

# Physical Chemistry in the Industries\*

Some of the General Principles Which Govern Its Application to Manufacturing Processes

By Dr. James C. Philip, M.A.

NEARLY up to the end of the past century chemical reactions were expressed in the form of equations, viz.,  $\text{BaCl}_2 + \text{H}_2\text{SO}_4 = \text{BaSO}_4 + 2\text{HCl}$ . The equation was to be read from left to right and to indicate that in order to precipitate all the barium chloride in a solution, the equivalent amount of sulphuric acid should be added. This mode of expression was correct for the "complete" reactions of the analytical chemist who wished to remove one of the elements or components from his solution. It was quite understood, however, that the equation is only an approximation, that the last traces of a substance can hardly be determined in this way, since no substance is absolutely insoluble, while most reactions are reversible with conditions and proceed in one particular direction only until a state of balance is reached. Hence it became customary to replace the sign of equality  $=$  by two arrows,  $\rightleftharpoons$ , and that change in notation was by no means unimportant. The old notation too much suggested finality, as if we could always direct a reaction in the desired sense, so as to obtain two new products. As a rule a mixture of the two original substances (reactants) and of the two decomposition products (resultants) will be obtained in proportions varying with concentration, temperature, pressure and other factors.

Investigated from the new standpoint of equilibrium reactions old-established technical processes have assumed very different aspects, an enormous amount of valuable quantitative data has accumulated, and physical chemistry shows also how new processes, considered possible but hopeless, can be rendered practicable under suitable conditions. The present generation of chemists is duly initiated into the principles of physical chemistry at the technical colleges. The older generation did not enjoy that advantage, which many other students have to miss likewise, and they will be grateful to Dr. James C. Philip, M.A., for devoting the three Cantor lectures delivered before the Royal Society of Arts to "Physical Chemistry and its Bearing on Chemical and Allied Industries." Dr. Philip is Professor of Physical Chemistry at the Imperial College of Science and Technology, South Kensington. We will attempt—although the task is difficult—to give an outline of these Cantor lectures, since the subject is of interest to engineers as well as to chemists and physicists.

Let us start from two reacting substances—gases, for simplicity sake—A and B yielding the products

C and D according to the formula  $\text{A} + \text{B} \xrightleftharpoons[k_2]{k_1} \text{C} + \text{D}$

At any moment we have to deal with a mixture of the four substances. The symbols  $v$  indicate that the change from left to right proceeds at the rate  $v_1$  and the reversed change at the rate  $v_2$ . Action between the molecules of A and B is only possible according to the kinetic theory, when A and B collide; the number of collisions, and hence the  $v_1$  and  $v_2$  depend, other conditions being constant, on the number of molecules present, i. e., their concentrations, which we designate by  $a, b, c, d$ ; hence  $v_1 = k_1 ab$ , and  $v_2 = k_2 cd$ , where  $k_1$  and  $k_2$  are constants. The observer can only determine the difference  $v_1 - v_2$  not  $v_1$  and  $v_2$  separately; as equilibrium is approached, this difference becomes smaller, until  $v_1 = v_2$ . Equilibrium does not mean stagnation and stoppage of the reaction, however; it signifies that there is as much change in the one direction as in the other, and that  $k_1 ab = k_2 cd$ , so that  $k_1/k_2 = c d/a b = K$ , the equilibrium constant. Here the  $a b c d$  are the equilibrium concentrations. However the individual concentration values may vary, the law of mass action says that, at any given temperature,  $Y/X$  is a constant, where  $X$  indicates the product of the momentary concentrations on the left, and  $Y$  this product on the right side of equations.

Dr. Philip exemplified these relations in the first instance with respect to the contact process of sulphuric acid manufacture:  $2\text{SO}_2 + \text{O}_2 \rightleftharpoons 2\text{SO}_3$ . The formula means that the combination of sulphur dioxide and oxygen to trioxide goes together with a dissociation of the trioxide. The process was the subject of a British patent as early as 1831; it requires the use of a catalyst, and troubles with the catalyst and imperfect knowledge of the principles of the reaction prevented technical success until the equilibrium was worked out in Germany a few decades ago. When we designate the equilibrium concentrations in the cus-

tomary manner by the symbol C with the suffix of the substance, the quotient  $C_{\text{SO}_3}^2 \cdot C_{\text{O}_2}/C_{\text{SO}_2}^2$  should be a constant K at any temperature, irrespective of the initial concentrations. The  $C^2$  in the formula indicates that two molecules of the substance enter into the reaction. The constancy of the K has been proved by experiments with various mixtures of  $\text{SO}_2$  with oxygen and also with nitrogen at various rates of flow. At 727 deg. C., e. g.,  $K \times 10^3$  was found to have the value 3.55, the presence of nitrogen not affecting this value. As the temperature was raised from 528 deg. to 897 deg., the K increased from 0.015 to  $81.6 \times 10^3$ . This K, however, refers to the reverse reaction, the decomposition of  $\text{SO}_3$ , and we see that the higher the temperature, the more trioxide will be dissociated, and that we should therefore work at relatively low temperatures. The combination of  $\text{SO}_2$  and O is, in fact, an exothermic reaction, evolving heat, and the quantity Q of heat evolved is given by:  $d \log K/dT = -Q/R T^2$ , T being the absolute temperature and R the gas constant; the value Q is  $-47,300 + 4T$ . To arrive at the optimum gas proportions we write the equilibrium formulae  $C_{\text{SO}_3}^2/C_{\text{SO}_2}^2 = C_{\text{O}_2}/K$  or  $C_{\text{SO}_3}/C_{\text{SO}_2} = \sqrt{C_{\text{O}_2}/K}$ , which shows that the ratio of trioxide to dioxide in the mixture is proportional to the square root of the oxygen concentration and will rise, as the latter is increased.

The falling-off in the yield of trioxide at high temperatures can also be derived from Le Chatelier's principle: When any change in the external conditions (pressure and temperature) is imposed upon any equilibrium system, then the equilibrium shifts in such a direction as partially to neutralize the change in question. This principle—really inherent in the laws of thermodynamics and in the general principle of action and reaction—says, e. g., that, since heat is evolved by the formation of the trioxide, the reverse process, the dissociation of the trioxide, must absorb heat, and rise of temperature hence favors the dissociation. Similarly increase of pressure favors the formation of the system occupying a smaller volume, and would hence promote the formation of the  $\text{SO}_3$ , there being two molecules on that side of the equation against three on the other; so far, however, there is little inducement to work the contact process at high pressures. Dr. Philip did not indicate how quantitative relations can be determined by the principle of Le Chatelier and Braun, which does not seem to lend itself to calculations.

For the manufacturer it is essential that equilibrium should be reached in a reasonably short time. The velocity of most chemical reactions now is doubled and even trebled by the small temperature rise of 10 deg. C.; but high temperatures, the lecturers informed us, lower the yield. A compromise has hence to be effected as to temperature, depending upon the choice of the catalyst. With the very efficient catalyst, platinum, the contact process can be worked at 400 deg. or 500 deg. C.; ferric oxide  $\text{Fe}_2\text{O}_3$  (from roasted pyrites) has to be heated to 600 deg. to become efficient. Dr. Philip mentioned that at Mannheim a first rough catalysis with  $\text{Fe}_2\text{O}_3$  is followed, after absorption of the  $\text{SO}_3$  formed, by a second catalysis with platinum.

Dr. Philip took his second illustration from the synthesis of ammonia:  $\text{N}_2 + 3\text{H}_2 \rightleftharpoons 2\text{NH}_3$ , a reaction long known, but only worked out by Haber about 1905. The formation of ammonia requires high pressure. Designating the partial pressures by  $p$ , the total pressure of the mixture by P, he showed that  $p_{\text{NH}_3}^2/p_{\text{N}_2} \cdot p_{\text{H}_2}^3 = K$  at any given temperature, and that, since  $p_{\text{NH}_3}$  is small at high temperatures by comparison with the other partial pressures,  $p_{\text{NH}_3} = 0.325 K \times P^2$ , that is to say, the partial pressure of the ammonia in the equilibrium mixture is, for low ammonia concentrations, proportional to the square of the total pressure, while the volume percentage of ammonia at equilibrium is equal to  $0.325 K \times P$ , and thus proportional to the total pressure. Haber demonstrated, e. g., that the volume percentage of ammonia in the equilibrium mixture was 0.12 at 800 deg. C. and 1 atm. and 3.4 (30 times as great) at 30 atm. and the same temperature. This synthesis being again exothermal, very high temperatures are not desirable; at 30 atm. the value of  $K \times 10^4$  went down (Haber) from 21.3 at 561 deg. C. to 1.18 at 952 deg. C., experiment and calculation being in closest agreement, while at 200 atm. the equilibrium percentage of ammonia was raised to 85.8. Pressures of 150 atm. and 180 atm. and temperatures between 500 deg. and 600 deg. are hardly ex-

ceeded in practice. The actual time of contact between catalyst and gas is only a few seconds or a fraction of a second. Dr. Philip mentioned that by extrapolation from the formula, Maxted has recently shown that the ammonia yield should decrease when the temperature was raised to 2,500 deg. at 1 atm., and should increase on further raising the temperature. He stated that he had supported this deduction by experiments; technically very high temperatures have not been tried yet.

In his second lecture Dr. Philip passed to further consideration of the reaction velocity,  $V = v_1 - v_2 = k_1 a b - k_2 c d$ . Let  $a_0$  and  $b_0$  be the initial concentrations of A and B, and  $x$  the concentrations of both C and D after the interval  $t$ ; then  $V = k_1 (a_0 - x) (b_0 - x) - k_2 x^2$ . When the velocity of the reverse reaction is negligible,  $k_2 = 0$ , and when in a particular case the change of  $x$  with  $t$  can experimentally be observed, the velocity  $k_1$  or K can quantitatively be determined. This can be done, e. g., in experiments on the saponification of ethyl acetate with caustic soda, and the velocity coefficient is found to be constant. Going back to the general case, a reaction  $\text{A} + \text{B} \rightleftharpoons \text{C} + \text{D}$  is called bimolecular; a reaction of the type  $\text{A} \rightleftharpoons \text{B}$  (conversion into a modification) or  $\text{A} \rightleftharpoons \text{B} + \text{C}$  (dissociation of a molecule or compound) is unimolecular; a reaction involving more than 2 molecules is one of higher order. When all the reactants are either gaseous or liquid, the change is called homogeneous; when solids enter, the change is heterogeneous.

In homogeneous reactions the catalyst—a substance which accelerates the reaction—retains its efficiency unimpaired for long periods, provided it can be kept pure. Working with pure gases the Badische Anilin- und Soda-Fabrik used the same platinised asbestos continuously for ten years, realizing a 95 per cent. yield of  $\text{SO}_3$ . But when they utilized the  $\text{SO}_2$  from roasted blende and pyrites, the yield diminished much in spite of all purification by cooling, scrubbing and filtering, mainly owing to the arsenic fumes apparently. To facilitate the recovery of the platinum, the catalyst is, in the Schröder-Grillo process, prepared by soaking a solution of magnesium sulphate with platinum salt and then heating the mixture; the platinum of this catalyst makes up 0.1 per cent. of the mass, and 5 grammes of platinum suffice for an output of 1 ton of oleum per day with a loss of 20 milligrammes of platinum. The exceedingly small percentage of the catalyst supports the view that the final equilibrium is not dependent upon the presence of the catalyst which acts like a nail facilitating the sliding down of a weight on an inclined plane, without affecting the total energy rendered available by the falling mass.

In the case of the conversion of acetaldehyde into paraldehyde the various catalysts (several acids,  $\text{SO}_2$ , zinc sulphate, &c.), at different concentrations all give the same K, and as K is the ratio  $k_1/k_2$ , it follows that both the reversible reactions must be accelerated to the same extent. The rate of inversion of cane sugar by acids, on the other hand, varies greatly with the acid, the relative rates obtained with hydrochloric, sulphuric and acetic acids being 100 : 54 : 0.4. Most technical catalyses, moreover, are of the heterogeneous type, and there the relations are not so simple, other factors coming into operation besides mass action. Dr. Philip referred in this connection to the hot-surface combustion (Bone-Court), and to the studies of Bone and Wheeler on the reaction  $2\text{H}_2 + \text{O}_2 \rightleftharpoons 2\text{H}_2\text{O}$ , the combustion of electrolytic gas. This combustion looks like a trimolecular reaction; in the many series of experiments made with different gas mixtures and unglazed porcelain as catalyst the values of K did not at all prove constant on that assumption, however, but did prove constant when the reaction was considered to be unimolecular. That fact, Bone suggested, shows that the rate of change essentially depends upon the occlusion of hydrogen by the porcelain; what is measured is hence not the chemical combination of hydrogen and oxygen, which is probably instantaneous, but the physical process of hydrogen occlusion.

Another class of technically important catalyses, the hydrolysis of carbohydrates by enzymes (living organisms of complex nature) deviates from the law of mass action in so far as the velocity of the reaction, instead of being constant throughout, first increases for 40 minutes, in the case of starch and malt extract, e. g., and then remains practically constant; with maltose, however, this initial period is very short. In another

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field, that of the hardening of oils and fats by hydrogenation—a problem to which we have referred on previous occasions—the previous history of the catalyst plays an important, not yet understood part. The catalyst generally used for the purpose of making the oil combine with more hydrogen is metallic nickel, reduced from the oxide or the hydroxide, themselves obtained from various salts; the method of reduction is of great influence. In order to secure a very fine subdivision of the catalyst, nickel carbonyl, which decomposes at 200 deg. C., has been directly mixed with the oil. Still more efficient is the Lesing process which supplies the nickel carbonyl along with the current of hydrogen passing into the oil at 200 deg. C.; the nickel then acts as soon as liberated, and excellent results have been obtained with 0.1 per cent. of nickel, while of ordinary nickel catalysts 5 per cent. may be wanted. For these nickel catalysts carbon monoxide seems to be a “poison.”

Dr. Philip also dwelt on the oxidation of ammonia by air in the presence of bright platinum at dull red heat. The reaction is  $4\text{NH}_3 + 5\text{O}_2 \rightarrow 4\text{NO} + 6\text{H}_2\text{O}$ . We referred to this process recently in our issue of November 1 (page 498). As regards the mechanism of catalysis, it has been suggested, Dr. Philip stated, that the catalyst forms intermediate compounds, *e. g.*, with the oxygen which are decomposed again by the hydrogen. The chemical view, Dr. Philip pointed out, was only tenable if this rate of the formation and decomposition of the intermediate compound were greater than that of the uncatalysed reaction, and in many cases, for instance, with catalysis by glowing porcelain, such compounds seemed to be out of the question. Yet the physical condition of the surfaces might be altered by these intermediate reactions, and surface condensation and concentration were certainly to be reckoned with. No single theory would fit all cases of catalysis, however, and chemical and physical factors had to be taken into account.

In the domain of absorption phenomena we find again that the problems can be exactly formulated for gases and liquids, but become more complicated when solids are concerned. According to Henry's law the volume  $V$  of a gas taken up by unit volume of a liquid is proportional to the pressure  $P$  under which the absorption takes place. Thus for carbon dioxide and water, when  $P$  is expressed in centimeters of mercury and  $V$  in cubic centimeters at normal temperature and pressure,  $V/P$  has the fairly constant value 0.145. That holds also for the absorption of acetylene by acetone which takes up 250 volumes of acetylene; the acetone expands when absorbing the acetylene, and for this and other reasons the steel cylinders are partly charged with some porous absorbent, as we noted in our article, published early this year, on “Cylinders for Dissolved Acetylene.”

Since the absorption increases with pressure, and water absorbs at ordinary temperature nearly 50 times more carbon dioxide  $\text{CO}_2$  than hydrogen, the bulk of  $\text{CO}_2$  can be removed and separated from the hydrogen in water gas by exposing the gas to water under pressure. Water dissolves at 0 deg. C., 0.0489 volume of oxygen, 0.0239 of nitrogen, 0.0215 of hydrogen and 1.713 of carbon dioxides, and at 20 deg. C. 0.031, 0.0164, 0.0182, 0.0878 volumes. More oxygen is thus taken up from air than nitrogen, and more oxygen given up again subsequently on releasing the pressure. Now air contains 21 per cent. of oxygen; by one absorption this percentage is raised to 33, and by eight successive absorptions to 97; such processes for the commercial production of oxygen have been patented, but they are hardly commercial. The purification of the crude ammoniacal liquor from sulphuretted hydrogen  $\text{H}_2\text{S}$  and from  $\text{CO}_2$  is, however, carried out on this principle by a process patented by Hills in 1868. The liquor is passed in a tower over a series of trays steam-heated from the bottom; the  $\text{CO}_2$  and  $\text{H}_2\text{S}$  being less soluble in the liquor than the ammonia, small percentages of the former two gases can be reduced to about one-tenth of their values, 0.12 and 0.04 per cent. Dr. Philip also referred to the caisson-sickness, which is mainly due to the liberation of nitrogen from the blood on decompression; the oxygen remains bound in the blood, in labile fixation.

Since the concentration of a gas is proportional to its pressure, we may write Henry's law also  $C_1/C_0 = K$ , designating by the  $C$  the concentration in the liquid and the gaseous phase. When a solid is present, the amount of gas taken up by the solid  $C_s$  is also found to increase regularly, but at a slower rate than the pressure; the simple relation  $C_s/C_0 = K$  does not hold, therefore, but in many cases the formula

$C_s/C_0 \frac{1}{n} = k$  is applicable, *e. g.*, for charcoal and

carbon dioxide where  $n = 3$ . It is believed that the gas absorbed by a solid is not uniformly distributed throughout the solid as it is in a liquid. There is a “dual” relation, in fact. There is first a very rapid adsorption of gas or liquid by the surface layer of the charcoal, followed by a much slower diffusion and penetration of the gas into the interior of the charcoal (absorption). The former surface effect is a question of seconds or minutes, the latter of hours and days. The regularity of the phenomena may therefore be obscured; but many experiments made at rising and falling pressures and temperatures have established the applicability of rules. The whole series of the phenomena of surface films of gases and occlusion of gases fall into this category. It is well known that charcoal becomes a very powerful absorbent for most gases at very low temperatures. It is not understood, however, why different kinds of charcoal from various woods, differently treated, differ so strongly as to absorptive power. The masks developed during the war for the absorption of poison gases contain charcoal. Treated successfully with “doses” of 6 liters of air charged with 1 per cent. of poison gas, Dr. Philip mentioned three charcoals, A, B, C retained successively: A, 78, 5, 0; B, 100, 20, 0; C, 100, 100; 97 per cent. of the gas; all the three charcoals were the same, but B had been heated four hours, and C six hours longer than A.

The dual character of the sorption by solids is also distinct in cases when charcoal and other absorbents are first charged with a substance (iodine, acetic acid) by being left in contact with a solution of the substance and then shaken or left in contact with a more diluted solution of the same substance. Silk, *e. g.*, takes up picric acid from solutions, and gives it up again when shaken with the solvent afterwards, the equilibrium being reversible. If the whole dyeing process relied on this sorption only, fast colors would be impossible, but chemical reactions and other factors come into play in dyeing. Vegetable and animal charcoals, Fuller's earth, clays, colloids, are largely utilized as absorbents. We do not know why certain modifications of their preparation, frequently merely shorter or longer heating, or the presence of ashes apparently, so strongly affect their efficiency, and we cannot help that the animal charcoal, which is to remove the coloring matter and other impurities from the sugar solution, also absorbs sugar. But part of this sugar can be recovered again by washing the charcoal with water, because the process is an equilibrium reaction. All these considerations are of signal importance also in soil problems. If the soil were not able to retain the salts used for fertilization, the rain would wash out the fertilizer. Colloidal gels in the soil seem, however, to be capable of absorbing the base (ammonia, *e. g.*), leaving the sulphuric acid to combine with the lime, somewhat as the fibre combines with the basic dye, and sewage farming is based on an adsorption of organic matter by the soil. But these problems are still obscure.

### Experimental Wireless Telegraphy and Telephony (Continued from page 85)

#### SIMPLE RECEPTION OF UNDAMPED WAVES.

While damped waves are transmitted as detached groups or trains, undamped waves are usually not separated into groups. Undamped waves, even if rectified, will not be detected in a telephone receiver unless the waves are broken up into groups in some way. This is because the telephone diaphragm and the ear cannot respond to so high a frequency as that of the radio oscillations. Hence it is necessary to interrupt the undamped wave dot or dash into many groups by rapid interruptions of the current. It is arranged in practice to have, for example, 1,000 interruptions a second, giving a 500-cycle note in the telephones; and as long as a signal continues a note of pitch 1,000 is heard. These interruptions may be made to take place either at the transmitting or the receiving station. A method for producing them at the transmitting station is to insert a rapidly operating circuit breaker called a “chopper” in the antenna wire; or if it is inconvenient to break the current, the chopper may be used to short circuit some of the turns of the antenna inductance coil to throw the circuits out of resonance periodically. This divides up the waves into groups to which the receiving telephone can respond. A rather more convenient method is to have the chopping done at the receiving station, for then the receiving operator can control the pitch of the received signals at will thereby listening to the note best adapted to his ear. There are at least five ways of modifying the waves at a receiving station to obtain an audible frequency: (1) a

chopper in series with the detector and telephone; (2) a variable condenser with rapidly rotating plates; (3) a “tikker” used instead of a detector; (4) a “heterodyne” in a separate circuit; (5) an “autodyne” or vacuum tube device arranged so that the detecting tube also produces the heterodyne action. The last method is explained in the section dealing with vacuum tubes, further on.

The chopper may be any device for rapidly making and breaking the current. It is inserted in the circuit of the detector and telephone as in the ordinary damped wave set. It consists of a rotating toothed wheel with stationary contact touching the successive teeth, or a break controlled by an electrically-operated tuning fork, or it is sometimes a light high speed vibrator similar to that of an electric bell.

If the movable plates of the tuning condenser in an inductively coupled set are rotated rapidly the apparatus will be in tune once for each revolution. Each of these revolutions will produce an impulse of the telephone diaphragm. The speed can be adjusted so that the impulse will cause sounds while waves are being received. In practice it is found best to keep part of the capacitance of the condenser constant, and vary only a part of it. If the main plates were rotated the apparatus would give sounds at only a small sector of each revolution, near the resonance adjustment. To accomplish a more prolonged train of impulses during one revolution the adjustment can be held near resonance for a longer proportion of the time if the rotating condenser is made very small, and is placed in parallel with the condenser. The large condenser does not then rotate except for ordinary hand tuning. The capacitance of the large condenser plus the maximum capacitance of the rotating condenser is adjusted to give resonance. The circuit is not far from this condition when the moving plates are farthest apart, so that the signals affect the receiver during a considerable portion of the revolution.

The tikker is usually a stationary fine wire of steel or gold with its end running in the groove of a smooth, rotating brass wheel. It is a slipping contact device. The wires do not remain in perfect contact with the wheel, but owing to the slight irregularities there are variations of contact, which in effect keep making and breaking the circuit. Referring to the thirteenth sketch, with the tikker contact open, suppose the secondary inductance and condenser  $C_2$  to be tuned to resonance with the incoming waves. If now the tikker is closed when  $C_2$  has any stated value of charge, some of the charge will be given to the condenser  $C$  and furthermore the radio oscillations cease because the addition of  $C$  throws the apparatus out of tune. When the tikker is opened the condenser  $C$  discharges through the telephone, and in the meantime the secondary oscillations build up again, ready to give a charge over to  $C$  when the contact is closed. In this manner the current impulses through the telephone are of the same frequency as the operation of the tikker, and this can be controlled by the speed of the wheel. The capacity of  $C$  should be about 1 mfd. No separate rectifier is needed. The tone obtained is not musical, since  $C_2$  is charged to different potential differences at the different times when the tikker closes, and the action depends also upon a somewhat irregular contact.

In the heterodyne method an apparatus is arranged to produce undamped electric oscillations in the receiving circuit, of nearly the same frequency as that of the waves which are being received, and their combined action is made to affect the receiving telephone. Beats are produced having a frequency equal to the difference of the frequencies of the two waves. The connections are shown in the fourteenth sketch. Any source of undamped or slightly damped oscillations is connected at A. In the antenna circuit at B is a single turn or loop, coupled inductively to A. The antenna circuit thus gets the effect of the oscillations from A as well as from the incoming waves. Suppose those received have a frequency of 100,000, and the heterodyne A is adjusted to give a frequency of 99,000. As long as both act, the telephone will respond to a pitch of 1,000 vibrations per second, which is of course audible. When the incoming waves cease, the heterodyne continues to act along at 99,000, but this is inaudible. Therefore signals are heard only during the time when the incoming radio waves are received.

While a radio telephone transmitting apparatus operates on undamped waves it is not necessary, or indeed permissible, to use a chopper, tikker, or heterodyne at the receiving station. The transmitted waves are modified or varied in intensity by the spoken sounds and these sounds are reproduced in the telephone of the ordinary receiving set such as is used for damped waves.

(To be continued.)

<sup>1</sup>See *Engineering*, February 8, 1918, page 155.

<sup>2</sup>See *Engineering*, 1918, page 562 and 583 ante.