in cells in various parts of the battery. The results of the studies made under paragraph 71 of this Section should also be checked on a practical scale.

Study of Temperature Regulation

74. With the results of the tests given in this report and with data secured from the above recommendations, an experimental set-up should be constructed that would admit study of the possibility of temperature control. For this purpose a cell or cells should be enclosed in a box capable of holding either air or water, the temperature of which could be accurately regulated. This would enable one easily to determine whether or not the cooling of cells on shipboard is desirable from the standpoing of temperature control. It is thought that with properly constructed equipment cell temperatures could be prevented from becoming excessive. This is an especially important item from the standpoint of charging procedure dur-

ing maneuvers in tropical waters. With nightly charging battery temperatures become excessuve due to the accumulation of the heat in the cells. Artificial cooling beyond the means now employed would probably help keep these temperatures within proper range and thus greatly increase the military efficiency of the submarine.

75. Of the above recommendations, those listed under "Studies Concerning the Gassing Phase of the Charge could best be carried out on a semi-practical basis. The results could then be checked on a large cell. "Gravity Equalization Studies" would likewise probably be a semi-practical study. Of course "Further Practical Tests of General Nature" and "Study of Temperature Regulation" would be practical studies. All the recommendations could easily be carried out with the possible exception of paragraph 72. Considerable difficulty might be encountered in that particular phase of the problem. With the completion of the studies recommended, it is thought that a complete knowledge would be obtained of all temperature phenomena in battery charging and a complete solution of the temperature question could be arrived at. This solution would probably enable a charging procedure involving a much shortened period of time to be developed.

76. Of the recommendations above, "Studies Concerning the Gassing Phase of the Charge" and "Gravity Equalization Studies" are now underway at the University of North Carolina, under authority of Bureau of Engineering letter S62-4/L5 (9-13-Ds) of 4 October 1934.

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TABLE 1.

Conversion Units and Formulas Used in Calculations

1 Faraday = 96,540 coulombs = 96,500 ampere-seconds

4.186 joules = 4.186 watt-seconds = 1 calorie

1 BTU = 1060.4 joules at 40°F

1000 calories = 3.9685 BTU

1 BTU per minute = 17.580 watts

1 cu.ft. = .02832 cu. meters = 28.32 liters

35.314 cu.ft. = 1,000 liters

$1^{\circ}C = 1.8^{\circ}F = 1^{\circ}$ Absolute

1 gram = 15.432 grains

1 pound = 453 grams

Formulas

Temperature (Absolute) = Temperature (Centigrade) + 273°

$$\frac{\text{Current (in amperes) x Time (in seconds)}}{96{,}540} = \text{no. Faradays}$$

1 Faraday produces 1/2 mol (103.6 grams) of lead, 1/2 mol (119.6 grams) of lead peroxide, 1/2 mol (1 gram) hydrogen gas, 1/4 mol (8 grams) oxygen gas.

1 Faraday converts 1/2 mol (151.6 grams) lead sulphate to active material.

Calculation of hydrogen evolution.

Air flow x % Hydrogen = No. cu.ft. of hydrogen at temperature of duct air.

$$\frac{\text{1.92 cu.ft. x }\%H_2\text{ x 28.32 liters x }273/T}{\text{22.4 liters}} = \text{no. mols of hydrogen evolved}$$

per minute when air flow is 1.92 cu.ft.

Table 1 continued

Calculations of moisture content of air.

Grams H_2O per liter of air x 1.92 cu.ft. x 28.32 liters = no. grams of water in air passing through duct in one minute.

28.32 liters x grams of water per liter = grams of water per cu.ft.

Calculations of increase of moisture content of air when passing over electrolyte. (Water loss by evaporation from electrolyte per minute.)

Moisture content of 1.92 cu.ft. of duct air - moisture content of 1.92 cu.ft. of air before passing over electrolyte $\frac{273 + T_1}{273 + T_2}$ = water loss by evaporation per minute.

T_1 = Centigrade temperature of entering air, T_2 = Centigrade temperature of air in duct.

Calculation of reversible heat of water electrolysis.

96,540 coulombs x T (Absolute) x dE/dT = q (per mol of water electrolyzed)

Heat of formation of molecular gas.

Heat of formation of H_2 + 1/2 heat of formation of O_2 = heat of formation of molecular gas per mol of water electrolyzed.

Irreversible heat effect.

I^2R = irreversible heat effect per second.

IE x T (seconds) = irreversible heat for time T.

TABLE 2.

Heat Capacity for Dry Air

Temperature		Volume 1 mol gas (liters)	grams gas per		Heat Capacity per cubic foot		
F	C		liter	cu.ft.	Calories	Watt-sec.	BTU
60	16	23.7	1.215	34.40	8.11	1.945	.00184
70	21	24.0	1.200	34.00	8.01	1.910	.00181
80	27	24.6	1.170	33.15	7.83	1.875	.00178
90	32	25.0	1.150	32.60	7.70	1.839	.00174
100	38	25.5	1.127	32.00	7.56	1.805	.00171
110	43	26.0	1.106	31.40	7.42	1.772	.00168
120	49	26.5	1.085	30.75	7.28	1.740	.00165

Molar Heat Capacity for Moist Air
(Calories per degree C)

Relative Humidity	Temperature						
	60	70	80	90	100	110	120
0	6.79	6.79	6.80	6.80	6.81	6.81	6.82
50	6.78	6.78	6.79	6.79	6.80	6.80	6.81
100	6.77	6.77	6.78	6.78	6.79	6.79	6.80

The following were used in the calculations of the above values.

Molar heat capacity (C_p)

Nitrogen $6.5 + .001T$

Oyxgen $6.5 + .001T$

Water $8.81 - .0019T : .00000222T^2$

Dry air: 79 mol per cent nitrogen, 21 mol per cent oxygen

Above formulas from Chemical Engineers' Handbook, Page 549.

TABLE 3.

Specifications for WLH-29 Cell and Data for Calculation of Heat Capacity of Same.

Jar. Outside height, exclusive of poles, not to exceed 45-9/16"; outside width. not to exceed 17-11/16", length not to exceed 14-11/16". Inside depth not less than 44", width not less than 13-3/16".

Positive Plate, Ironclad. Height not less than 35", width not less than 15-5/16", thickness not less than .52".

Negative Plate, Exide Type. Height not less than 33-7/8", width not less than 15-1/8", thickness not less than .22".

Separators, Treated Wood Veneer. Thickness not less than .05"

Sediment Space. 3-3/8" maximum, 3" minimum.

Weight complete, cell charged: 1210 electrolyte not to exceed 1205 lbs.
1250 " " " " 1210 "
1280 " " " " 1215 "

Weight of electrolyte. Nominal weight for filling cell containing dry plates and wet separators, fully charged,

SG 1210 use 175 lbs. 1240 electrolyte
SG 1250 use 180 lbs. 1280 electrolyte
SG 1280 use 185 lbs. 1310 electrolyte

Weight of One Positive Plate, dry, not less than 29 lbs.

Weight of One Negative Plate, dry, not less than 24 lbs.

Permissible Temperatures. For regular service charging, 110°F. For charging as part of continuous cycle as war conditions, boat trials, etc., 130°F.

Percent by weight, plate active material (weight of plate includes lugs), positive 48%, negative 58%.

Calculation of Heat Capacity of Cell

Estimated Weights of Various Materials		Total Heat Capacity
Jar, top, etc.	90 lbs.	6,523 calories
Separators	0	0
Electrolyte, 1280 gravity	225 lbs.	71,340 calories
Lead	631 lbs.	9,717 calories
Lead Peroxide	214 lbs.	6,200 calories
Total	1,160 lbs.	93,780 calories per degree C.

Heat capacity per degree Fahrenheit = 52,110 calories.

Table 3 continued.

Heat Capacity Values used:

Lead	.034 calories per gram
Lead Peroxide	.064 calories per gram
Lead Sulphate	.084 calories per gram
Rubber	.48 calories per gram
Sulphuric Acid solution	.70 calories per gram

TABLE 4.

Temperature Conversion Table
(Centigrade-Fahrenheit)

Centigrade	Fahrenheit	Centigrade	Fahrenheit
20	68.0	39	102.2
21	69.8	40	104.0
22	71.6	41	105.8
23	73.4	42	107.6
24	75.2	43	109.4
25	77.0	44	111.2
26	78.8	45	113.0
27	80.6	46	114.8
28	82.4	47	116.6
29	84.2	48	118.4
30	86.0	49	120.2
31	87.8	50	122.0
32	89.6	51	123.8
33	91.4	52	125.6
34	93.2	53	127.4
35	95.0	54	129.2
36	96.8	55	131.0
37	98.6		
38	100.4		

1° Fahrenheit = .0528°C

1° Centigrade = 1.8°F

TABLE 5.

Moisture Content of Air.

Weight of water vapor per 100 cubic feet of air.

Per Cent Saturation.

	10		20		30		40		50	
Temp.F	Grams	lbs.	Grams	lbs.	Grams	lbs.	Grams	lbs.	Grams	lbs.
60	3.745	.00828	7.46	.0164	11.16	.0246	16.64	.0367	18.60	.0411
70	5.180	.0148	10.36	.0228	15.50	.0342	21.18	.0456	25.80	.0572
80	7.080	.0156	14.16	.0313	21.28	.0469	28.34	.0626	35.50	.0774
90	9.580	.0212	19.16	.0424	28.78	.0633	38.30	.0844	47.90	.1057
100	12.80	.0286	25.60	.0572	38.85	.0849	51.10	.1130	64.10	.1415
110	16.93	.0374	33.86	.0748	51.00	.1126	67.70	.1443	84.60	.1867

	60		70		80		90		100	
	Grams	lbs.	Grams	lbs.	Grams	lbs.	Grams	lbs.	Grams	lbs.
60	22.32	.0493	26.05	.0575	29.82	.0658	33.50	.0740	37.52	.0828
70	31.04	.0685	36.23	.0800	41.40	.0914	46.58	.1028	51.65	.1142
80	42.52	.0938	49.65	.1095	56.85	.1252	64.00	.1415	70.80	.1563
90	57.50	.1270	67.10	.1484	76.60	.1690	86.16	.1906	96.00	.2117
100	76.90	.1700	89.60	.1990	102.60	.2265	115.30	.2548	128.20	.2828
110	101.50	.2240	118.50	.2613	135.30	.2983	152.20	.3355	169.30	.3740

Above values calculated from data on Page 84, Psychrometric Tables, C.F. Marvin, WB No. 235.

TABLE 6.

Vapor Pressure of Acid Solutions and Heat of Vaporization of Water from Same.

Vapor Pressure (mm mercury)

Weight percent, acid	0	10	20	25	30
Gravity	1.000	1.0661	1.1394	1.1783	1.2185
Temperature - C					
10	9.2 mm	8.80	8.05	7.46	6.91
15	12.79	12.3	11.3	10.5	9.65
20	17.54	16.6	15.4	14.3	13.2
25	23.76	22.4	20.8	19.4	17.8
30	31.83	30.0	27.8	26.0	23.8
35	42.18	40.1	37.2	35.0	31.9
40	55.32	52.9	48.6	45.6	41.7
45	71.88	68.1	63.3	59.0	54.7
50	92.51	88.5	82.2	76.7	71.3

Heats of Vaporization
(Calories per Gram)

Percent Acid	10	20	30
A	8.925	8.922	8.864
B	2259	2268	2271
Heat of Vaporization	574	576	577

Vapor Pressure Equation: $\mathrm{Log}_{10}P_{mm} = A - B/T$

Data from Chemical Engineers' Handbook, Pages 346 and 338.

TABLE 7.

Resistance of Cell and Voltage Drop for Various Currents.

Current	Voltage	Resistance
1300	.15	.000112
1050	.13	.000123
800	.10	.000125
550	.08	.000145
330	.05	.000150
250	.05	.000200
190	.04	.000211
165 (small gassing)	.035	.000217
165 (**large** gassing)	.06	.000370

PLATE I.

Location of Thermocouples and Explanation of Grouping of Same.

1. Between separator and positive 14, 3 in. from side, 5 in. from bottom.
2. Between separator and positive 3, center of plate, 11 in. from bottom.
3. Between separator and negative 6, 12 in. from side, 9 in. from bottom.
4. Between separator and positive 10, center of top of cell.
5. Between separator and negative 3, 10 in. from side, 24 in. from bottom.
6. Between separator and positive 8, center of plate, 15 in. from bottom.
7. Between separator and negative 12, center of plate, 24 in. from bottom.
8. Under pin, by negative 7, 15 in. from side.
9. Against cell jar, 1 in. below top of elements, left center.
10. In electrolyte at top of cell, 1 in. from left side of cell.
11. In electrolyte at top of cell, center.
12. Between separator and positive 8, 10 in. from side of cell, 11 in. from bottom.
13. Between separator and negative 6, 12 in. from side, 16 in. from bottom.

Groups

1.	Top electrolyte, direct ventilation.	Nos. 10, 11, 4
2.	Top electrolyte, unventilated.	Nos. 9, 8
3.	Bottom part of elements.	Nos. 1, 2, 12
4.	Middle center of elements.	Nos. 6, 7
5.	Middle side of elements.	Nos. 3, 5, 13

See diagram for approximate location.

SECTION 13.

Tabulated Data for Charges and Discharges.

CHARGE NO. 1

Time	Current	Voltage	$\%H_2$	Gravity NRL Battmeter	Air	Temperature Cell Box
1000	0-1050	1.96-2.14	0	1124	82.5	87
1030	1050	2.16	.06	1131	84	89
1100	1050	2.18	.10	1149	85	89
1130	1050	2.19	.22	1165	86	89
1200	1050	2.20	.22	1184	87	91
1230	1050	2.21	.27	1198	88	95
1300	1050	2.23	.33	1210	88	95
1330	1050	2.25	.47	1220	88	97
1400	1050	2.26	.52	1238	88	98
1415	1050-800	2.28-2.24	.65-.55	--	—	—
1430	800	2.25	.58	1247	89	99
1500	800-550	2.27-2.23	.76-.71	1256	89	99
1530	550	2.25	.83	1260	89	100
1600	550-330	2.27-2.22	.91-.83	1268	89	100
1630	330	2.23	.91	1272	88	100
1700	330	2.26	.97	1276	89	100
1715	330-250	2.27-2.25	1.23-1.06	1276	89	100
1730	250	2.25	1.12	1276	89	100
1800	250-190	2.27-2.25	1.36-1.02	1280	89	100
1815	190-0	2.27	1.26	1280	88	100

Bureau Charge
Air Flow Constant at 1.92 cu.ft./minute
Non-adiabatic Procedure

Charge No. 1, Sheet No. 2.

	Temperatures				Moisture Analysis			
					Air		Duct	
Time	1	2	3	4	Temp.	gH_2O/liter	Temp.	gH_2O/liter
1000	105	105	107	102	82.5	.0160	90	.0330
1030	105	107	107	102	84	.0174	91	.0206
1100	106	109	109	104	85	.0174	92	.0224
1130	108	111	112	107	87	.0168	93	.0226
1200	109	113	112	108	87	.0170	93	.0214
1230	109	113	112	108	87	.0170	93	.0212
1300	111	109	113	108	88	.0170	94	.0206
1330	111	114	113	109	88	.0150	95	.0234
1400	113	118	116	112	88	.0155	96	.0236
1430	114	116	114	112	89	.0163	97	.0234
1500	115	117	116	111	89	.0160	97	.0252
1530	115	116	116	112	89	.0156	97	.0245
1600	117	117	117	112	89	.0152	97	.0218
1630	117	118	116	116	88	.0156	97	.0260
1700	117	117	115	113	89	.0160	98	.0274
1730	116	117	117	113	89	.0162	98	.0264
1800	117	117	121	118	89	.0162	98	.0240

Temperatures-Thermocouples

1 Below, and under lead bus bar
2 Between plates near side of cell, one inch below surface of acid
3 On top of elements, center of cell
4 On top of elements, side of cell

	Grams water/100 cu.ft.air		Evaporation per
Time	Induction	Duct	minute
1000	45.31	93.45	.365
1030	49.28	58.33	.192
1100	49.28	63.44	.288
1130	47.58	64.00	.332
1200	48.14	60.60	.255
1230	48.14	60.03	.244
1300	48.14	58.33	.212
1330	42.48	66.27	.470
1400	43.90	66.83	.454
1430	46.16	66.27	.402
1500	45.31	71.37	.518
1530	44.17	69.38	.498
1600	43.05	61.74	.372
1630	44.17	73.63	.578
1700	45.31	77.60	.634
1730	45.88	74.76	.568
1800	45.88	67.97	.438

Charge No. 1, Sheet No. 3

	Heating Effects				Cooling Effects		Total Effect	Rise	
Time	1	2	3	4	5	6		Predicted	Found
1000	1955	1825	0	66	210	0	3504		
1030	1955	1825	221	58	111	44	3790		
1100	1955	1800	340	58	166	68	3800	4.4°	2.25°
1130	1955	1800	816	42	192	163	4176		
1200	1955	1800	816	50	147	163	4214	4.7°	3.5°
1230	1955	1800	968	50	140	194	4340		
1300	1955	1790	1200	50	122	240	4535	5.0°	2.0°
1330	1955	1775	1730	58	271	346	4785		
1400	1955-1146	1775	1920	66	261	385	4940-4130	5.5°	4.0°
1430	1146	1750-1320	2140	66	231	428	4310-3910		
1500	1146-636	1300-872	2750-2580	66	299	550-516	4290-3200	4.8°	1.0°
1530	636	856	3060	66	287	612	3587		
1600	636-236	840-465	3380-3060	66	215	676-612	3900-2868	4.0°	1.5°
1630	236	465	3380	74	333	672	3000		
1700	236	448	3625	73	365	725	3146	3.4°	.2°
1730	236-179	420-313	4556-3890	73	327	911-780	4100-3200		
1800	179-109	269-207	4588	73	252	918	3793	4.0°	2.0°
1815	109-0		4588						
							Total	34.8°	14.0°

1. Irreversible Heat
2. Reversible Heat - Normal Reaction
3. Heat of Formation of Molecular Gas
4. Conductance to Air
5. Evaporation
6. Reversible Heat - Water Electrolysis

CHARGE NO. 2

Time	Current	Voltage	%H_2	Gravity NRL Battmeter	Temperature Air	Temperature Cell Box
0800	0-1050	1.96-2.16	00	1112	82	79
0830	1050	2.17	.04	1118	83	88
0900	1050	2.18	.10	1139	83	91
100	1050	2.21	.22	1174	83	94
1030	1050	2.23	.22	1180	83	94
1100	1050	2.24	.27	out	85	94
1130	1050	2.26	.33	of	85	94
1200	1050	2.29	.43	order	85	94
1230	1050-330	2.30-2.19	.47-.33	—	86	95
1300	330	2.20	.39	—	86	96
1330	330	2.20	.43	—	86	96
1400	330	2.21	.47	—	86	96
1430	330	2.22	.47	—	86	95
1500	330	2.24	.47	—	86	96
1530	330	2.26	.47	—	85	96
1600	330	2.27	.50	—	85	97
1630	330	2.30	.65	—	86	97
1700	330	2.32	.71	—	85	96
1730	330-0	2.34	.96	1274	85	96

Manufacturer's Charge
Air Flow Constant at 1.92 cu.ft./minute
Non-adiabatic Procedure

	Temperatures				Moisture Analysis			
					Air		Duct	
Time	1	2	3	4	Temp.	gH_2O/liter	Temp.	gH_2O/liter
0800	93	93	93	93	79	.0130	87	.0167
0830	94	94	94	94	84	.0133	88	.0157
0900	97	96	95	95	85	.0132	91	.0170
0930	99	97	97	100	83	.0134	90	.0170
1000	101	101	99	99	83	.—	90	.0182
1030	103	102	101	101	83	.0138	90	.0200
1100	104	103	102	102	85	.0123	91	.0202
1130	105	105	103	103	85	.0130	92	.0200
1200	107	106	103	105	85	.0122	93	.0226
1230	105	105	103	105	86	.0130	93	.0200
1300	103	105	103	105	86	.0122	93	.0208
1330	103	103	102	102	86	.0123	93	.0200
1400	102	102	101	101	86	.0122	93	.0200
1430	103	103	102	102	86	—	93	.0208
1500	103	104	102	103	86	.0130	93	.0187
1530	106	106	105	106	85	.0118	93	.0220
1600	106	113	107	105	85	.0132	93	.0200
1630	107	108	108	107	85	.0128	93	.0206
1700	106	106	108	109	85	.0122	93	.0212
1730	108	109	109	109	85	—	93	.0215

Location of Couples the same as in Charge No. 1.

Charge No. 2, Sheet No. 2.

	Air at Intake		Air in Duct		Evaporation
Time	gH_2O/100 cu.ft.	Temp.	gH_2O/100 cu.ft.	Temp.	per minute
0800	36.81	26	47.29	31	.2052
0830	37.66	28	44.64	32	.1440
0900	37.38	30	48.14	33	.2063
0930	37.95	29	48.14	32	.1960
1000	39.08	29	51.53	32	.2390
1030	34.83	29	56.64	33	.4200
1100	34.83	29	57.20	33	.4300
1130	36.81	30	56.64	34	.3810
1200	34.54	30	64.00	34	.5660
1230	36.81	30	56.64	34	.3810
1300	34.54	30	58.90	34	.4680
1330	34.83	30	56.64	34	.4190
1400	34.54	30	56.64	34	.4230
1430	37.66	30	58.90	34	.4080
1500	36.81	30	53.00	34	.3135
1530	33.42	30	62.34	34	.5560
1600	37.38	30	56.64	34	.3700
1630	36.25	30	58.33	34	.4230
1700	31.72	30	60.03	34	.5480
1730	34.26	30	60.90	34	.5120

	Heat Effects			Cooling Effects			Total	Temp. Rise	
Time	1	2	3	4	5	6	Effect	Cal.	Found
0800	1955	1831	0	118	70	0	3598		
0830	1955	1825	126	83	56	25	3742		
0900	1955	1820	340	119	42	68	3886	4°	2°
0930	1955	1820	340	113	42	68	3892		
1000	1955	1808	816	138	42	162	4236	4.5°	4°
1030	1955	1808	816	242	56	163	4138		
1100	1955	1797	959	248	56	194	4223	4.8°	3°
1130	1955	1792	1205	220	56	241	4434		
1200	1955	1780	1580	327	56	316	4616	5°	2°
1230	1955-236	1774- 531	1733- 1205	220	56	347-241	4839- 1455		
1300	236	527	1433	270	56	287	1583	3.6°	-1°
1330	236	521	1580	242	56	316	1723		
1400	236	515	1733	244	56	347	1837	2°	-1°
1430	236	515	1733	235	56	347	1846		
1500	236	515	1733	181	56	347	1900	2°	1°
1530	236	515	1733	321	56	347	1760		
1600	236	510	1870	214	56	374	1972	2°	3°
1630	236	493	2405	244	56	481	2353		
1700	236	387	2581	316	56	516	2416	4.5°	3°
1730	236-0	554-0	3580	295	56	716	3203		
					Total change			32°	16°

1. Irreversible Heat
2. Reversible Heat, Normal Reaction
3. Heat of Formation of Gas
4. Radiation Loss to Air
5. Evaporation Loss
6. Reversible Heat, Water Electrolysis

CHARGE NO. 3

Time	Current	Voltage	%H_2	Temp.-Gravity Top		Temp.-Gravity Bottom		Gravity NRL Battmeter
0800	0-1050	1.99-2.18	0	1137	88	1148	88	1145
0830	1050	2.19	.10	1137	91	1159	89	1146
0900	1050	2.20	.20	1137	93	1168	90	1172
0930	1050	2.22	.20	1140	95	1186	92	1184
1000	1050	2.24	.22	1143	96	1201	93	1204
1030	1050	2.25	.27	1149	97	1215	93	1214
1100	1050	2.27	.32	1158	98	1224	95	1226
1130	1050	2.30	.41	1168	99	1238	96	1234
1147	1050-330	2.31-2.20	.48-.41	1180	99	1248	96	1244
1200	330	2.20	.41	1190	100	1253	97	1252
1230	330	2.21	.41	1198	99	1257	98	1256
1300	330	2.21	.45	1207	100	1260	98	1260
1330	330	2.22	.48	1213	99	1268	98	1262
1400	330	2.24	.48	1220	99	1267	99	1262
1430	330	2.25	.48	1229	98	1270	99	1266
1500	330	2.26	.48	1237	99	1274	99	1264
1530	330	2.28	.58	1247	99	1274	99	1268
1600	330	2.31	.66	1257	101	1269	103	1264
1630	330	2.35	.98	1265	101	1265	105	1274
1700	330	2.39	1.58	1269	102	1269	105	1275
1730	330-0	2.41	2.75	1269	102	1269	105	1275

Manufacturer's Charge
Air Flow Constant at 1.92 cu.ft./min.
Non-adiabatic Procedure

Time	Temperatures 1	2	3	4	5	Cell Box
0800	83	84	84	85	84	82
0830	88	88	86	90	88	88
0900	90	91	89	92	90	90
0930	92	93	89	93	91	92
1000	94	95	90	96	93	92
1030	95	97	91	98	95	92
1100	98	98	93	100	96	92
1130	100	100	95	102	98	92
1200	101	101	97	104	100	93
1230	100	101	98	104	100	94
1300	101	101	98	103	100	94
1330	100	100	98	103	101	95
1400	101	101	99	103	101	95
1430	101	102	99	104	102	95
1500	101	102	101	104	103	96
1530	100	101	101	104	102	92
1600	102	102	101	104	102	94
1630	103	103	102	105	103	95
1700	105	105	103	105	103	95
1730	107	107	104	106	105	95
1800	108	108	105	107	106	95

Group 1. Top Electrolyte, direct ventilation.
2. Top Electrolyte, unventilated.
3. Bottom of Elements.
4. Middle Center of Elements.
5. Middle Side of Elements.

Charge No. 3, Sheet No. 2.

Time	Air at Intake				Air in Duct				Evaporation Grams per minute
	1	2	3	4	1	2	3	4	
0800	.0200	56.64	28	82	.0203	57.30	30	86	.0234
0830	.0186	52.70	30	86	.0216	61.17	31	88	.1726
0900	.0164	46.44	30	86	.0208	58.90	32	90	.2465
0930	.0205	57.95	31	88	.0232	65.70	33	91	.1592
1000	.0182	51.53	32	90	.0212	60.03	33	91	.1726
1030	.0174	49.28	31	88	.0219	62.04	33	91	.2540
1100	.0162	45.88	31	88	.0218	61.74	33	91	.3130
1130	.0198	56.10	32	89	.0224	63.50	34	93	.1527
1200	.0154	43.61	32	89	.0222	62.90	34	93	.3780
1230	.0172	48.71	31	88	.0210	59.47	34	93	.2160
1300	.0128	36.25	32	90	.0220	62.34	34	94	.5263
1330	.0168	47.58	32	90	.0196	55.50	34	94	.1610
1400	.0198	56.10	33	91	.0197	55.80	34	94	.0050
1430	.0154	43.61	33	91	.0215	60.90	35	95	.3400
1500	.0140	39.65	28	83	.0223	63.20	33	91	.4600
1530	.0134	37.95	30	86	.0190	53.81	34	93	.3105
1600	.0190	53.81	31	87	.0200	56.64	34	93	.6440
1630	.0154	43.61	31	87	.0230	65.13	34	93	.4210
1700	.0158	44.75	29	84	.0240	67.97	34	93	.4530
1730	.0140	39.65	29	83	.0200	56.64	33	92	.3335
1800	.0138	44.75	29	83	.0214	60.60	33	92	.3240

1. Grams H_2O per liter of air.
2. Grams H_2O per 100 cu.ft. air.
3. Temperature, Centigrade.
4. Temperature, Fahrenheit.

Time	Heating Effects			Cooling Effects			Total Effect	Evaporation Grams per min.	
	1	2	3	4	5	6			
0800	1955	1831	00	28	13	366	3380		
0830	1955	1820	340	14	99	364	3924		
0900	1955	1809	747	28	146	362	4187	4.2°	6°
0930	1955	1809	747	28	92	362	4241		
1000	1955	1804	816	14	99	163	4300	4.3°	3°
1030	1955	1798	969	28	147	194	4353		
1100	1955	1792	1170	28	180	234	4475	5°	4°
1130	1955	1781	1506	28	87	300	4827		
1200	1955-	1775-	1765-	28	218	353-	4696-	4.5°	3°
	236	521	1506			300	1610		
1230	236	521	1506	28	124	300	1811		
1300	236	515	1655	28	303	331	1744	2°	0°
1330	236	515	1765	14	93	353	2056		
1400	236	515	1765	28	2	353	2133	2°	.2°
1430	236	515	1765	70	196	353	1900		
1500	236	515	1765	56	265	353	1844	2°	.6°
1530	236	499	2140	42	178	428	1897		
1600	236	492	2430	42	371	486	1842	2°	.2°
1630	236	448	3670	70	242	734	3308		
1700	236	375	5880	56	261	1176	5000	3°	2°
1730	236	235	10,198	56	188	2040	8385	3.2°	2°
							Total	32.2°	21°

1. Irreversible Heat Effect.
2. Reversible Heat, Normal Reaction.
3. Heat of Formation of Gases.
4. Radiation Loss.
5. Evaporation Loss.
6. Reversible Heat, Water Electrolysis.

CHARGE NO. 4.

Time	Current	Voltage	%H_2	Temp.-Gravity				Gravity
				Top		Bottom		NRL Battmeter
0700	0-1300	2.0-2.21	0	1142	88	1155	90	1150
0730	1300	2.22	.15	1142	91	1167	92	1154
0800	1300	2.24	.20	1144	93	1178	93	1175
0830	1300	2.26	.27	1149	94	1203	95	1199
0900	1300	2.29	.33	1157	95	2191	95	1218
0940	1300-1050	2.32-2.29	.35	1162	98	1231	97	1225
1000	1050	2.31	.50	1182	98	1245	97	1240
1015	1050-800	2.32-2.29	.58-.50	--	--	--	--	--
1030	800	2.30	.58	1201	100	1255	99	1251
1050	800-550	2.32-2.28	.70-.58	1216	99	1263	99	1261
1130	550	2.30	.70	1232	99	1267	101	1262
1145	550-330	2.32-2.28	.83	--	--	--	--	--
1200	330	2.29	.70	1244	100	1272	102	1266
1230	330-250	2.32-2.30	.95-.83	1257	101	1273	105	1266
1300	250-190	2.32-2.29	.95	1264	102	1267	105	1275
1320	190-165	2.31-2.30	.95	1267	104	1266	104	1278
1400	165	2.32	1.12	1270	104	1269	105	1278
1430	165	2.34	1.36	1272	104	1270	105	1278
1500	165-330	2.34-2.41	1.6-4.50	1272	103	1271	107	1278
1530	330-0	2.42	4.50	1273	104	1272	108	1278
1600	0	2.18	.58	--	--	--	--	--
1615	0	--	--	--	--	--	--	--

Bureau Procedure
Air Flow Constant at 1.92 cu.ft./min.
Non-adiabatic Procedure

Time	Air at Intake				Air in Duct				Evaporation Grams per min.
	1	2	3	4	1	2	3	4	
0700	.0144	40.78	23	74	.0177	50.00	28	82	.1920
0730	.0153	43.22	25	78	.0180	50.98	29	83	.1650
0800	.0140	39.65	25	78	.0200	56.64	29	83	.3390
0830	.0140	39.65	25	78	.0193	54.70	30	85	.3040
0900	.0146	41.40	25	77	.0217	61.47	30	85	.4000
0930	.0132	37.38	25	78	.0213	60.31	30	85	.4550
1000	.0140	39.65	25	78	.0222	62.90	31	88	.4610
1015	.0150	42.48	25	77	.0222	62.90	31	88	.4080
1030	.0140	39.65	25	78	.0222	62.90	31	88	.4620
1050	.0152	43.05	25	78	.0222	62.90	31	88	.3980
1130	.0132	37.38	25	78	.0227	64.30	31	88	.5305
1145	.0140	39.65	26	79	.0200	56.64	32	90	.3420
1200	.0138	39.08	26	79	.0200	56.64	32	90	.3530
1230	.0128	36.25	26	79	.0195	55.22	32	90	.3790
1300	.0152	43.05	27	80	.0195	55.22	32	90	.2500
1330	.0156	44.17	27	80	.0203	57.30	32	90	.2690
1400	.0144	40.78	27	80	.0200	65.64	32	90	.3200
1430	.0146	41.40	27	80	.0230	54.13	33	91	.4710
1500	.0134	37.95	27	80	.0193	54.70	33	91	.3360
1530	.0150	42.48	27	80	.0247	69.95	33	91	.5440

Charge No. 4, Sheet No. 2.

Temperatures

	Couple Groups					Cell
Time	1	2	3	4	5	Box
0700	92	92	95	95	95	86
0730	94	94	98	100	97	86
0800	97	98	100	103	101	89
0830	101	101	102	105	103	90
0900	102	102	103	106	105	91
0930	103	104	105	108	106	92
1000	105	106	106	111	108	92
1015	106	106	106	112	109	92
1030	106	106	107	112	110	92
1100	106	107	108	114	111	92
1130	106	108	110	114	111	93
1145	107	108	111	113	110	94
1200	108	108	111	113	111	94
1230	109	109	111	113	111	95
1300	110	109	110	112	110	95
1330	110	109	109	111	110	95
1400	110	110	108	111	109	96
1430	111	110	108	110	109	96
1500	111	110	109	110	109	96
1530	112	112	110	112	110	97
1600	111	111	110	111	110	97

1. Top Electrolyte, direct ventilation.
2. Top Electrolyte, unventilated.
3. Bottom Part of Elements.
4. Middle Center of Elements.
5. Middle Side of Elements.

	Heating Effects				Cooling Effects		Total	Temp. Rise	
Time	1	2	3	4	5	6	Effect	Est..	Found
0700	2794	2250	00	70	111	00	4863		
0730	2794	2250	545	84	95	109	5300		
0800	2794	2250	747	56	196	149	5390	6°	6°
0830	2794	2250	973	70	175	194	5578		
0900	2794	2220	1270	70	231	254	5730	6°	4°
0930	2794- 1955	1850- 1440	1270	70	262	254	5328- 4070		
1000	1955	1770	1870	84	266	374	4871	5.7°	3°
1015	1955- 1146	1760- 1327	2140- 1870	84	235	428- 374	5508- 4000		
1030	1146	1315	2140	84	266	428	3823		
1100	1146- 636	1305- 885	2548- 2140	84	229	510- 428	4176- 2920	4.7°	1.8°
1130	636	875	2548	84	306	510	3159		
1145-	636- 236	856- 470	3060	84	197	612	3660- 2873		
1200	236	487	3548	84	203	510	3474	3.5°	1°
1230	236- 179	448- 336	3548- 3060	84	219	710- 612	3220- 2662		
1300	179- 109	319- 213	3548	70	145	710	3121- 2945	3.2°	.2°
1330	109-82	213- 168	3548	70	155	710	2835		
1400	82	148	4180	70	185	836	3319	3°	0°
1430	82	112	5046	84	272	1009	3875		
1500	82- 109	33- 16	5046- 1683	84	194	1009- 31650	3874- 13510	4.5°	2°
1530	109-0	16-0	1683-0	84	314	31650	13510	7°	1.3°
							Total (exclusive of last 30 minutes)	36.6°	18°

Charge No. 4, Sheet No. 3.

1. Irreversible Heat
2. Reversible Heat, Normal Reaction
3. Heat of Formation of Gases
4. Radiation Loss to Air
5. Evaporation Loss to Air
6. Reversible Heat, Water Electrolysis

CHARGE NO. 5

Time	Current	Voltage	%H_2	Temp.-Gravity				Gravity
				Top		Bottom		NRL Battmeter
0700	0-1300	2.00	0	1143	85	1155	86	1153
0730	1300	2.22	.08	1142	87	1171	88	1168
0800	1300	2.24	.15	1144	90	1184	90	1182
0830	1300	2.27	.25	1147	92	1203	90	1200
0900	1300	2.29	.27	1155	94	1219	92	1213
0930	1300-330	2.33-2.19	.39-.30	1165	97	1232	94	1232
1000	330	2.19	.30	1178	98	1244	95	1243
1030	330	2.20	.30	1188	97	1249	98	1248
1100	330	2.20	.38	1198	97	1254	97	1253
1130	330	2.21	.38	1204	97	1256	98	1255
1200	330	2.22	.39	1213	97	1260	97	1258
1230	330	2.23	.39	1219	96	1269	98	1262
1300	330	2.24	.39	1228	96	1267	98	1264
1330	330	2.26	.48	1233	96	1270	99	1266
1400	330	2.28	.48	1242	97	1273	99	1268
1430	330	2.31	.50	1253	97	1274	100	1270
1500	330	2.35	.70	1263	100	1262	103	1272
1530	330	2.38	1.12	1268	101	1266	105	1274
1600	330	2.40	1.80	1271	103	1270	105	1274
1630	330-0	2.41-2.30	2.75	1272	104	1271	107	1275

334 Watts Heating Current in Box
Air Flow Constant at 1.92 cu.ft./min
Manufacturer's Procedure

Time	Temperatures					Cell Box
	1	2	3	4	5	
0700	83	84	85	87	85	74
0730	85	85	86	89	87	77
0800	89	88	89	92	90	79
0830	90	90	90	92	90	80
0900	91	92	91	95	92	82
0930	95	95	94	100	96	82
1000	97	98	97	102	98	82
1030	97	98	98	103	99	83
1100	97	98	99	103	100	82
1130	98	99	99	103	101	82
1200	98	99	99	103	102	82
1230	98	99	100	103	102	82
1300	98	99	100	103	102	82
1330	99	99	101	104	102	82
1400	100	100	102	105	103	82
1430	101	101	103	105	103	82
1500	103	103	103	104	104	83
1530	104	104	104	104	104	83
1600	106	106	106	106	106	83
1630	107	107	107	107	107	83

Group
1. Top Electrolyte, direct ventilation.
2. Top Electrolyte, unventilated.
3. Bottom of Elements.
4. Middle Center of Elements.
5. Middle Side of Elements.

Charge No. 5, Sheet No. 2.

	Air at Intake				Air in Duct				Evaporation
Time	1	2	3	4	1	2	3	4	Grams per minute
0700	.0117	33.13	24	75	.0148	41.91	26	78	.1780
0730	.0120	33.98	26	77	.0160	45.31	28	82	.2242
0800	.0100	28.32	26	78	.0177	50.00	29	84	.4230
0830	.0126	35.68	27	80	.0200	56.64	30	87	.4100
0900	.0137	38.80	27	80	.0185	52.39	32	90	.2770
0930	.0133	37.66	27	79	.0211	59.77	32	90	.4230
1000	.0142	40.21	27	79	.0226	64.00	33	91	.4720
1030	.0146	41.91	26	78	.0230	65.13	32	90	.4620
1100	.0154	43.61	26	78	.0228	64.60	32	90	.4190
1130	.0166	47.01	27	79	.0203	57.95	32	90	.3450
1200	.0150	42.48	27	79	.0216	61.17	32	90	.3770
1230	.0144	41.91	26	78	.0213	60.31	32	90	.3690
1300	.0154	43.61	27	79	.0212	60.03	32	90	.3300
1330	.0146	41.40	27	79	.0203	57.30	32	90	.3210
1400	.0156	44.17	27	79	.0203	57.30	32	90	.2690
1430	.0136	38.52	27	79	.0216	61.17	33	91	.4500
1500	.0150	42.48	27	80	.0234	66.27	33	91	.4740
1530	.0150	42.48	27	80	.0232	65.70	33	91	.4620
1600	.0130	36.81	27	80	.0210	59.47	34	92	.4300
1630	.0163	46.16	27	80	.0230	65.13	34	93	.4850

	Heating Effects			Cooling Effects			Total	Temp. Rise	
Time	1	2	3	4	5	6	Effect	Est.	Actual
0700	2794	2253	0	29	102	0	4915		
0730	2794	2253	289	29	129	58	5119		
0800	2794	2244	543	44	244	109	5184		
0830	2794	2232	900	44	237	180	5465		
0900	2794	2230	969	74	160	194	5564	12°	8°
0930	2794	2216	1390	74	244	278	5804		
1000	2794-	2215-	1433-	74	244	287-	5837-	6.5°	6°
	236	535	1105			221	1337		
1030	236	535	1105	89	266	221	1300	1.5°	
1100	236	525	1390	89	242	278	1542	1.5°	1°
1130	236	525	1390	74	199	278	1600		
1200	236	524	1433	74	217	287	1615	1.8°	1°
1230	236	524	1433	89	213	287	1604		
1300	236	524	1433	74	191	287	1641	1.8°	0°
1330	236	513	1765	74	185	353	1902		
1400	236	513	1765	74	155	353	1932	2.0°	2°
1430	236	510	1870	89	260	374	1893		
1500	236	487	2548	89	273	510	2399	2°	1.5°
1530	236	433	4182	89	266	836	3660		
1600	236	351	6695	103	248	1339	5593	4°	3°
1630	236	235	10198	103	280	2040	8246	3.5°	1°
							Total	35°	23.5°

1. Irreversible Heat
2. Reversible Heat, Normal Reaction
3. Heat of Formation of Gases
4. Conductance to Air
5. Evaporation Loss
6. Reversible Heat, Water Electrolysis

CHARGE NO. 6

Time	Current	Voltage	%H_2	Temp-Gravity Top		Bottom		Gravity NRL Battmeter
0600	0-1300	1.99-2.20	0	1141	91	1150	93	1148
0630	1300	2.22	0	1139	93	1165	94	1160
0700	1300	2.24	.10	1144	96	1174	96	1174
0730	1300	2.26	.20	1146	98	1198	97	1201
0800	1300-1050	2.29	.20	1155	99	1215	98	1215
0830	1050	2.29	.45	1167	100	1229	99	1230
0900	1050-800	2.31-2.29	.45	1185	102	1243	100	1242
0930	800	2.30	.58	1200	104	1251	103	1253
0945	800-550	2.31-2.27	.63	—	—	—	—	—
1000	550	2.28	.63	1217	105	1261	103	1260
1030	550-330	2.31-2.27	.80-.70	1229	103	1265	104	1262
1100	330	2.28	.70	1243	102	1270	104	1266
1130	330-250	2.30-2.29	.80	1252	107	1270	107	1270
1200	250-190	2.30-2.29	.80	1260	107	1271	109	1271
1230	190-165	2.30-2.29	.80	1263	107	1263	110	1276
1300	165	2.30	.80	1266	107	1266	110	1276
1330	165	2.31	.95	1269	107	1268	111	1276
1400	165-330	2.31-2.40	1.30-2.75	1270	109	1268	111	1276
1430	330-0	2.40-2.29	3.12-.70	1270	109	1269	113	1276
1500	0	2.18	.68	—	—	—	—	—
1530	0	2.16	.68	—	—	—	—	—

Bureau Procedure
Air Flow Constant at 1.92 cu.ft./minute

Adiabatic Procedure

Time	Temperature Couple Groups 1	2	3	4	5	Cell Box
0600	92	92	95	96	95	82
0630	93	93	96	98	96	92
0700	96	96	98	100	98	96
0730	99	99	100	103	101	99
0800	101	103	101	106	102	100
0830	103	104	103	109	104	103
0900	105	105	105	109	105	103
0930	105	106	106	110	107	105
1000	105	107	107	112	108	105
1030	108	108	109	112	109	105
1100	108	109	109	112	109	105
1130	109	109	110	113	110	106
1200	110	110	110	112	110	106
1230	111	111	110	112	111	106
1300	111	111	110	111	110	107
1330	111	111	111	110	110	107
1400	112	112	110	110	111	107
1430	112	113	112	113	112	108
1500	112	112	112	113	113	108
1530	112	112	112	113	113	108

Group
1. Top Electrolyte, direct ventilation.
2. Top Electrolyte, unventilated.
3. Bottom Part of Elements.
4. Middle Center of Elements.
5. Middle Side of Elements.

Charge No. 6, Sheet No. 2.

	Air at Intake				Air in Duct				Evaporation
Time	1	2	3	4	1	2	3	4	Grams per minute
0600	.0155	43.90	26	79	.0215	60.90	30	85	.2650
0630	.0180	50.98	27	81	.0220	62.34	30	86	.2280
0700	.0183	51.83	27	81	.0240	67.97	32	90	.3300
0730	.0172	48.71	27	81	.0252	71.37	33	90	.4540
0800	.0192	54.40	26	80	.0290	82.12	33	91	.5565
0830	.0183	51.83	29	83	.0240	67.97	34	93	.3290
0900	.0195	55.22	29	83	.0300	84.96	35	95	.5920
0930	.0152	43.05	28	83	.0270	76.46	35	95	.6840
1000	.0190	53.81	28	82	.0270	76.46	35	95	.4650
1030	.0198	56.10	28	83	.0278	78.72	35	95	.4660
1100	.0198	56.10	29	83	.0286	81.00	36	96	.5060
1130	.0182	51.53	29	84	.0254	71.94	36	96	.4220
1200	.0206	58.13	29	84	.0250	70.80	36	96	.2730
1230	.0206	58.33	29	84	.0238	67.40	36	97	.2075
1300	.0182	51.53	29	85	.0238	67.40	36	97	.3350
1330	.0182	51.53	29	85	.0233	65.99	36	97	.3070
1400	.0188	53.30	30	86	.0286	81.00	37	98	.5620
1430	.0180	50.98	30	86	.0290	82.13	37	98	.6280
1500	.0180	50.98	30	86	.0252	71.37	36	97	.4120
1530	.0180	50.98	30	86	.0252	71.37	36	97	.4120

1. Grams of water per liter of air. 3. Temperature, Centigrade.
2. Grams of water per 100 cu.ft. of air. 4. Temperature, Fahrenheit.

	Heating Effects			Cooling Effects			Total	Temp.Rise	
Time	1	2	3	4	5	6	Effect	Est.	Found
0600	2794	2262	00	56	198	00	4802		
0630	2794	2262	00	42	130	00	4884		
0700	2794	2252	340	70	190	68	5058	5°	3.5°
0730	2794	2240	747	85	262	149	5285		
0800	2794-1955	2240-1808	747	99	324	149	5210-3940	5.5°	4.5°
0830	1955	1775	1700	70	190	340	4830		
0900	1955-1146	1775-1332	1700	85	342	340	4663-3410	5°	3.5°
0930	1146-636	1316	2140	99	395	428	3679-3169		
1000	636	879	2345	99	268	470	3023	3.8°	2.5°
1030	636	874	2548	99	268	509	3182		
1100	636-236	487	2548	99	292	510	2770-2370	3°	2°
1130	236-179	476	2950	99	244	590	2729-2672		
1200	179-109	342-235	2950	99	157	590	2625-2448	2.8°	1°
1230	109-82	235-190	2950	99	119	590	2486-2414		
1300	82	190	2950	99	194	590	2340	2.5°	.5°
1330	82	168	3540	99	177	708	2806		
1400	82-236	123-202	10180	99	325	2036	7925-8158	3°	1°
1430	236-0	185	11220	99	364	2224	8954	4.5°	1°
							Total	35°	18°

1. Irreversible Heat 4. Radiation Loss
2. Reversible Heat, Normal Reaction 5. Evaporation Loss
3. Heat of Formation of Gases 6. Reversible Heat, Water Electrolysis

Charge No. 7,

Sheet No. 1

is missing from original.

Charge No. 7, Sheet No. 2.

	Air at Intake				Air in Duct				Evaporation
Time	1	2	3	4	1	2	3	4	Grams per minute
0600	.0153	43.33	76	24	.0170	48.14	80	27	.1085
0630	.0136	38.52	78	26	.0178	50.30	84	28	.2400
0700	.0138	39.08	79	26	.0178	50.30	85	29	.2110
0730	.0120	33.98	80	27	.0200	56.64	86	30	.4470
0800	.0144	40.78	81	27	.0220	62.34	88	31	.4290
0830	.0123	34.83	82	28	.0220	62.34	89	32	.5400
0900	.0140	39.65	84	29	.0208	58.90	91	33	.3840
0930	.0147	41.66	84	29	.0208	58.90	91	33	.3460
1000	.0137	38.80	83	28	.0217	61.47	91	33	.4320
1030	.0124	35.11	83	28	.0185	52.39	91	33	.3460
1100	.0130	36.81	83	28	.0193	54.70	90	32	.3570
1130	.0130	36.81	83	28	.0184	52.10	90	32	.3080
1200	.0130	36.81	82	28	.0195	55.22	90	32	.3680
1230	.0132	37.38	82	28	.0200	56.64	91	33	.3840
1300	.0137	38.80	83	28	.0200	56.64	90	32	.3570
1330	.0137	38.80	83	28	.0200	56.64	90	32	.3570
1400	.0127	35.96	83	28	.0192	54.40	91	33	.3620
1430	.0130	36.81	82	28	.0200	56.64	91	33	.3950
1500	.0150	44.48	83	28	.0203	57.30	91	33	.2630
1530	.0110	31.15	82	28	.0196	55.50	91	33	.4800
1600	.0110	31.15	82	28	.0164	46.44	91	33	.3000
1630	.0108	30.58	82	28	.0150	42.48	91	33	.2385

1. Grams H_2O per liter of air
2. Grams of H_2O per 100 cu.ft. air
3. Temperature Fahrenheit
4. Temperature Centigrade

	Heating Effects			Cooling Effects			Total	Temp. Rise	
Time	1	2	3	4	5	6	Effect	Est.	Actual
0600	3930	2260	00	42	614	00	5534		
0630	2050	2250	170	28	369	34	4040		
0700	2610	2240	662	42	123	133	5014	5°	5°
0730	2420	2240	747	42	284	149	4932		
0800	2610	2240	747	56	246	149	5146	4.2°	5°
0830	2980	2240	900	56	255	180	5629		
0845	2980-189	2230-540	900	56	222	180	5652-1171		
0900	189	540	900	56	222	180	1171	5°	4°
0930	189	540	900	56	198	180	1195		
1000	237	518	1660	70	159	332	1854	1.5°	0°
1030	237	518	1660	70	198	332	1817		
1100	189	518	1660	56	208	332	1771	2°	.2°
1130	189	518	1660	56	178	332	1801		
1200	237	518	1660	56	198	332	1829	2°	0°
1230	286	518	1660	70	222	332	1840		
1300	189	518	1660	56	318	332	1660	1.8°	.2°
1330	189	504	2015	56	318	404	1931		
1400	237	494	2345	70	214	469	2323	2.4°	.3°
1430	332	476	2955	70	225	591	2877		
1500	142	414	4845	70	277	969	4085	3.2°	1.5°
1530	332	370	6120	70	178	1224	5350		
1600	426	325	7480	70	274	1496	6391	5.6°	3°
							Total	32.7°	19.2°

1. Irreversible Heat
2. Reversible Heat, Normal Reaction
3. Heat of Formation of Gas
4. Radiation Loss
5. Fvaporation Loss
6. Reversible Heat, Water Electrolysis

CHARGE NO. 7A

		Voltage			Temp.-Gravity				Gravity
Time	Current	Closed	Open	$\%H_2$	Top		Bottom		NRL-Battmeter
0-600	0-1300	2.20	1.99	00	1135	87	1148	89	1146
0630	1300	2.22	2.11	.05	1134	90	1164	90	1158
0700	1300	2.24	2.10	.18	1138	92	1178	92	1174
0730	1300	2.26	2.13	.20	1140	94	1192	92	1191
0800	1300	2.28	2.14	.20	1150	96	1213	93	1208
0830	1300	2.31	2.15	.25	1159	97	1225	94	1225
0845	1300-330	2.32-2.19	—	—	—	—	—	—	—
0900	330	2.19	2.15	.25	1175	98	1240	96	1237
0930	330	2.19	2.15	.25	1184	97	1249	96	1242
1000	330	2.20	2.15	.45	1197	98	1249	98	1246
1030	330	2.20	2.15	.45	1024	97	1253	97	1249
1100	330	2.21	2.16	.45	1213	97	1257	97	1254
1130	330	2.22	2.18	.45	1220	96	1260	98	1258
1200	330	2.24	2.19	.45	1227	96	1263	98	1261
1230	330	2.26	2.20	.45	1234	97	1266	98	1263
1300	330	2.27	2.23	.45	1240	96	1270	98	1265
1330	330	2.30	2.26	.55	1250	99	1271	100	1265
1400	330	2.33	2.28	.63	1257	99	1265	102	1266
1430	330	2.36	2.29	.80	1266	102	1265	104	1269
1500	330	2.38	2.30	1.30	1269	103	1268	105	1272
1530	330	2.39	2.30	1.65	1270	103	1269	105	1275
1600	330-0	2.40	2.30	2.00	1271	103	1270	105	1276
1630	0	—	2.20	.65	—	—	—	—	—
1700	0	—	2.15	.40	—	—	—	—	—

	Temperatures Couple Groups					
Time	1	2	3	4	5	Cell Box
0600	86	86	91	92	90	84
0630	89	91	92	94	92	84
0700	92	92	94	96	94	86
0730	94	95	96	100	98	87
0800	97	97	97	101	99	88
0830	99	100	100	103	101	91
0900	100	101	101	106	103	91
0930	100	102	102	106	102	92
1000	100	101	102	106	103	92
1030	99	101	102	106	103	93
1100	99	101	104	106	104	92
1130	99	100	103	106	104	92
1200	98	99	103	106	104	92
1230	99	100	104	106	104	92
1300	99	100	103	106	103	92
1330	101	101	104	105	103	92
1400	102	102	104	103	103	92
1430	104	104	104	104	104	93
1500	104	105	104	105	104	94
1530	105	105	105	105	105	93
1600	107	107	107	107	107	93
1630	106	106	107	107	107	93
1700	106	106	107	107	107	93

CHARGE NO. 7B
(Continuation of Charge 7A)

					Temperatures		
Time	Current	Voltage	%H_2	Air	Cell Top	Main Cell	Insulating Box
0800	0-330	2.11-2.35	0.00	75.6	89	89	78
0830	330	2.44	2.40	79	92	92	82
0900	330	2.45	2.70	84	94	96	86
0930	330	2.45	2.70	83	97	97	89
1030	330	2.45	2.70	82	101	101	89
1130	330	2.45	3.15	82	103	103	90
1200	330-0	2.45-2.25	3.65	81	104	104	91
1300	0	2.17	.48	79	103	104	89
1330	0	2.16	.48	79	102	104	89
1400	0	2.15	.48	79	102	103	89
1500	0	2.14	.48	79	101	102	89
1600	0	2.13	.48	79	100	101	89

Non-adiabatic procedure.

	Heating Effects			Cooling Effects			Total	Temp. Rise	
Time	1	2	3	4	5	6	Effect	Est.	Found
0800	236	280	00	125	300	00	191		
0830	236	235	8956	125	300	1800	7200		
0900	236	235	10,028	125	300	2005	8050	8°	7°
0930	236	235	10,028	125	300	2005	8050		
1000	236	235	10,028	125	300	2005	8050		
1030	236	235	10,028	125	300	2005	8050		
1100	236	168	10,028	125	300	2005	7980		
1130	236	112	11,763	125	300	2353	9333		
1200	236	112	13,620	125	300	2724	10818	10.5°	8°
1230	000	000	1765	125	300	—	—		
1300	—	—	1765	125	300	—	—		
1330	—	—	1765	125	300	—	—		
1400	—	—	1765	125	300	—	—		
1430	—	—	1765	125	300	—	—		
1500	—	—	1765	125	300	—	—		
1600	—	—	1765	125	300	—	—		
							Total Effect	18.5°	15°

1. Irreversible Heat
2. Reversible Heat, Normal Reaction
3. Heat of Formation of Gases
4. Conductance to Air, Estimated
5. Radiation to Air, Estimated
6. Reversible Heat, Water Electrolysis

CHARGE NO. 8

Time	Current	Voltage			Temp.-Gravity				Gravity NRL Batt-meter
		Closed	Open	$\%H_2$	Top		Bottom		
0600	0-1300	2.20	2.00	.00	1147	84	1162	85	1156
0630	1300	2.23	2.10	.00	1147	85	1175	86	1166
0700	1300	2.24	2.10	.10	1150	90	1188	88	1186
0730	1300	2.26	2.11	.20	1156	91	1211	89	1203
0830	1300	2.31	2.15	.32	1180	95	1238	93	1235
0842	1300-1050	2.33-2.30	--	--	--	--	--	--	--
0900	1050	2.32	2.19	.50	1200	97	1252	94	1248
0910	1050-800	2.33-2.30	--	--	--	--	--	--	--
0930	800	2.32	2.22	.50	1220	98	1264	94	1256
0940	800-550	2.33-2.29	--	.56-.50	--	--	--	--	--
1000	550	2.30	2.22	.55	1236	95	1270	96	1268
1030	550-330	2.33-2.28	2.23	.70-.60	1254	95	1274	97	1272
1100	330	2.30	2.26	.70	1261	97	1277	98	1276
1130	330-250	2.33-2.31	2.27	.75-.70	1270	98	1273	101	1280
1140	250-190	2.32-2.31	--	.83-.75	--	--	--	--	--
1200	190	2.31	2.27	.75	1274	98	1273	101	1282
1230	190-165	2.32	2.28	.95-.83	1277	98	1276	102	1284
1300	165-0	2.32	2.29	.95	1279	98	1278	102	1285
1330	0	--	--	--	--	--	--	--	--

Non-adiabatic Procedure
Air Flow Constant at 1.92 cu.ft./min.

Time	Temperatures Couple No. 1	2	3	4	5	6	7	8	9	10	Cell Box
0600	84	86	86	85	88	90	89	85	86	88	75
0630	87	91	90	88	91	92	92	87	87	88	78
0700	87	91	90	90	93	94	94	91	90	88	81
0730	89	93	92	91	95	95	96	92	92	90	81
0800	87	93	91	91	95	97	97	94	92	91	82
0830	89	95	93	93	98	99	100	95	96	95	85
0900	92	98	96	98	101	103	104	98	99	99	86
0930	93	100	99	99	103	104	105	99	100	100	89
1000	96	103	101	100	103	107	106	100	102	100	89
1030	97	103	103	100	103	108	104	100	102	100	89
1100	98	103	103	101	103	107	104	101	102	101	89
1130	100	103	103	103	103	106	104	102	103	101	89
1200	101	103	103	103	103	104	103	103	103	101	89
1230	101	103	103	104	104	104	103	103	103	101	89
1300	103	103	103	104	103	103	103	103	103	103	89

For location of couples, see Plate No. I.

Charge No. 8, Sheet No. 2.

	Air at Intake				Air in Duct				Evaporation
Time	1	2	3	4	1	2	3	4	in grams
0600	.0094	26.60	21	70	.0106	30.01	25	77	.0768
0630	.0075	21.34	21	71	.0120	33.98	25	77	.2500
0700	.0090	25.49	23	74	.0156	44.17	27	81	.3800
0730	.0082	23.22	25	77	.0176	49.84	29	84	.5200
0800	.0095	26.90	26	79	.0184	52.10	31	87	.4940
0830	.0100	28.32	26	78	.0200	56.64	32	90	.5550
0842	.0084	23.79	26	78	.0200	54.40	31	89	.5970
0900	.0084	23.79	26	78	.0192	54.40	31	89	.5970
0910	.0084	23.79	26	80	.0186	54.40	31	89	.5650
0930	.0084	23.79	26	80	.0186	52.70	31	89	.5700
0940	.0083	23.51	25	76	.0188	52.70	31	89	.5700
1000	.0083	23.51	24	75	.0190	53.81	31	89	.6504
1030	.0075	21.34	24	75	.0171	48.42	31	89	.5720
1100	.0075	21.34	26	78	.0176	49.84	31	88	.6130
1120	.0070	19.82	26	78	.0163	46.16	31	88	.5680
1140	.0070	19.82	26	78	.0163	45.00	31	88	.5680
1230	.0078	22.09	25	77	.0157	44.46	31	88	.4390
1300	.0074	20.96	25	78	.0174	49.28	31	88	.5520

1. Grams of water per liter of air. 3. Temperature, Centigrade.
2. Grams of water per 100 cu.ft. of air. 4. Temperature, Fahrenheit.

	Heating Effects			Cooling Effects			Total	Temp. Rise	
Time	1	2	3	4	5	6	Effect	Est.	Found
0600	3857	2240	00	43	56	0	5998		
0630	2890	2240	00	144	56	0	4930	5.6°	4°
0700	2890	2240	340	219	56	68	5127	5.6°	4°
0730	2890	2240	750	300	56	150	5374		
0800	2890	2240	750	285	70	150	5375	6°	2°
0830	2890	2240	1170	320	84	240	5656		
0900	2890-1950	2240-1760	1870	345	70	400	6185-4765	6°	6°
0910	1950-1150	1760-1325	1870	326	70	400	4783-3549		
0930	1150	1325	1870	328	80	400	3537		
0940	1150-630	1325-924	1870	340	80	400	3525-2604		
1000	630	924	2000	304	98	500	2652	4°	3°
1030	230	924-505	2548-2225	319	98	510-445	2775-2098		
1100	230	505	2548	296	70	510	2407	2.7°	1°
1120	143	505-336	2690	283	70	540	2445-2276		
1140	140	336-241	2690	283	70	540	2273-2178	2.7°	.5°
1230	99	213-180	3125	253	84	625	2475-2442		
1300	66	180	3540	318	84	710	2674	3°	.5°
							Total	30°	17°

1. Irreversible Heat
2. Reversible Heat, Normal Reaction
3. Heat of Formation of Gases
4. Evaporation Loss
5. Radiation Loss to Air
6. Reversible Heat, Electrolysis of Water

CHARGE NO. 9

Time	Current	Voltage		%H_2	Temp.-Gravity				Gravity
		Closed	Open		Top		Bottom		NRL Battmeter
0700	0-1300	2.20	2.00	0.00	1167	81	1181	81	1175
0730	1300	2.25	2.12	.00	1163	85	1195	82	1185
0800	1300	2.27	2.13	.02	1156	89	1206	83	1203
0830	1300	2.31	2.15	.07	1153	91	1225	86	1219
0900	1300-1050	2.34	2.17	.10	1159	95	1237	88	1237
0930	1050-800	2.34-2.30	2.18	.15	1172	95	1252	88	1248
1000	880-550	2.34-2.30	2.24	.18	1190	97	1261	91	1256
1030	550-330	2.33-2.27	2.25	.19	1208	97	1268	92	1261
1100	330	2.30	2.28	.19	1220	96	1272	92	1264
1130	330-250	2.34-2.28	2.28	.40	1243	98	1274	94	1265
1200	250-190	2.34-2.31	2.28	.40	1254	99	1271	97	1265
1230	190	2.32	2.28	.40	1261	99	1260	101	1270
1300	190-165	2.35-2.32	2.28	.40	1264	99	1263	101	1272
1330	165	2.33	2.28	.40	1266	100	1265	101	1274
1400	165	2.33	2.28	.50	1268	100	1267	102	1275
1430	165	2.33	2.28	.55	1269	100	1268	102	1276
1500	165	2.33	2.28	.60	1269	101	1268	104	1278
1530	165	2.34	2.28	.90	1270	102	1269	105	1278
1600	165	2.36	2.28	1.00	1270	103	1269	107	1278
1630	165	2.36	2.28	1.00	1270	104	1269	107	1278
1700	165-0	2.36	2.28	1.00	—	—	—	—	—

Adiabatic Procedure
Air Flow Constant at 1.92 cu.ft./min.

Time	Air	Temperatures									
		1	2	3	4	5	6	7	8	9	10
0700	75	79	79	80	79	80	81	81	80	80	80
0730	77	80	81	81	81	83	83	83	81	81	80
0800	79	82	83	83	84	85	84	86	84	83	83
0830	79	82	84	84	87	88	86	88	88	84	84
0900	78	84	86	86	91	91	90	92	92	91	91
0930	78	86	88	88	93	93	92	94	94	92	94
1000	78	88	89	90	94	95	95	96	96	96	96
1030	78	90	91	93	96	98	97	99	96	97	97
1100	79	91	94	94	97	98	98	99	97	97	97
1130	79	92	96	96	97	99	99	99	97	98	97
1200	78	94	96	95	98	99	99	99	98	99	99
1230	80	96	99	98	99	99	99	99	99	99	99
1300	78	98	99	99	99	99	99	99	99	99	99
1330	79	100	100	100	100	101	100	100	100	100	100
1400	80	101	101	101	101	101	101	101	101	101	101
1430	80	102	102	103	103	101	102	101	102	102	103
1500	80	103	103	103	103	102	103	102	103	103	103
1530	80	104	104	104	104	103	104	103	104	104	104
1600	80	104	105	104	104	104	104	104	104	104	104
1630	80	105	105	105	105	105	105	105	105	105	105
1700	80	106	106	106	106	106	106	106	106	106	106

DISCHARGE TESTS

No. 1

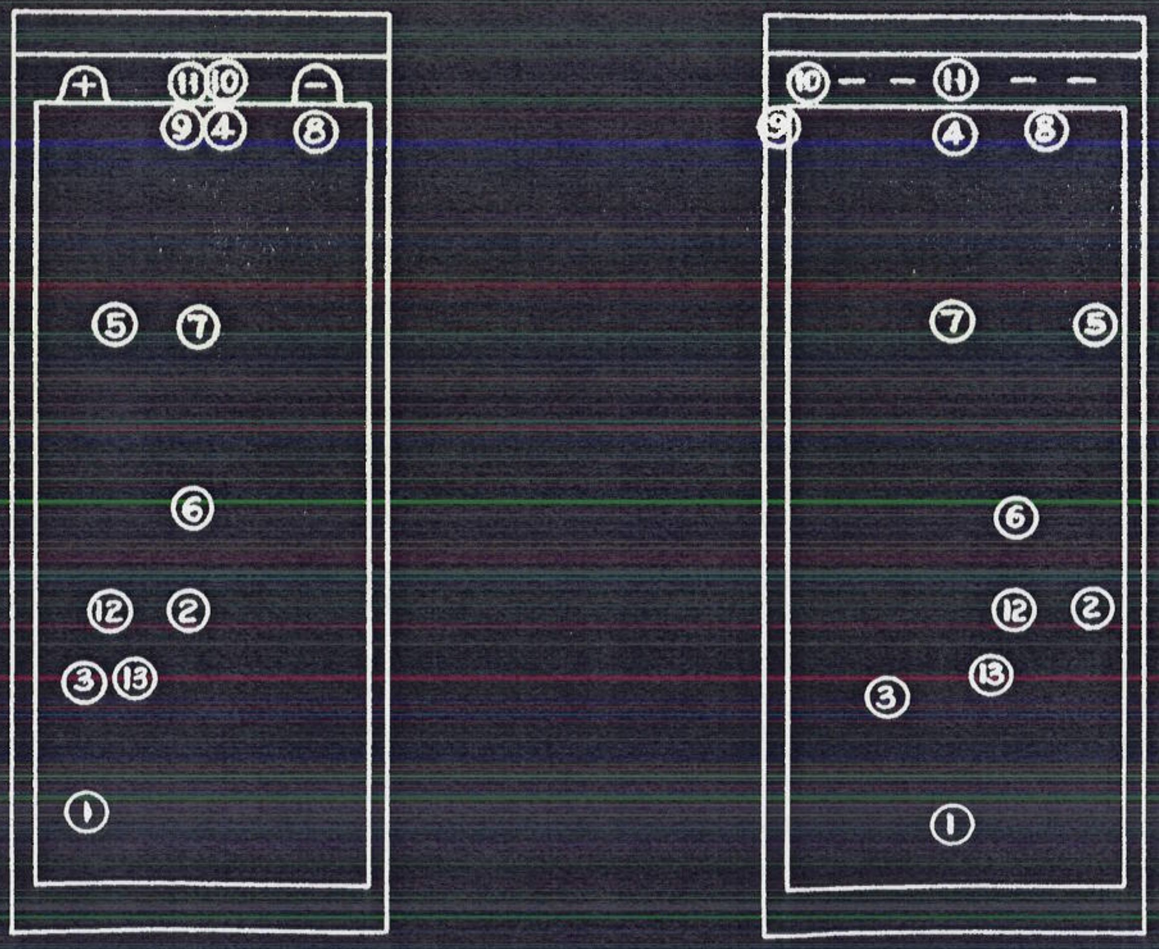
Time	Current	Temperatures 1	2	3	4	5	6	7	8	9	10	11	12	Cell Box
0800	0-2000	96	96	98	95	100	100	99	95	95	95	95	96	84
0840	2000	97	97	99	106	102	101	102	106	106	106	106	99	85
0900	2000	98	97	100	107	103	102	102	108	108	108	108	101	85
1000	2000	101	103	103	113	108	106	106	115	115	115	115	104	87
1030	2000-0	102	103	106	116	112	111	110	118	118	118	118	106	90
1130	0	103	103	106	114	110	108	109	114	114	114	114	106	90
1230	0	103	103	106	108	110	107	109	109	109	109	109	104	89
1330	0	103	103	106	108	108	106	108	108	108	108	108	104	87
1430	0	102	102	106	106	106	106	106	104	104	104	104	103	86
1530	0	101	102	104	104	105	106	106	104	104	104	104	103	86

No. 2

Time	Current	Temperatures 1	2	4	5	6	7	8	9	10	11	12	Cell Box
0830	0-2000	93	93	93	94	94	94	92	93	93	93	94	79
0900	2000	94	94	100	97	95	96	100	100	100	100	95	91
0930	2000	94	94	104	101	98	100	105	105	105	105	98	91
1000	2000	96	96	105	104	102	103	109	109	109	109	100	93
1030	2000	97	97	108	106	104	104	111	111	111	111	102	94
1100	2000-0	101	101	110	112	106	107	114	114	114	114	105	97
1300	0	103	103	106	106	104	107	106	106	106	106	103	89

Air range: 79-85°

APPROXIMATE LOCATION OF THERMOCOUPLES



FOR EXACT LOCATIONS SEE ATTACHED PLATE

PLATE 1

TEMPERATURE-TIME CURVES CHARGE 7

FOR LOCATION OF COUPLE GROUPS SEE PLATE I.

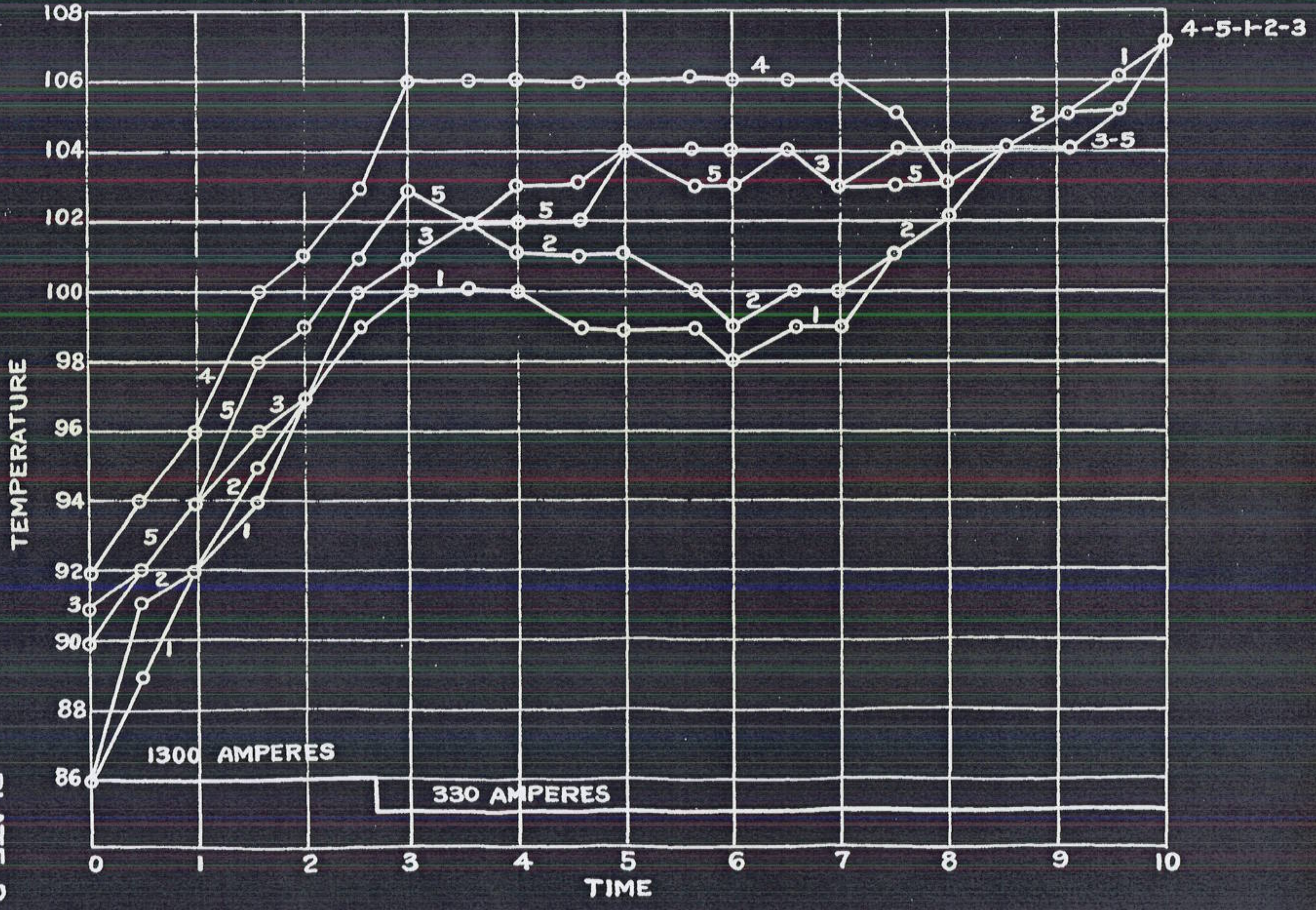


PLATE 2

TEMPERATURE-TIME CURVES CHARGE 9
FOR EXPLANATION OF THERMOCOUPLE GROUPS SEE PLATE 1

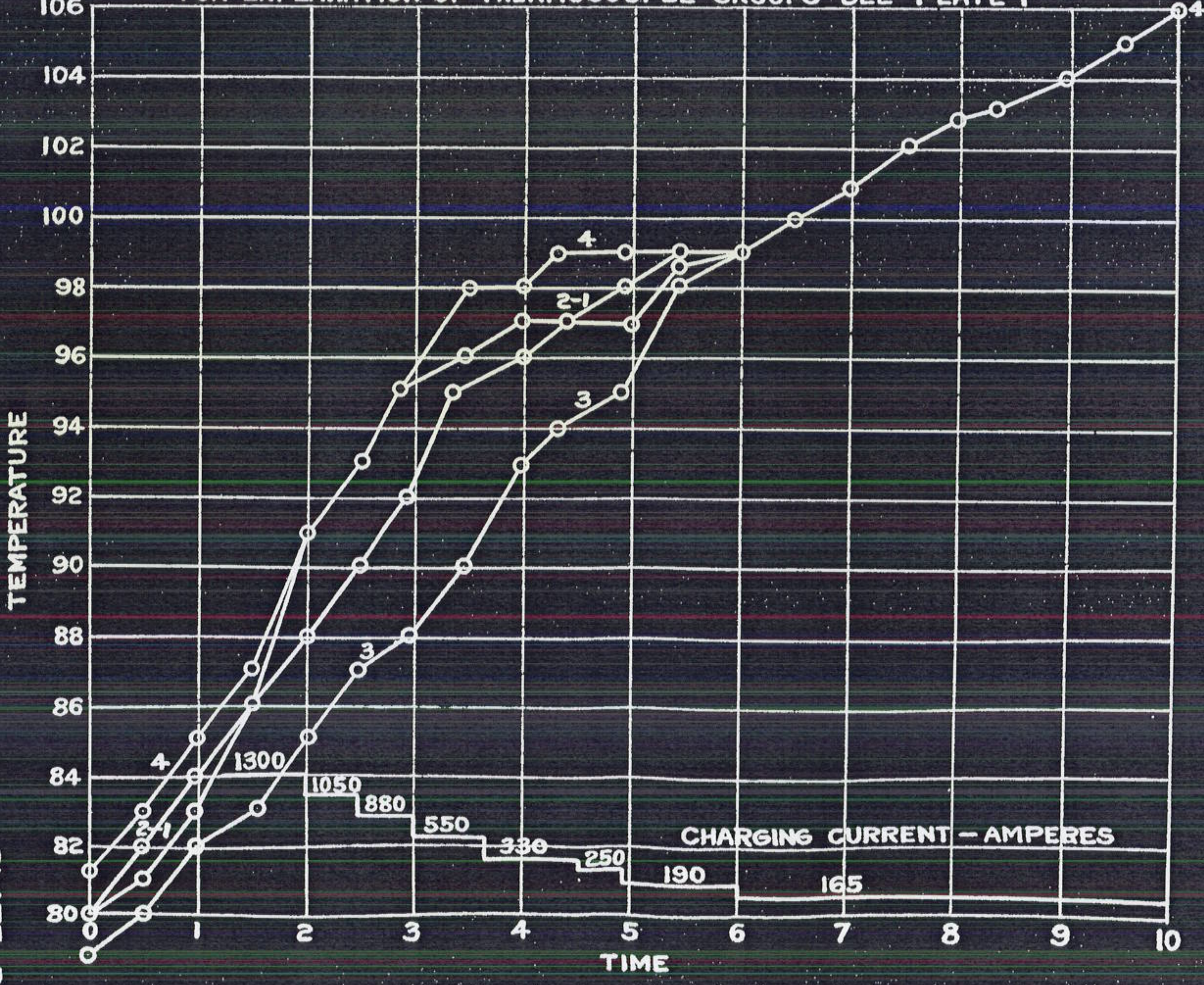


PLATE 3

TEMPERATURE-TIME CURVES CHARGE 10
FOR LOCATION OF COUPLES SEE PLATE 1.

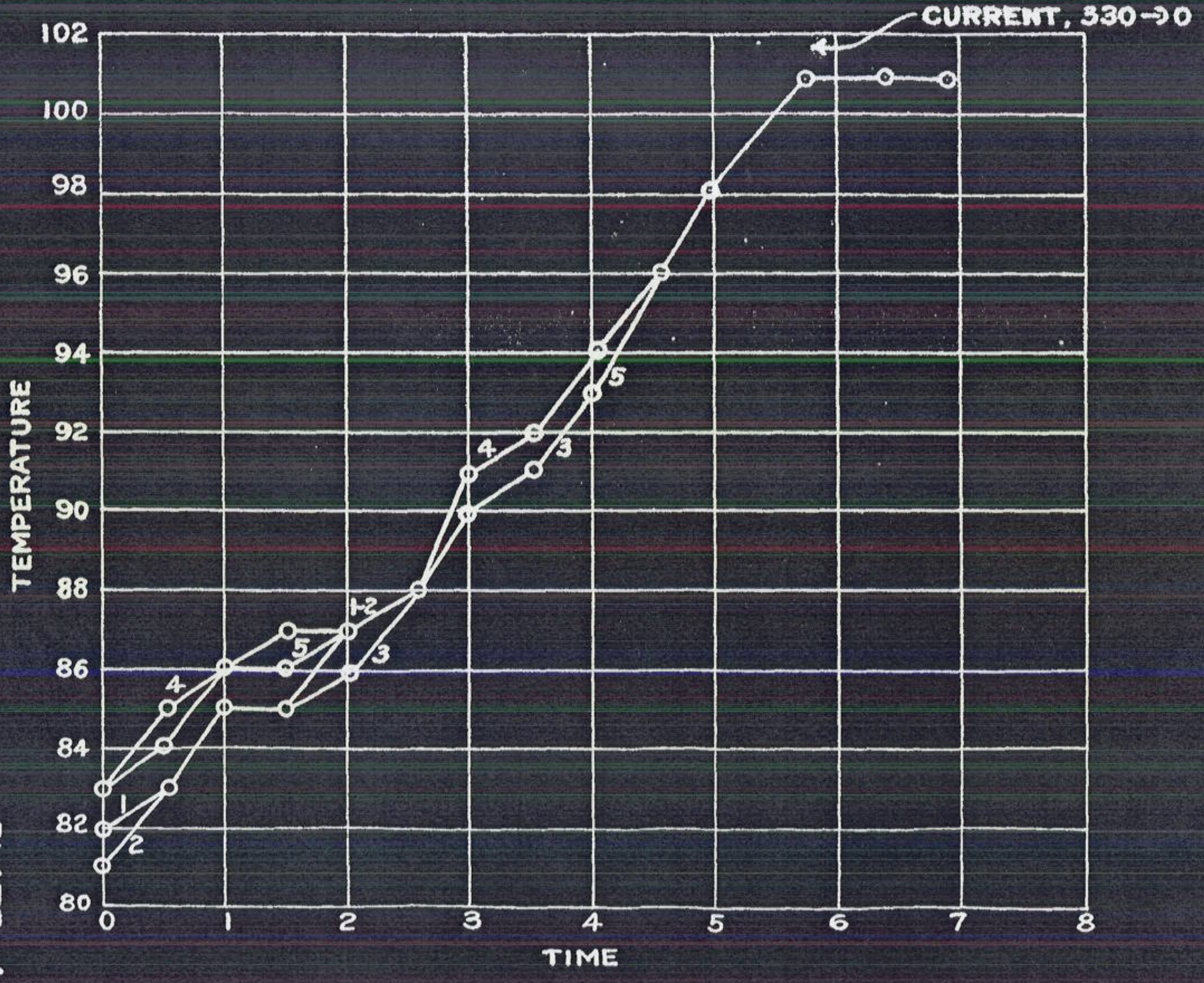
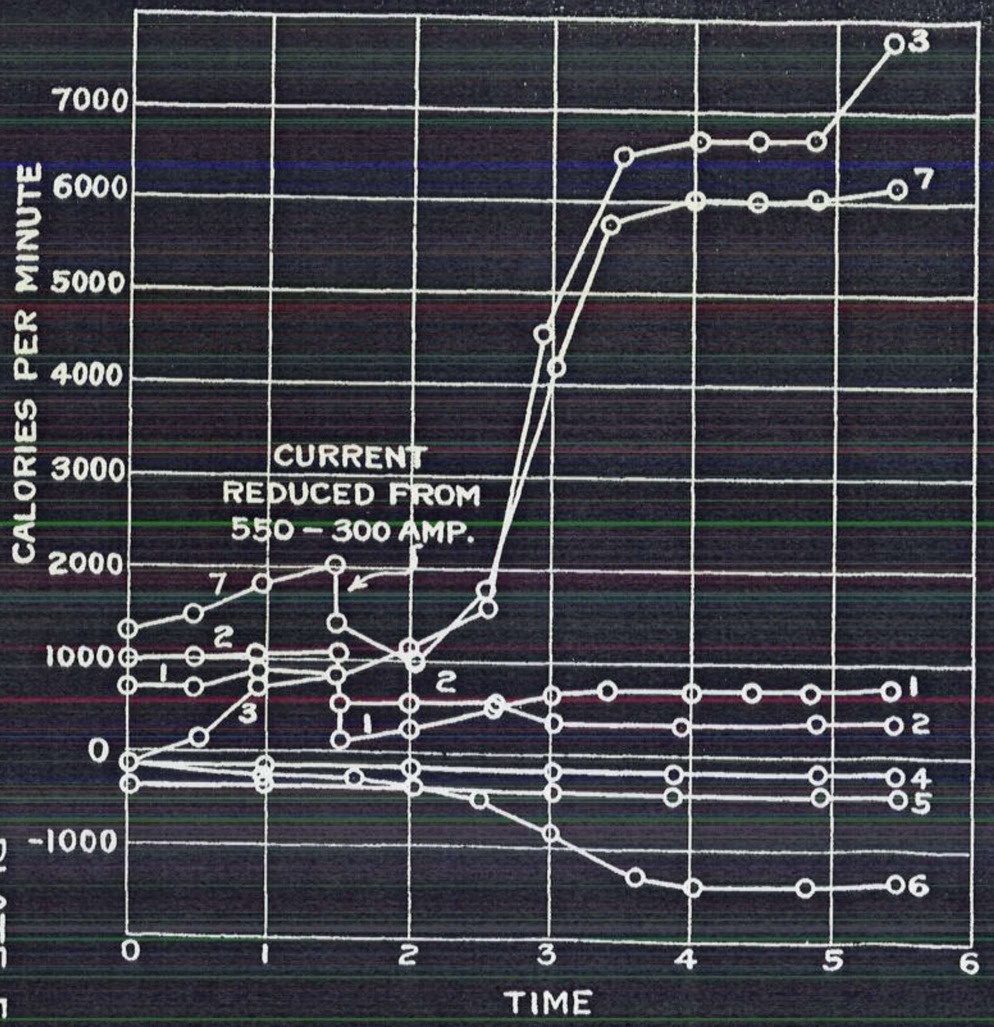


PLATE 4

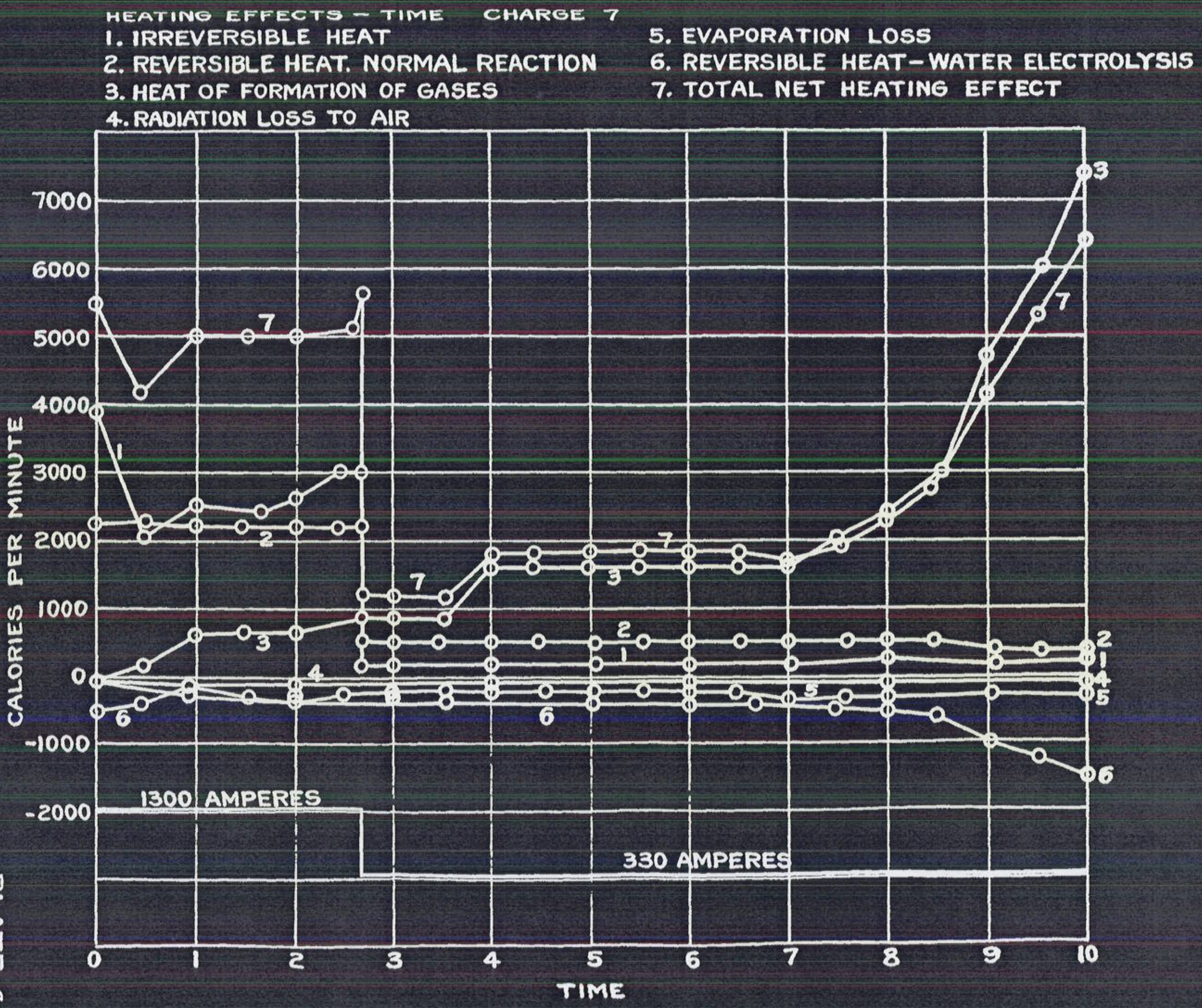
PLATE 5



HEATING AND COOLING EFFECTS - CHARGE 10

1. IRREVERSIBLE HEAT
2. REVERSIBLE HEAT, NORMAL REACTION
3. HEAT OF FORMATION OF GASES
4. RADIATION LOSS TO AIR
5. EVAPORATION LOSS
6. REVERSIBLE HEAT, WATER ELECTROLYSIS
7. TOTAL EFFECT

PLATE 6


HEATING EFFECTS — TIME CHARGE 7
1. IRREVERSIBLE HEAT
2. REVERSIBLE HEAT. NORMAL REACTION
3. HEAT OF FORMATION OF GASES
4. RADIATION LOSS TO AIR
5. EVAPORATION LOSS
6. REVERSIBLE HEAT-WATER ELECTROLYSIS
7. TOTAL NET HEATING EFFECT
CALORIES PER MINUTE
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000
TIME
0
1
2
3
4
5
6
7
8
9
10
1300 AMPERES
330 AMPERES
1
2
3
4
5
6
7

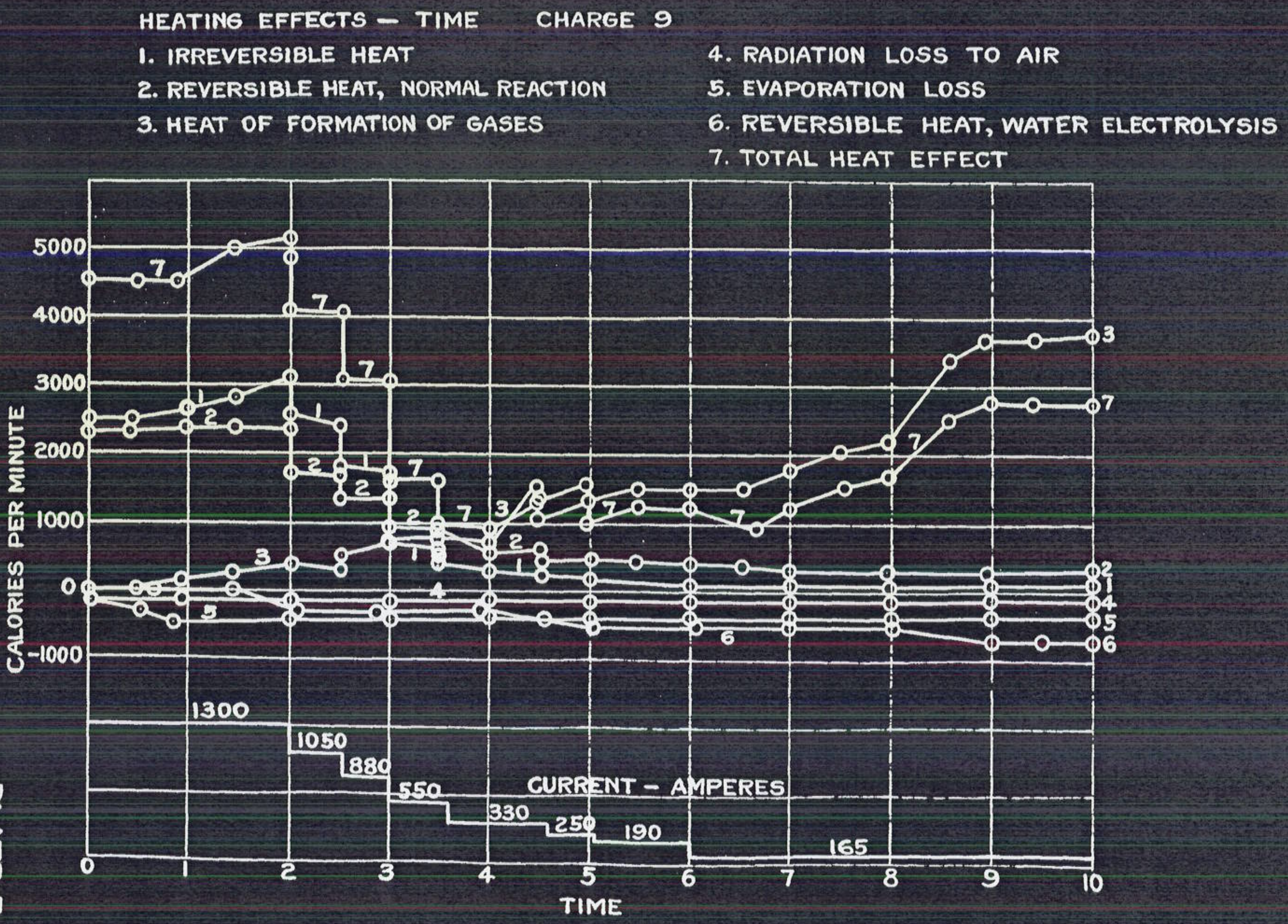

HEATING EFFECTS — TIME CHARGE 9
1. IRREVERSIBLE HEAT
2. REVERSIBLE HEAT, NORMAL REACTION
3. HEAT OF FORMATION OF GASES
4. RADIATION LOSS TO AIR
5. EVAPORATION LOSS
6. REVERSIBLE HEAT, WATER ELECTROLYSIS
7. TOTAL HEAT EFFECT
CALORIES PER MINUTE
5000
4000
3000
2000
1000
0
-1000
CURRENT - AMPERES
1300
1050
880
550
330
250
190
165
TIME
0
1
2
3
4
5
6
7
8
9
10

PLATE 7

MOISTURE LOSS (EVAPORATION) - TIME HYDROGEN PERCENTAGE - CHARGE 7

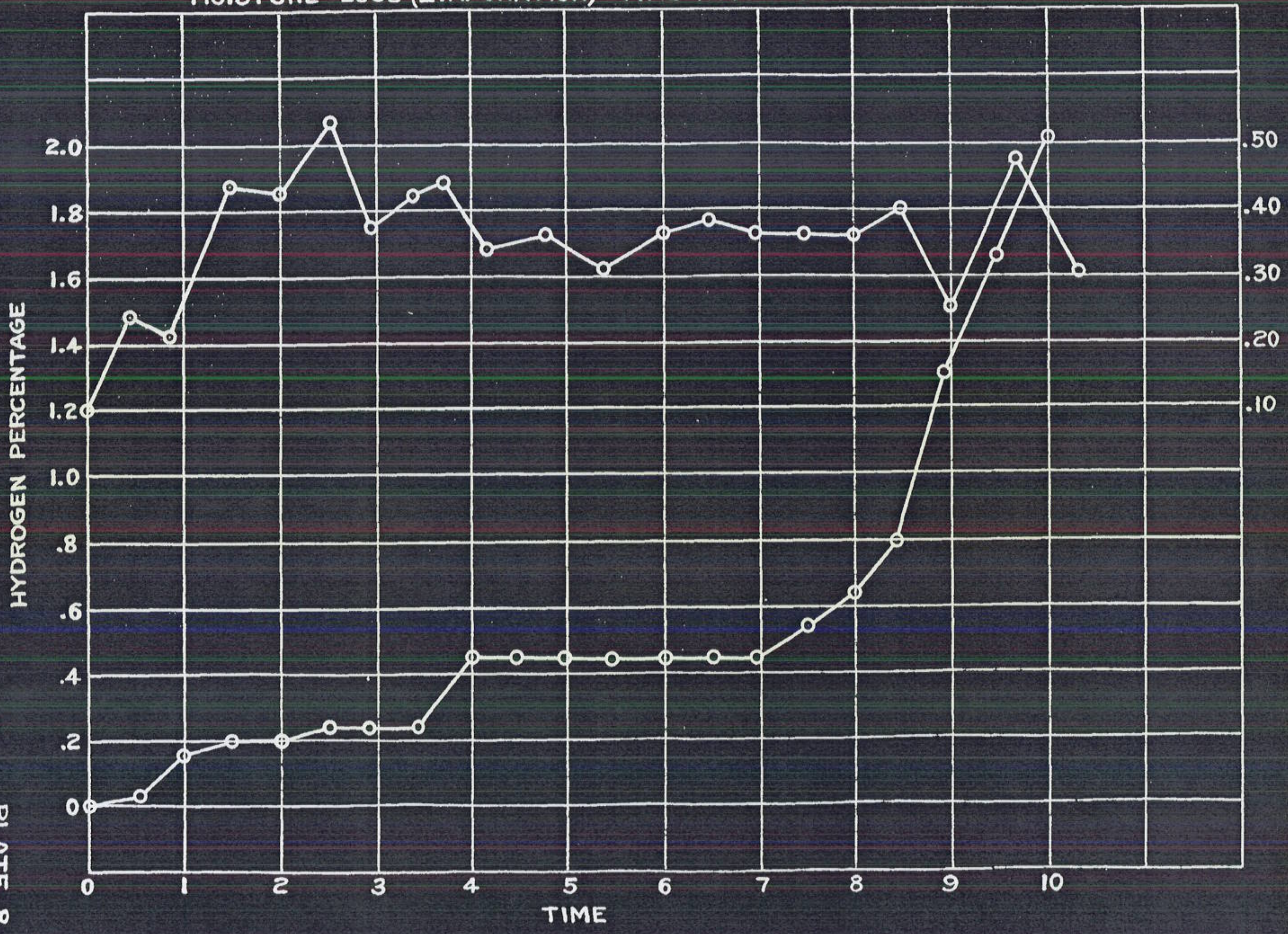


PLATE 8

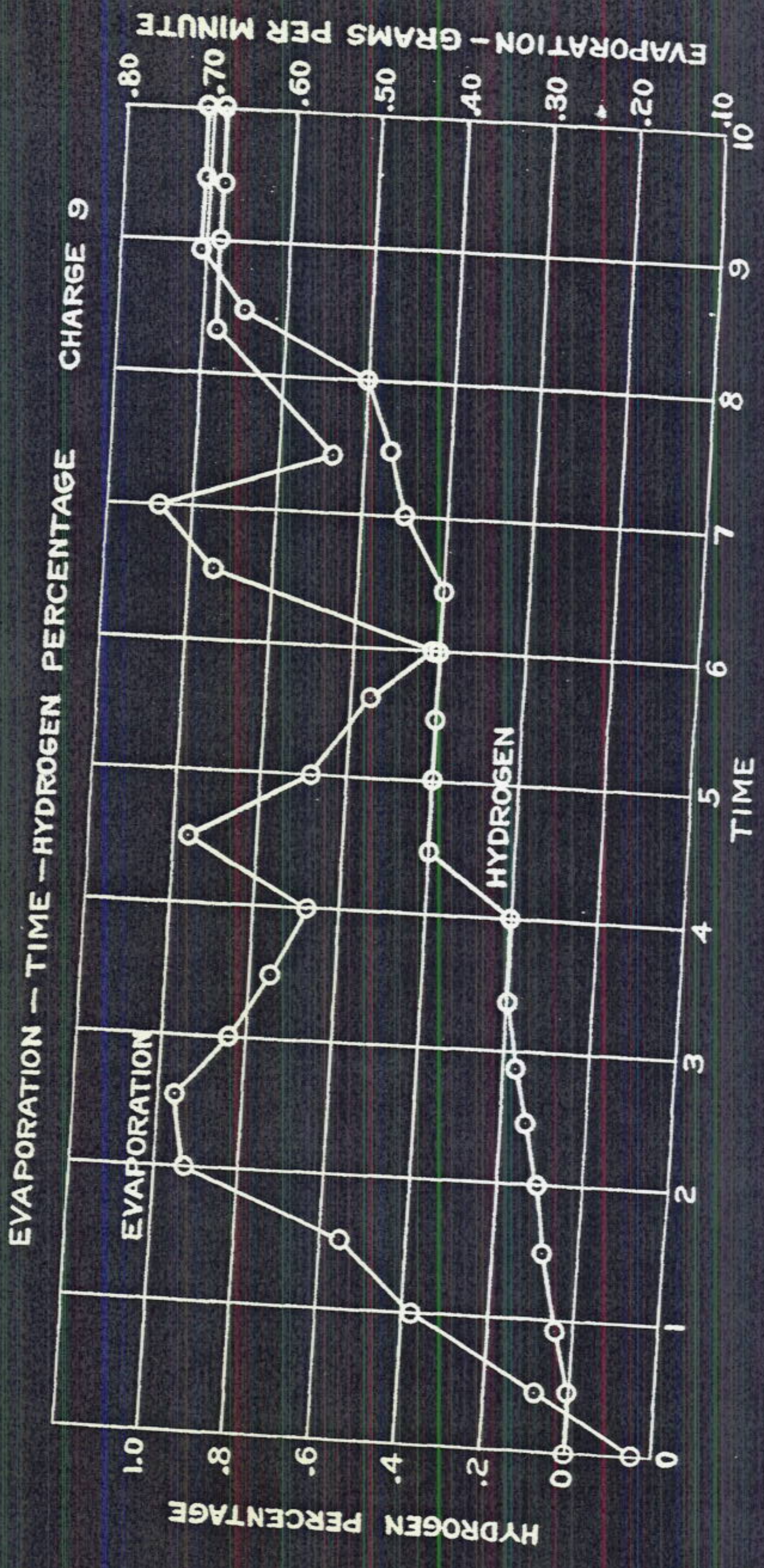

EVAPORATION — TIME — HYDROGEN PERCENTAGE CHARGE 9
EVAPORATION
HYDROGEN
TIME
EVAPORATION - GRAMS PER MINUTE
HYDROGEN PERCENTAGE
.80
.70
.60
.50
.40
.30
.20
.10
1.0
.8
.6
.4
.2
0.0
0
0
1
2
3
4
5
6
7
8
9
10

PLATE 9