Lead-Acid Battery:

Electrochemical Characterization of the Bell System Battery: Field Trials of the Battery

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The electrochemical characteristics of pure lead circular grids, pasted plates and seperators were studied individually and then extrapolated to encompass a full battery. We present polarization data for grids and pasted plates. These can be scaled to predict battery behavior when one takes the role of the separator into consideration.

Proper venting of entrapped gases results in capacity behavior of the circular cell which is at least equal to equivalent commercial cells. The overcharge or float behavior was shown in the laboratory to be excellent. Field trials have confirmed the laboratory tests and have shown that the battery has excellent capacity and float characteristics which ensure that this capacity will be retained for long periods of time.

I. INTRODUCTION

In a preceding paper P. C. Milner has outlined a quantitative description of the float characteristics of the lead-acid battery in terms of the various electrode reactions occurring under float conditions and has summarized some of the available data on lead-calcium cells by providing numerical values for the various parameters.[1] In this paper we present the results of measurements on the polarization of the two electrodes of the new Bell System lead-acid battery and analyze them in the framework of Milner's model. On the basis of these measurements, we can make certain statements about the float operation of the new cell.

A second topic covered in this paper is the capacity of the cell and the factors that affect it: discharge rate and cell design, including electrode configuration and venting arrangements. We include, also,

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some results of field trials that have been carried out in the New Jersey Bell Murray Hill Central Office and four AT & T Long Lines locations.

II. FLOAT CHARACTERISTICS

To determine the float characteristics of the new cell, it has proved advantageous to study separately the polarizations of the positive and negative plates. During the early stages of the work, it was found that the current drawn by an unpasted grid at some specified overpotential was quite appreciable in comparison with that drawn by a fully formed, fully charged pasted plate at the same overpotential, in spite of the fact that the surface areas, as determined by the B. E. T. technique, are grossly different. In Sections 2.1 and 2.2, therefore, we present polarization data on both pasted and unpasted grids, first for the positive and then the negative.

2.1 *Polarization of Positive Plates and of Unpasted Grids Held Near the Positive Plate Reversible Potential*

Polarization data were obtained by standard techniques. Design "B" pure lead circular positive grids were used in this investigation.[2] The properties of this grid design are as follows: 2.6 lbs. grid weight; 164 in.^{2} grid surface area; 15.2 in.^{3} pasteable volume; 5.0 lbs. pasted plate weight. All pasted positive plates referred to in this paper were pasted with tetrabasic lead sulfate.[3] The plate to be measured was placed in a tank of 1.210 specific gravity sulfuric acid. The tank also contained appropriate circular counter-electrodes and separators made of microporous rubber, placed approximately 5 cm from the plate. Electrode potential measurements were made by connecting through a H_2SO_4 salt bridge to a standard Hg/Hg_2SO_4 reference electrode.
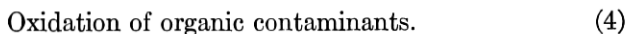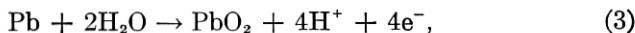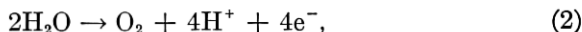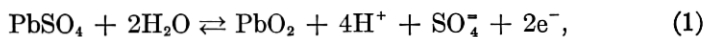
All measurements to be reported in this section were carried out at room temperature. Measurements were carried out either galvanostatically or at constant voltage. The results obtained by these two different methods were found to agree; however, since the galvanostatic method was found in practice to yield reproducible data more rapidly, this method was used for most of the measurements. To perform a set of measurements, the current was set at the desired value and potential measurements using a high impedance digital voltmeter that is accurate to 0.3 mV was begun.

Typically, a time interval of two to ten days would be required for the potential to reach a steady value; at the higher currents a steady state was reached more rapidly. No effort was made to stir the electro-

lyte or to control the dissolved oxygen level. Once a stable electrode potential had been reached, the current would be changed and a new value for the potential obtained in the same manner. A typical experimental run of this kind occupied approximately two months; on this time scale, the polarization data were usually reasonably reproducible and independent of the order in which the points had been obtained.

Measurements were also made on grids that had been held for a prolonged interval (3 months) at a large positive overpotential ($>$ 1.340 V vs Hg/Hg_2SO_4). Here again it was found that a reproducible polarization curve was obtained, displaced, however, from the initial polarization curve.

Figure 1 shows the results of typical sets of measurements and we begin by noting that the following reactions may contribute to the current required to polarize the positive electrode:

$$PbSO_4 + 2H_2O \rightleftarrows PbO_2 + 4H^+ + SO_4^- + 2e^-, \tag{1}$$

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^-, \tag{2}$$

$$Pb + 2H_2O \rightarrow PbO_2 + 4H^+ + 4e^-, \tag{3}$$

$$\text{Oxidation of organic contaminants.} \tag{4}$$

The first thing to note is that Fig. 1 shows that current passed by the unpasted grid at an overpotential similar to that found in Bell System
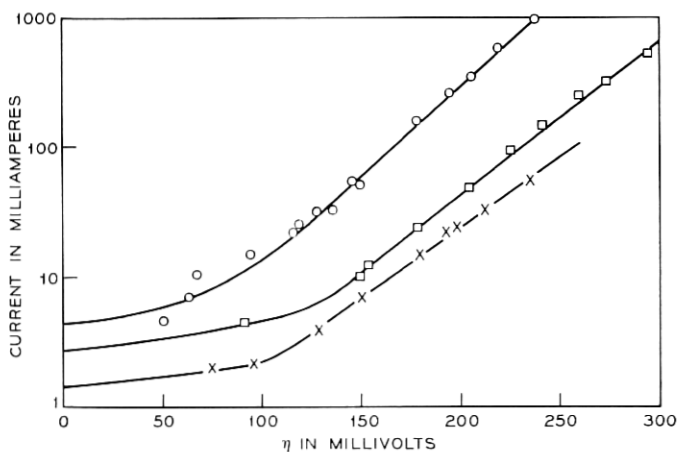

Fig. 1—Polarization data for pasted and unpasted pure-lead circular positive grids. Positives: O, pasted plates; ×, □, bare grids; ×, initial; □, after prolonged high polarization.

usage is only a factor of four lower than that passed by the pasted plate, whereas the surface areas are obviously very different. Measurements of surface area, made by the B. E. T. method, indicated in fact that the ratio of real area to superficial area of the pasted plate is about 20,000 : 1.[4] The current density distribution on porous electrodes is very complex and work is in progress to aid our understanding of this fundamental problem. The data show, however, that the PbO_2 paste utilizes proportionately only a very small fraction of the current supplied to the pasted grid and this implies that the PbO_2 paste material plays a relatively minor role in the evolution of oxygen based on its overall surface area [reaction (2)]. The second thing to note is that the currents passed by the unpasted plates at a given overpotential increase after being held for a prolonged period at a relatively large positive overpotential. We attribute this increase in current to the enhanced corrosion at high overpotentials and the subsequent increase in the true surface area of the electrode.[2]

It would, of course, be desirable to be able to separate the observed currents into the four component parts represented by equations (1) to (4). In particular, it would be of the very greatest interest to determine how much of the current is to be ascribed to reaction (3), since it is this reaction—the corrosion of the grid—that limits the life of the battery.[5-6] Unfortunately, we cannot report on this at this time. The contribution of reaction (1) can be obtained by careful Tafel measurements at very low overpotentials and reaction (4) can be eliminated by using very pure systems. Thus one is left with reactions (2) and (3). Where a soluble species is involved, the associated current may be detected by rotating ring-disc methods. Since the O_2 that is evolved is a soluble species that can be reduced at the ring, one can obtain the fraction of the current that goes into grid corrosion. We have obtained some preliminary ring-disc measurements and will report on this at a later date.

Fitting the data to equation (13) of Milner's paper, we obtain values for the parameters b_+ , and I_0^+ shown in Table I. We also define a parameter "I_e" which is the difference between the intercept of the extension of the Tafel line to $\eta_+ = 0$ and the true extrapolated float current at $\eta_+ = 0$. In using Milner's equation (13), we have in effect obtained a first-order fit to the departure from the Tafel law by subtracting out a constant current which we call "I_e", neglecting, as does Milner, the potential dependence of the corrosion current which Baker reported.[7] Otherwise, the following points deserve comment. The values for b_+ on unpasted grids are consistently higher than the

TABLE I—ELECTROCHEMICAL CHARACTERISTICS
OF BTL POSITIVE ELECTRODES

	b_+ (mV/decade)	"I_e"* (μA/AH)	I_0+* (μA/AH)
Pasted Plates	73	60 ± 10	8.5
Unpasted Grids 1 (Initial)	87	26	3.0
Unpasted Grids 2	84	41	3.4

* Data for both pasted and unpasted plates were normalized by dividing by 53 AH which is the 5 hour rated capacity for the positive pasted plate.

"typical value" of 70 mV cited by Milner for lead-calcium pasted plates. Data obtained by us on commercial Pb/Ca pasted grids show values of b_+ , I_0 and "I_e" which are comparable to our data obtained for the pure lead pasted plates indicating that the effect is not alloy dependent but results from omission of the paste. This is to be expected since, at time zero at least, there are no fundamental reasons why the Pb/Ca and pure Pb systems should have different Tafel slopes (b_+). These values would be expected to change, however, as the positive plates age and the area for corrosion and oxygen evolution increase.[2] This is indicated by our observation that holding the grids at a relatively high overpotential increased I_0^+ and "I_e". As was stated previously, we attribute this to enhanced corrosion at high overpotentials which has resulted in an increase in the true surface area of the electrode.

2.2 Polarization of Negative Plates and Negative Grids Held Near the Negative Plate Potentials

Experimental data were obtained in exactly the same way as those for the positive plates. The geometry, counter-electrode, separator and reference electrode were all the same; the electrolyte was unstirred and no effort was made to control the oxygen content. Again, measurements were made for the most part galvanostatically; steady-state potentials were typically reached in two to ten days. Since corrosion of the negative electrode does not occur, no effect was anticipated of holding this electrode for a long period under high negative polarization conditions. Experimental results have verified this.

The physical properties of the negative plates studied are summarized later (see Section 3.1). Pasted negative plates used in this study were pasted with a commercial negative paste formulation. Figure 2 shows the results of a typical set of measurements on unpasted grids and on pasted plates. We note again that the current passed by the unpasted
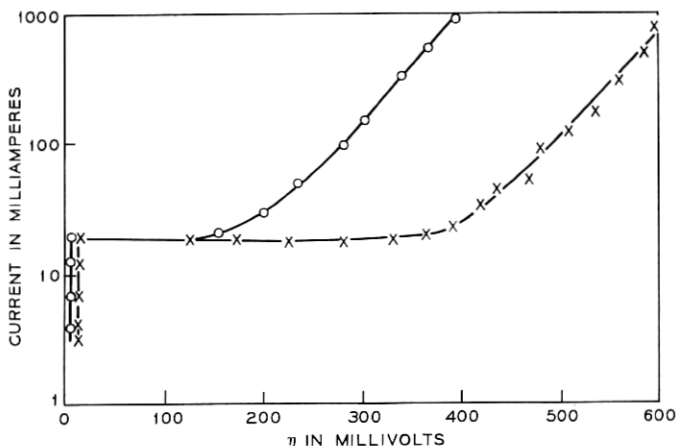
Fig. 2—Polarization data for pasted and unpasted pure-lead circular negative grids. Negatives: ○, pasted plate; ×, bare grid.

grids is surprisingly high, although the disparity between the currents and the measured B. E. T. areas is not quite so dramatic as for the positive grids or plates. For a given overpotential, the unpasted grids draw about 3 percent of the current drawn by the pasted plates; the areas, on the other hand, were found to be approximately in the ratio 3000 : 1.[4] Analysis of this discrepancy is further complicated by the influence of adsorbed expanders on the hydrogen evolution reaction.

Figure 2 indicates Tafel behavior at high negative overvoltages, with an additional, potential-independent component showing up in the low overpotential region. Following Milner,[1] we ascribe the Tafel behavior to the reaction:

$$2H^+ + 2e^- \rightarrow H_2 \tag{5}$$

while the potential-independent current is ascribed to the inverse of reaction (ii):

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O. \tag{6}$$

Fitting to Milner's equation (14), we derive b− and I_0− from the Tafel asymptote; the limiting current gives I_d directly. Results are shown in Table II.

We note first that the values for b− come close to the theoretical value of 118 mV. The values for I_d are substantially higher than those quoted by Milner for complete cells. As we shall see later, the limiting currents observed in the new Bell System cells are themselves 1 to 2

TABLE II—ELECTROCHEMICAL CHARACTERISTICS
OF BTL NEGATIVE ELECTRODES

	b_- (mV/decade)	I_{0-}^* (μA/AH)	I_d^* (μA/AH)
Pasted Plates	117	6.5	380
Unpasted Grids	120	.15	380

* Data for both pasted and unpasted plates were normalized by dividing by 53 AH which is the 5 hour rated capacity for the positive pasted plate.

orders of magnitude lower than those in Table I, consistent with Milner's data. We explain the apparent discrepancy with the data shown in Table II as follows. The value of I_d depends on the rate at which oxygen can be transported to the negative electrode. Since, in the experimental geometry used for studying the polarization of isolated plates, the separator is relatively remote from the plates, considerable convection can occur in this system. This would allow more efficient transport of O_2 to the negative plate than would be encountered in a compactly constructed real cell. The potential of the negative electrode would then be poised close to the reversible value at all currents less than I_d as is shown in Fig. 2.

2.3 *Temperature-Dependence of the Polarization at the Positive Plate*

An understanding of the activation energies for all of the various processes occurring under float is of importance, not only because of the guidance it should give as to the preferred float conditions for operation in a given temperature range, but also because it is alternately needed to justify the extrapolations of cell life estimates[2] from measurements at elevated temperatures. The problem is one of great complexity and is not yet fully resolved. The only measurements which we wish to describe at the present time are some that we have made on the temperature-dependence of the current drawn by unpasted grids held in the oxygen evolution domain and all polarized approximately 80 mV at each temperature. Results of these measurements are indicated in Fig. 3.

The activation energy derived from Fig. 3 is approximately 18 K cal/mole which is similar to that found for the oxygen evolution reaction on Pt.[8] If the evolution of oxygen at the unpasted grid proceeds by a mechanism similar to that at a pasted plate, we may tentatively iden-
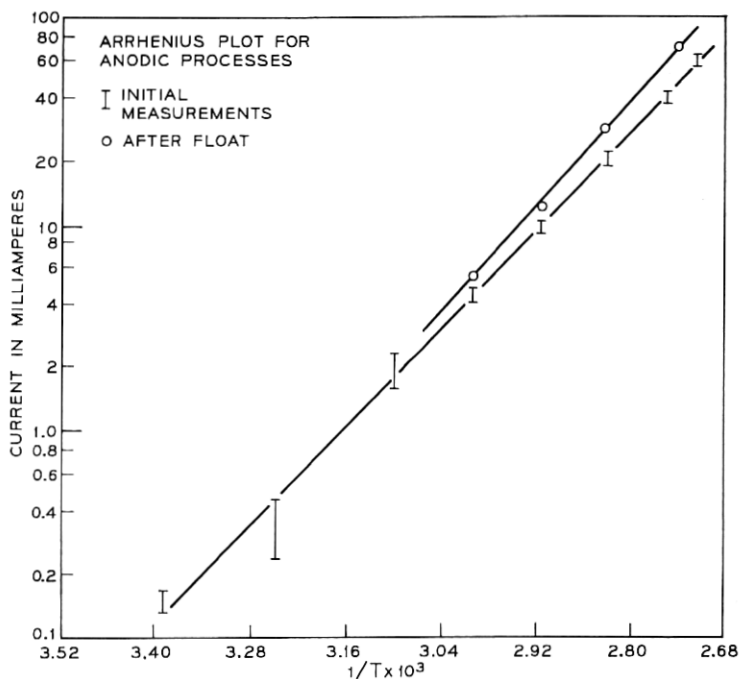
Fig. 3—Log current vs $1/T$ for a pure lead grid held anodic at 80 mV polarization at test temperatures from 25–95 °C.

tify this number with the E_+ of Milner's paper, the value of which for "typical cells" is quoted by him as 17.8 K cal/mole, in good concurrence.

2.4 Float Measurements on Complete Cells

We have made a substantial number of polarization measurements on complete cells. A typical result is shown in Fig. 4. If the conditions within the cell were exactly identical to those prevailing in the experimental arrangements described in the preceding sections, we should be able to derive Fig. 4 by adding the polarizations for pasted plates shown in Figs. 1 and 2. It is obvious at a glance that this cannot be done. However, the slopes in Fig. 4 in the high overvoltage region as well as the intercepts do agree reasonably well with the slopes and intercepts of the two Tafel asymptotes in Figs. 1 and 2; it is only in the low overvoltage region that discrepancies occur. Inspection shows the principal difference to be the displacement of the steep part of the negative polarization curve, which may be reasonably associated with

limiting oxygen transfer current I_d, to much lower values of the current. This must be owing, as argued above, to the slow transport of oxygen through the separator.

The practical importance of the results shown in Fig. 4 resides in the fact that typical telephone float conditions (2.17 V) leave the cell precisely in the region where η_- is changing most rapidly. Similar measurements on conventional Pb/Ca cells show this to be the case for this system also. The consequences of this are clear. First, since the precise location of the steep part of the negative polarization curve is sensitive to subtle variations in cell construction, one would expect variations of cell voltages in a battery on float similar to that observed for Pb/Ca batteries. Secondly, small current changes during float will cause the negative plate potential to fluctuate moderately which would be reflected in cell voltage fluctuations. Thus, during periods of telephone plant instability, especially during peak load conditions, moderate fluctuations in cell voltages are to be expected. As we shall see later,
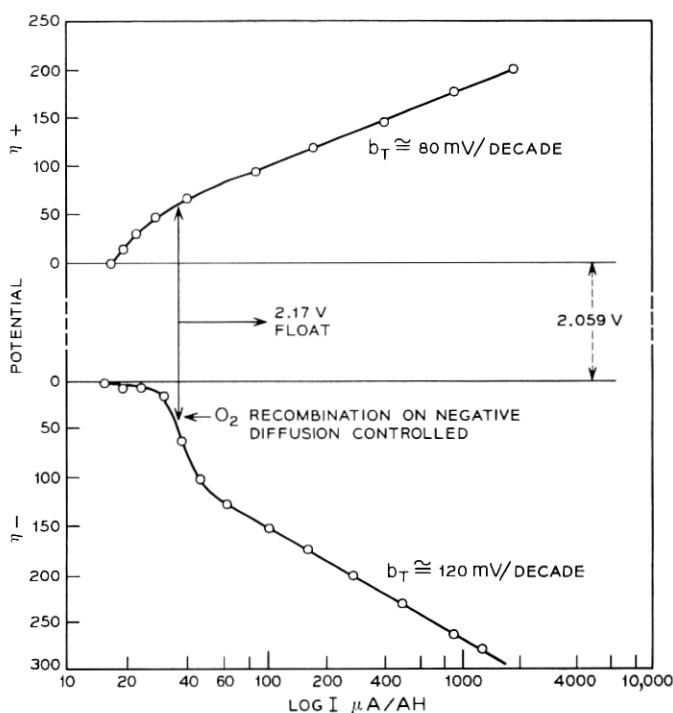

Fig. 4—Polarization data for the Bell System lead-acid cell design.

measurements on field trial cells show this to be the case. In addition, measurements on Pb/Ca cells in the field show the expected similar behavior.

The cell voltage variations and fluctuations observed with pure Pb and Pb/Ca cells are not a problem. They are a natural consequence of the electrochemical characteristics of the negative electrodes of these two battery systems. Figure 4 indicates, and actual measurements confirm, that the positive plate potentials are extremely stable.

The purpose of float operation is to have proper distribution of the total polarization between both the positive and negative electrodes. Close inspection of Fig. 4 shows that if the polarization characteristics of one electrode change seriously enough, one would have the undesirable situation of having the total cell polarization impressed on only one electrode with the other being at open circuit potential. The electrode polarization characteristics are sensitive to the presence of impurities and this is why particular attention has been given in the design of the Bell System battery to the electrochemical effects of trace contaminants.[9]

2.5 Recommendations for Float

It is generally believed that corrosion of the lead grid of the positive plate becomes very severe if the plate is held for any substantial period of time at an overpotential of less than 30 mV.[10] Thus, to ensure long battery life, the polarization on the electrode must be kept above 30 mV. The exact mechanism of this "catastrophic corrosion" is a subject of debate but our work has not progressed far enough to make quantitative statements. As corrosion of the positive grids occurs during the life of the cell on float, the positive plate polarization will show a gradual decrease due to the increasing surface area of the corroding electrode. Therefore, in order to ensure that the positive plate polarization does not fall below 30 mV during the life of the cell, it is essential that the cells have an initial polarization somewhat greater than 30 mV. A time zero positive plate polarization of 60 mV is quite adequate. At the negative electrode, all that is required is that the electrode not discharge. To ensure this, a polarization of only 5-10 mV is adequate in the absence of depolarizers.

For a number of years, Bell System practice has called for float conditions that result in a total overvoltage of 110 mV at 25°C. Examination of Fig. 4 shows that such operation would lead to values for η_+ and η_- shown in Table III. From Table III, it can be appreciated that float operation at 2.17 volts leaves both electrodes in a satisfactory

TABLE III— POSITIVE AND NEGATIVE PLATE POLARIZATIONS FOR
SPECIFIED FLOAT VOLTAGES, FOR THE CELL
CHARACTERIZED IN FIGURE 4

Float Voltage	η_+ mV	η_- mV
2.13	60	10
2.17	70	40
2.21	75	75

range of polarization. Floating at too high a voltage ($\gg$ 2.21) incurs the penalties of excessive float current and increased corrosion at very high overpotentials on the positive; floating at too low a voltage, on the other hand, might incur the risk of discharging the negative.

III. CAPACITY CHARACTERISTICS

It is well known that conventional lead-acid batteries, when discharged at a specified C rate, display a diffusion limited capacity[3] that is less than the theoretical value based on the weight of the paste and that also depends on the discharge rate. The dependence on discharge rate is given empirically by Peukert's equation $I = at^n$; typically, at a rate of C/5 (5-hour discharge), the capacity utilization of a conventional thick plate (0.25 inch) battery runs around 30 percent. In this Section, we report capacity figures for the new Bell System lead-acid battery. It might be a subject for concern that the use of horizontal rather than vertical grid stacking would lead to reduced capacity because of poor circulation of the electrolyte. However, this has been overcome by the adoption of the conical plate design and by leaving unpasted the grid holes immediately adjacent to the center hub on the negative as shown in Fig. 5, thereby facilitating percolation of the fluid. The result has been, as we shall show below, that the new cell has a capacity equivalent to that of conventional cells.

3.1 Factors Affecting Cell Capacity

Our earliest cells had conical plates, with a 10° cone angle, but were not adequately vented to allow the gases formed on charging the cells to escape and thus also limiting free circulation of the electrolyte. To see whether the horizontal stacking might be affecting cell capacity in an unfavorable manner, a cell was held with its axis at some chosen angle to the vertical and discharged at a fixed rate. The cell used was a
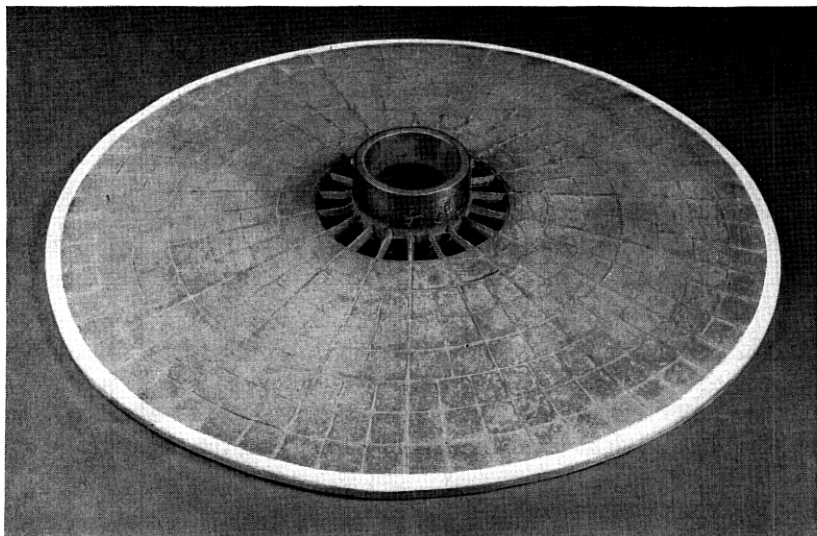
Fig. 5—Pasted negative plate showing vent area.

17-plate cell (8 positives and 9 negatives) using the design "B" positive plates and negative plates described in Table IV. Repeating this experiment at several angles to the vertical, the capacity could then be plotted as a function of orientation (Curve A, Fig. 6). The results clearly show that the capacity is indeed reduced, but rapidly recovers its normal value as the plates are made more vertical. As a result, venting holes were introduced by leaving the innermost ring of the

TABLE IV—PLATE COMPARISONS

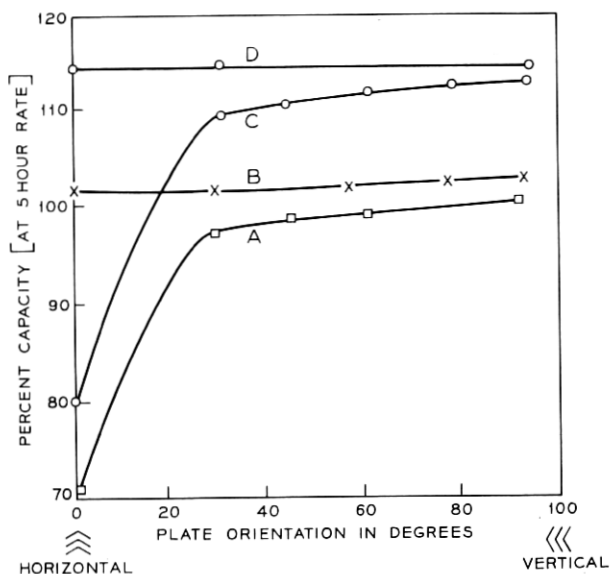| Positives	Design "C"	Commercial
Dimensions	10.9″ Dia. × .250″	9″ × 9.5″ × .250″
Grid Weight	3.2 lbs	3.0 lbs
Paste Vol.	14.0 in³	15.0 in³
Paste Weight	2.2 lbs	2.2 lbs
AH Capacity at 10.5 amps	63 ± 5	64 ± 5
Negatives	Bell System	Commercial
Dimensions	9.8″ Diam. × .187″	9″ × 9.5″ × .170″
Grid Weight	1.5 lbs	1.5 lbs
Paste Vol.	10.8 in³	11.85 in³
Paste Weight	1.9 lbs	2.0 lbs
AH Capacity at 10.5 amps	90 ± 5	90 ± 5

Fig. 6—Capacity vs orientation for the Bell System lead-acid cell design. Curve A, nonvented STD SEP; curve B, vented STD SEP; curve C, nonvented REV SEP; curve D, vented REV SEP.

negative grid holes unpasted (Fig. 5) and removing the innermost ring on the positive electrode. The capacity now no longer showed a significant increase when the cell axis was tilted away from vertical (curve B, Fig. 6). As an additional step, the separator and fiber glass mat were interchanged so that the glass mat was adjacent to the negative plate, thus reversing the configuration used in conventional batteries. This resulted in a uniform increase of around 10 percent in capacity, independent of orientation (Curves C and D, Fig. 6).

The venting problem has thus been solved, but it is worth noting

TABLE V—CELL CAPACITY AS A FUNCTION OF CELL ORIENTATION

Battery Orientation		% Nominal Capacity
Charge	Discharge	
vert.	vert.	114
vert.	hor.	105
hor.	vert.	77
hor.	hor.	76

here that in the process of solving it, clear indication was found that the problem is associated with failure to achieve complete charge. The charging was done at constant current and at least 120 percent of the discharge capacity was put back into the cells. A series of experiments was done with unvented cells held alternately vertical and horizontal on charge and alternately vertical and horizontal on discharge. Capacity figures obtained in this way, expressed as percent of nominal are shown in Table V.

3.2 Capacity Characteristics of the Bell System Cell

Figure 7 shows a discharge curve at the C/5 (84 A) rate for a 420 AH field trial cell along with a similar curve for a conventional cell of comparable size. This cell incorporates the design "C"[2] positive grids. The BTL and commercial cells have approximately equal weights of paste, and it can be seen that the discharge characteristics are very similar. Information on weights and volumes for the grids of the field trial cells is compared in Table V with that for a comparable commercial cell, along with the corresponding plate capacities. It is seen that the physical properties and performance of the design "C" positive plates are es-
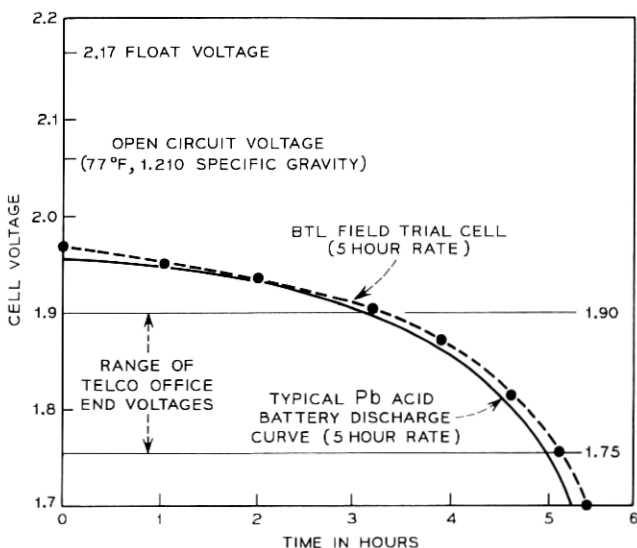

Fig. 7—Five hour rate discharge characteristics of a 420 AH Bell System cell compared to a typical conventional design.
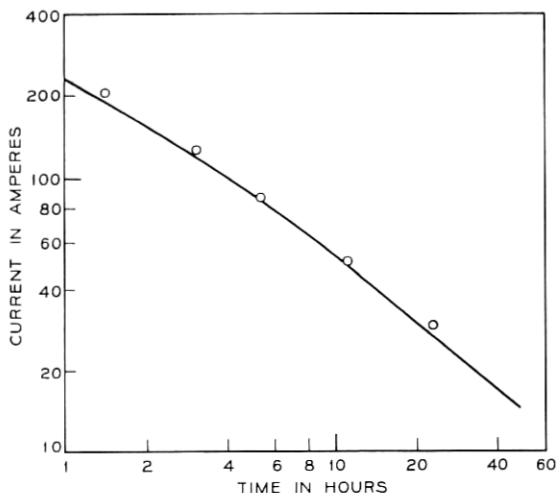
Fig. 8—Capacity vs discharge rate characteristics of field trial cell design compared to typical conventional design. —, performance of typical commercial telephone cells; ○, field trial cell.

sentially the same as those for the commercial plate. The same is true for the Bell System and commercial negative plates.

The capacity of a typical field trial cell was also measured as a function of the discharge rate and compared to the performance of an equivalent commercial cell. In all cases recharging was done at the C/10 rate (42 A) until 110 percent of the discharge capacity was returned to the cell. The results are shown in Fig. 8 in which the logarithm of the current is plotted as a function of the logarithm of the time required for the cell voltage to fall to 1.75 volts. According to Peukert's equation, these points should fall on a straight line, the slope of which is related to the design of the cell (plate thickness, acid concentration, and so on). It is seen that, at all currents investigated, the performance of the circular cell is at least equivalent to the commercial cell. We conclude, therefore, that the circular design cell gives satisfactory capacity behavior and that no performance penalties are incurred with this radically new design.

IV. FIELD TRIALS

Field trials of the circular lead-acid cell design[5] were initiated in January 1969. The objectives were to determine any problems associated with shipping, racking, interconnection, and float behavior, and also to
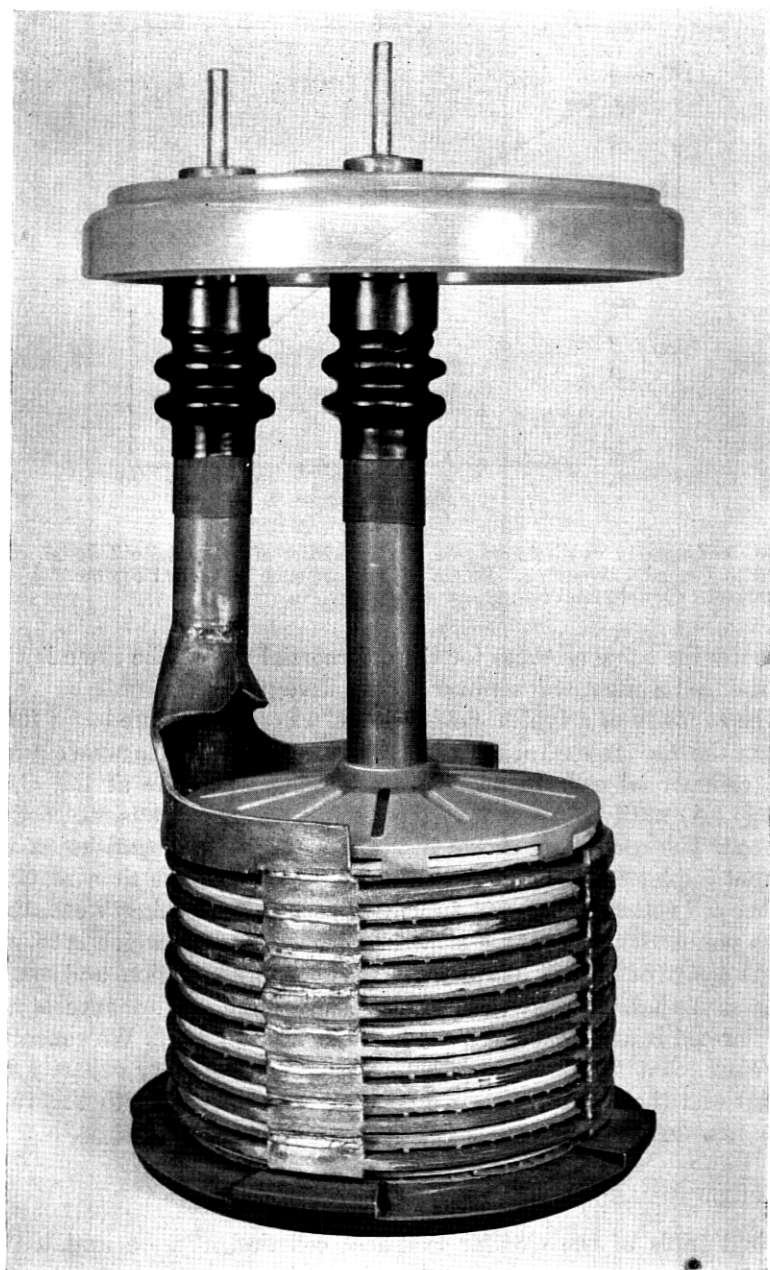
Fig. 9—Field trial cell element.

TABLE VI—FIELD TRIAL LOCATIONS

Date	Location	Company	No. of Cells
1/30/69	Murray Hill, N. J.	N. J. Bell Tel. Co.	23–(48V)
2/7/69	Gouldsboro, Pa.	AT & T Long Lines	6–(12V)
3/21/69	Shirley Long Island, N. Y.	AT & T Long Lines	6–(12V)
4/11/69	Noyac Long Island, N. Y.	AT & T Long Lines	6–(12V)
9/17/69	Dover, Missouri	AT & T Long Lines	11–(24V) +(2 end cells)

Fig. 10—Clamping fixture for lifting cell by its cover.

provide information concerning any necessary design modifications. The field trial cells (Fig. 9) were manufactured at our Design Capability Line.[5] These are 17-plate cells (8 positive and 9 negative plates) rated at 420 AH at the 5-hour discharge rate and incorporate the Design "C"[2] pure lead circular grid. The cells also incorporate the molded polyvinylchloride jar and cover.[11]

There are five field trial locations (Table VI) with a total of 54 cells under investigation. All cells were shipped via common carrier in square wood crates which were modified with polyurethane pads to accommodate the circular design. Upon arrival at the field trial sites, all cells were closely examined for physical damage and in no case was damage observed. In a subsequent cross-country shipment, shocks in excess of 500 G were experienced by the crated cells without damage to the battery. Racking, interconnection and turnover into plant service posed no problems. The unpacking and racking operation was, in fact,
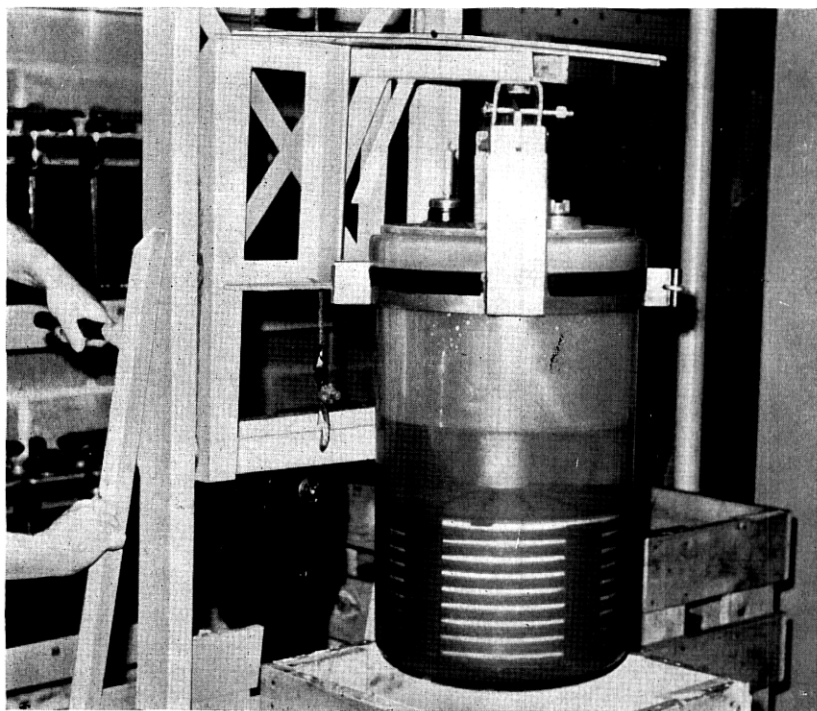

Fig. 11—Field trial cell being installed at Gouldsboro, Pa., TD-2.

Fig. 12—Trial installation at Murray Hill, New Jersey Bell Telephone Co. Central Office.

facilitated by the strength of the jar-to-cover seal[12] which permits the cell to be lifted by its cover. A clamping fixture (Fig. 10) fits under the lip of the cover while the cell is still in the crate. The cell can then be lifted by a hoist (Fig. 11) and moved into position on the rack where the cell is lowered and the clamp is easily removed.

Figure 12 shows the Murray Hill 23-cell (48 V) installation and Fig. 13 is a closeup view of a single cell in that installation. It can be seen that the jar is considerably oversized for the cell element. The reason for this is that the jar was designed to accommodate a 1680-AH cell and our limited production capabilities made it necessary to manufacture smaller cells (420 AH) in order to meet field trial commitments. It should also be noted that the round jar occupies the same rack space as a typical commercially supplied 1680-AH cell.

Lead-acid cells used in the Bell System must meet two major electrochemical requirements: (i) The cells, at the time of installation, must be capable of delivering 90 percent of rated capacity. (ii), At a battery
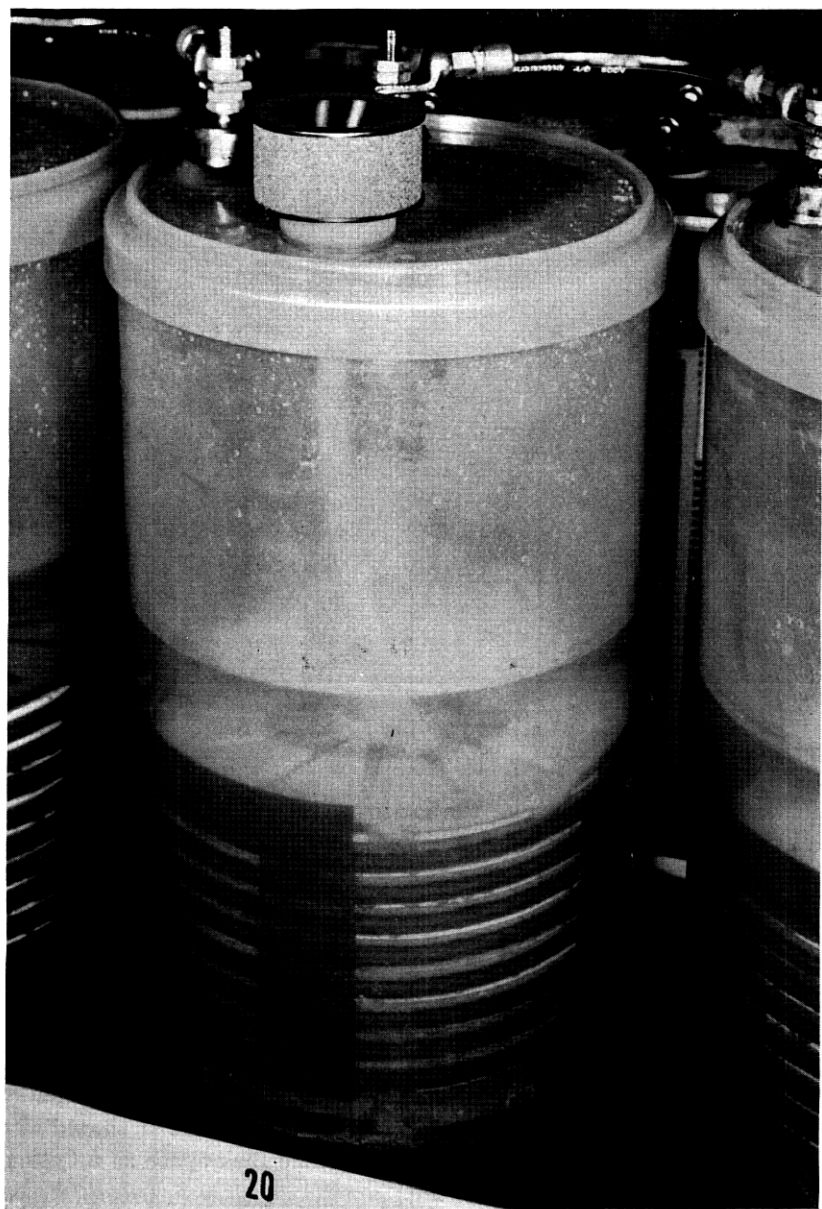
Fig. 13—Closeup of field trial cell.

float voltage of 2.16 to 2.18 volts per cell, all cells must be above 2.13 V minimum. The purpose of the 2.13 V minimum is to ensure adequate polarization to maintain cells in a full state of charge.

Capacity measurements prior to shipment showed that most cells had at least 100 percent capacity and that the 90 percent capacity requirement posed no problem. In addition, capacity measurements have been made on six cells subsequent to installation and these gave 116 to 130 percent of rated capacity.

With regard to the individual cell voltage distribution on float, Table VII shows that all cells meet the minimum 2.13 V requirement. These measurements are made periodically and the data in Table VI are the latest data available from each installation. Plate polarization measurements taken during the early stages of the field trials showed that positive plate polarizations of a few cells were much lower than desired. Specifically, one cell at Murray Hill, one at Gouldsboro and two at Shirley had positive polarizations very close to zero mV. This problem was diagnosed as resulting from cyclohexanone contamination.[9] This solvent was originally used to make jar-to-cover seals for the cells. For the four cells in question, the positive plate polarizations were brought to an acceptable value by boost charging. We feel that this treatment accelerated oxidation of cyclohexanone to electrochemically innocuous materials. Since this treatment, the previously contaminated cells have shown very satisfactory float behavior. Any future problems of this nature have been eliminated by the development of a heat-sealing technique for making jar-to-cover seals.[12] All cells in the Dover, Missouri, installation incorporate jar-to-cover seals made by this method.

Table VI also lists detailed positive and negative plate potential data. Average plate potentials are given for each installation and also the potential ranges. Fluctuations in plant voltage, especially during peak-load conditions, are naturally reflected in fluctuations of individual cell voltages. It was observed, during the course of these measurements, that fluctuations in cell voltage resulted in nearly equivalent fluctuations in negative plate potential, whereas positive plate potentials remained constant. This behavior is expected since Fig. 4 shows that under float conditions the negative plate potential is in a region where small changes in current will cause large fluctuations in that potential; the higher capacitance of the positive, of course, is also a factor.

The data in Table VI show very satisfactory polarizations for both positive and negative plates. Correcting the open circuit positive plate potentials for temperature variations, the voltage extremes of 1.150

TABLE VII—FIELD TRIAL FLOAT DATA

Installation	No. of Cells	Temp. (°F)	Cell		Positive Plate*		Negative Plate*	
			Avg. Voltage	Range	Avg. Voltage	Range	Avg. Voltage	Range
Murray Hill	23	75	2.161	2.131 / 2.174	1.166	1.156 / 1.182	-0.995	-0.976 / -1.006
Gouldsboro	6	63	2.180	2.159 / 2.212	1.191	1.182 / 1.196	-0.999	-0.972 / -1.019
Shirley	6	65	2.171	2.159 / 2.187	1.178	1.166 / 1.186	-0.992	-0.982 / -1.005
Noyac	6	69	2.183	2.168 / 2.200	1.180	1.179 / 1.181	-1.004	-0.989 / -1.021
Dover	11	72	2.160	2.140 / 2.170	1.158	1.150 / 1.164	-1.001	-0.980 / -1.011

* Measured vs a Hg/Hg_2SO_4 reference electrode.

and 1.196 correspond to polarizations of 60 and 105 mV respectively. The 60-105 mV polarization range is quite adequate for maintaining positive plates in a healthy state. Similarly the voltage extremes of -0.972 and -1.021 for the negative plate potentials correspond to polarizations of 5 and 53 mV respectively. This polarization range is satisfactory for maintaining negative plates in a fully charged condition.

V. SUMMARY AND CONCLUSIONS

Polarization measurements of individual positive and negative pure-lead circular plates have led to the following significant observations: (i) The differences in current drawn at a given overpotential for pasted plates as compared to unpasted grids are surprisingly small in view of their large differences in surface areas. This difference is much more pronounced for positive plates than for negative plates. (ii) The oxygen diffusion current (I_d) of the negative electrode is very sensitive to the design of the experimental setup. (iii) The Tafel parameters for pure lead are, as expected, very similar to those of Pb/Ca.

These polarization data for grids and pasted plates may be scaled directly to predict battery performance when one takes the oxygen diffusion characteristics of the separator into consideration. Polarization data on completed cells of the circular design show very satisfactory polarizations of both electrodes, adequate for long-term use in telephone float service.

It has been shown that the discharge performance of the circular cell is quite satisfactory. With proper venting, the capacity of the circular cell is at least equivalent to its commercial counterpart.

Field trials, in progress at five locations, show the circular design lead-acid cell to conform to the electrochemical requirements of the Bell System. Capacity data for these cells in the field show better than nominal performance. The voltage distributions of cells in batteries are satisfactory and individual electrode polarization data show these to be adequate.

REFERENCES

1. Milner, P. C., "Float Behavior of the Lead Acid Battery System," B.S.T.J., this issue, pp. 1321–1334.
2. Cannone, A. G., Biagetti, R. V., and Feder, D. O., "Positive Grid Design Principles," B.S.T.J., this issue, pp. 1279–1303.
3. Biagetti, R. V., and Weeks, M. C., "Tetrabasic Lead Sulfate as a Paste Material for Positive Plates," B.S.T.J., this issue, pp. 1305–1319.
4. Amlie, R. F., Ockerman, J. B., and Rüetschi, P., "Absorption of Hydrogen and Oxygen on Electrode Surfaces," J. Electrochem. Soc., 108, No. 4(April 1961), pp. 377–383.

5. Koontz, D. E., Feder, D. O., Babusci, L. D., and Luer, H. J., "Reserve Batteries for Bell System Use: Design of the New Cell," B.S.T.J., this issue, pp. 1253–1278.
6. Ness, P., "Gegenwörtiger Stand Der Forschungsarbeiten an Positiven Elektroden in Bleikakkumulatoren," *Electrochim. Acta, 12*, No. 2(February 1967), pp. 161–178.
7. Baker, R. A. Extended Abstracts, Battery Division, Electrochemical Society, Houston Meeting, Oct. 1960, p. 53.
8. Bockris, J. O'M., and Srinivasan, S., *Fuel Cells: Their Electrochemistry*, New York: McGraw Hill, 1969 p. 438.
9. Butherus, A. D., Lindenberger, W. S., and Vaccaro, F. J., "Electrochemical Compatibility of Plastics," B.S.T.J., this issue, pp. 1377–1392.
10. Lander, J. J., "Anodic Corrosion of Lead in H_2SO_4 Solutions," *J. Electrochem. Soc., 98*, No. 6(June 1961), pp. 213–219.
11. Huseby, T. W., Ryan, J. T., and Hubbauer, P., "PVC Battery Jars and Covers," B.S.T.J., this issue, pp. 1359–1376.
12. Dahringer, D. W., and Shroff, J. R., "Jar-Cover Seals," B.S.T.J., this issue, pp. 1393–1404.