It should also be noted that the spasmodic precipitation of the arid region has favored the washing-away of the products of decay, even if this was not all soluble. Doubtless a great quantity of pulverized rock, both limestone and sandstone, was spread widely over the plain. But this has been removed by solution and storm-wash of the torrential rains. The elevated rim of the crater prevented inwash from the surrounding desert.

All the facts concerning the C. D. irons clearly indicate that they were inclusions or nodules of resistant nature, inclosed in some kind of perishable material. And some of that matrix was chlorine-bearing iron.

The rotund or globular form of some of the "shale balls," the decomposable irons, strongly suggests that they also were only concretionary masses in a matrix of other substance. That substance could have been only the stony materials of which most known meteorites are composed. It may not be claimed that because of its greater size the Meteor Crater meteorite was entirely different in source and nature from all other celestial immigrants.

All the facts relating to meteorites in general, and the Meteor Crater bolide in particular, along with the theoretic probabilities, support the view that the Arizona visitor was a very large stony mass with metallic inclusions.

The stony matrix was brittle, even if without very low temperature, and it was shivered by the impact mostly or wholly to dust. And this was thrown high in air, and borne by the steam cloud it was disseminated far and wide, and any large fragments were quickly destroyed by decomposition and hydration.

This conclusion regarding the C. D. irons may imply that many other, if not all, of the known iron meteorites, even the largest, were originally inclusions in perishable matrix. The irregular, angular forms, perforations and characterless surfaces were probably produced by their imbedding as nodules or accretions in other materials. Only the irons which have traversed our atmosphere after losing their protective covering exhibit some frictional and flowage surfaces.

In the above study no estimate has been made as to the kinetic energy resident in the bolide, and the explosive effect has been attributed mainly to the water and air held in the rocks. But if the meteor was large, with high velocity and high density, the impact might have produced sufficient heat to vaporize both the meteor and the crushed rock. And more probably such would have been the case if the bolide was wholly or largely nickel-iron.

In such case the metallic vapor, with terrific expansion in all directions, should have coated all the surviving rocks with a green stain. The absence of such stain is another argument for a stony meteor.

If the meteor was dissipated in vapor then the thousands of C. D. irons found on the desert could not have been part of the main body. With or without enclosing matrix they had become detached from the central mass by atmospheric friction, and so far separated, and perhaps laggard, that they escaped the grand smash-up.

MICROPHONIC ACTION IN TELEPHONE TRANSMITTERS

By Dr. FREDERICK S. GOUCHER

BELL TELEPHONE LABORATORIES

A microphone may be defined as a transmitter which makes use of the resistance variation of one of its elements in changing a pressure wave into an electrical one. That element, in the case of our commercial carbon transmitter, is an aggregate of loosely packed carbon granules, which is compressed between the diaphragm and the wall of a cavity in which the granules are held. Other types of transmitters operate in accordance with other principles. Bell's original transmitter, for instance, reversed the action of the present-day receiver and was electromagnetic in its action. The condenser transmitter, now used extensively in the sound picture industry, depends, on the other hand, on changes in capacitance. Neither of these types has the advantage of amplification and high energy output characteristic of the carbon transmitter, and for this reason the latter is used almost exclusively in our present-day telephone system.

Microphonic action as applied to our commercial transmitters has to do then with those physical changes responsible for variations in resistance which take place in the aggregate of granules when this is subjected to variations of stress at audible frequencies. This process is complex, and as yet there has been no experimental demonstration of the precise nature of the changes involved.

Historical

An attempt at a quantitative theory of microphonic action was made by Professor P. O. Pedersen.[1] He assumed that microphonic action occurs as a conse-

[1] *Electrician*, February 4, 1916.

quence of the elastic deformation of the contact material resulting in a variation of the contact area. Considering the case of two elastic conducting spheres brought into contact, Pedersen assumed that the resistance is made up of two parts: *viz.* (1) the resistance of a conducting film, the specific resistance of which does not change under pressure, and (2) the so-called "spreading resistance" or that which is caused by the concentration of the current flow within the region of the contact area and which would exist independently of any film.

Using well-known principles of elastic and potential theory, he arrived at the equation

$$R = \frac{A}{(F)^{2/3}} + \frac{B}{(F)^{1/3}} \qquad (1)$$

where R is the contact resistance, A and B are constants and F is the contact force. The first term on the right is the film resistance which is inversely proportional to the contact area and the second term is the "spreading resistance" which is inversely proportional to the radius of the contact area.

Pedersen tested his theory by experiments on carbon spheres and found reasonable agreement over a wide force range. But there were reasons for doubting the existence of the high resistance film. It appeared reasonable to suppose that contact would not take place over the whole contact area owing to surface roughness (the existence of which could be observed under a microscope especially in the case of carbon) and that this roughness would behave somewhat like a high resistance film. F. Gray, of these laboratories,[2] worked out a theory based on this assumption which was so nearly like Professor Pedersen's that it was difficult to discriminate between them experimentally. He assumed that the microscopic hills in electrical contact not only increase in number as the contact force is increased but that the resistance per hill varies in accordance with the theory of spreading resistance as assumed by Pedersen.

Considering the simple case of two spheres having a surface of ideal roughness consisting of smooth spherically convex hills, the radius of curvature of which is small compared with that of the contacting spheres, he arrived at the relation

$$R = \frac{A}{(F)^{7/9}} + \frac{B}{(F)^{1/3}} \qquad (2)$$

The first term on the right shows the effect of the roughness and the second term the effect of the "spreading resistance" which would exist independently of the roughness. This equation differs from Pedersen's only by a factor of $(F)^{-1/9}$ in the first term on the right. Gray also investigated the effect of adding a film to this first order roughness and the effect of adding a second order roughness to the first order roughness and showed that these only serve to modify the equation slightly at small contact forces. A high degree of roughness gives a departure from the inverse 7/9 power law and a transition to the inverse first power law for the case infinite roughness.

Equation (2) was found to fit experimental curves remarkably well at large contact forces and over a very wide range of forces. It thus appeared that surface roughness behaves almost identically with a non-variable high resistance film. Marked departures from theory were found at very small contact forces, the resistance decreasing too rapidly with an increase in contact force. These departures are no doubt associated with plastic deformation of the contact material, as Gray was able to show.

However, the applicability of the theory to contacts between granules of microphone material was left in doubt, not only because the contact forces in this case are smaller—being of the order of 1 dyne—than those for which the theory had been demonstrated to hold, but also because of several effects which indicated that other factors might be dominant in this region of small contact forces.

For instance, it has been demonstrated[3] that adsorbed films of air are capable of producing a marked increase in the resistance of granular carbon contacts. It is reasonable to assume that these films may play some fundamental part not only in the conduction of current across the contact but in the mechanism of resistance change with variation of contact force. The late Emile Berliner, who was responsible for fundamental developments in carbon transmitters, believed that these air films are all important and even went so far as to claim that an actual gap could be observed—by means of a microscope—between contacts while they were transmitting.

Again there is a marked decrease in the resistance of granular carbon contacts with increase in voltage which has not been satisfactorily explained. This fact suggests among other possibilities that the conduction process may involve the passage of electrons across gaps of molecular dimensions in the manner of a cold point discharge; field gradients of sufficient magnitude to extract electrons from a solid could exist in these gaps with only a fraction of a volt across the contacts. If this were the case microphonic action might well be associated with a variation of the gap dimensions under strain.

Another suggestion has been that the resistance change is a strain phenomenon: that is, owing to cohesion, the contacts may be substantially welded to-

[2] *Phys. Rev.*, 36: 375, 1930.

[3] P. S. Olmstead, *Journal of Phys. Chem.*, 33: 69, 1929.

gether and the resistance is changed in much the same manner as that of a wire under tension or that of a solid under hydrostatic pressure. Bridgman has shown that the pressure coefficient of resistance of carbon is negative, so that we might reasonably expect at least part of the decrease in contact resistance with increase of contact force to be due to this cause. At a very early date Edison advanced the hypothesis that microphonic action is due to a change of specific resistance of the material in the contact junction.

RECENT EXPERIMENTAL WORK[4]

In view of these considerations it appeared very desirable to study the behavior of contacts—particularly those between granules of microphone carbon—under conditions of very small contact force. The work which will here be described has been undertaken with this object in view. A technique has been developed for controlling contact forces of the order of 1 dyne or less, either in the highest vacuum or in any desired gas atmosphere, also for controlling contact temperature over the range of temperatures which, we have reason to believe, covers that which holds for the contacts in a microphone.

The essential features of one of the tubes used in studying these contacts are shown diagrammatically in Fig. 1. The contacts C_1 and C_2 are fastened re-

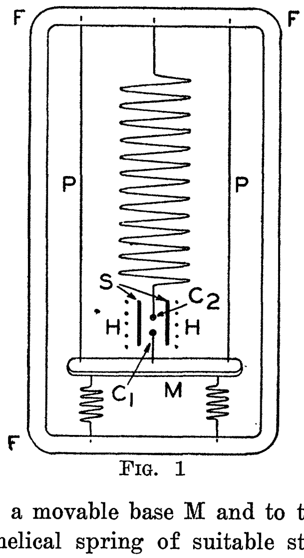

FIG. 1

spectively to a movable base M and to the lower end of a silica helical spring of suitable stiffness. The base M is supported from a fixed frame F by two vertical platinum wires P and two stretched springs as shown. M is moved by heating or cooling the platinum wires, through the passage of current, thereby causing them to expand or contract. In this way the contacts may be made or broken and any desired contact force applied through the compression of the helical spring. Control of the temperature of the contact is obtained by surrounding the contact region with a metal cylinder S which may be heated by means of radiation from a platinum heater H, the temperature within the cylinder being measured by means of a thermocouple placed near the contacts.

In practice C_2 consists of a single granule fastened to the end of a platinum wire by means of carbon paste, and C_1 consists of a number of granules attached to a horizontal metal plate by the same means; in this way a variety of contacts can be studied with the same tube. A small hole in the metal cylinder surrounding the contacts permits of direct observation of the contacts during measurement.

When set up for measurement the tube is suspended by rubber bands within a massive metal container which serves to protect the system from acoustic shock. This container is mounted on a suspension to minimize the effect of vibrations. Two reading telescopes are mounted in the side of the container for the purpose of measuring the spring compression, the lower one being focused directly on the contact.

Measurements made with this device have enabled us to draw a number of conclusions in regard to the nature of these contacts and their behavior when the contact force is varied.

In the first place, we have identified the conducting portions of the contacts as of the nature of carbon by means of measurements on the temperature coefficients of resistance of contacts. It is well known that the temperature coefficient for carbon is negative—as opposed to a positive value for most conductors—and the magnitude of this coefficient for the contacts was found to be of the right order and sign for solid carbon, prepared by special heat treatment. The value of the contact temperature coefficient may be modified by heat treatment of the carbon which probably does not affect its interior so that we have reason for believing that the surface material is a somewhat different carbon from that inside.

The magnitude of the temperature coefficient of resistance was found to be independent of gas pressure even though the presence of gas increased the contact resistance. The gas therefore must act as a non-conducting film limiting the areas of the conducting portions of the contact and not affecting their nature.

A reversible change of contact resistance with applied contact voltage—the resistance decreasing with an increase of voltage—was found to be due entirely to the heating of the contacts arising from the passage of current. This was shown by comparing contact behavior at known temperatures with that at known voltages and checking the theory of contact temperature arising from the heating effect of current. This theory based on earlier work of Kohlrausch had been

[4] F. S. Goucher, *Phys. Rev.*, 35: 1429, 1930; 36: 375, 1930.

worked out previously in these laboratories by F. Gray[5] and independently by R. Holm.[6] The theory gives as an approximate formula

$$T = \text{const.}\,\frac{V^2}{K_o/\sigma_o} \qquad (3)$$

where T is the increase of temperature above room temperature, V the contact voltage and (K_0/σ_0) the ratio of the thermal to electrical conductivity of the contact material. A reasonable value of (K_0/σ_0) for carbon is obtained from these experiments. The conduction process is thus shown to be that which occurs in solid carbon, and no other effect, such as electronic discharge across small gaps, can be an important factor. This result is therefore in line with recent experiments of Holm[7] which have demonstrated the metallic nature of contacts between metals, and of carbon for relatively large contact forces.

The following experimental results have a direct bearing on the mechanism of change of resistance with change of contact force. Reversible resistance changes accompanying changes of contact force between fixed limits are obtained with these contacts, the resistance decreasing with increase of force. Also, the temperature coefficient of resistance is found to be substantially constant as the resistance is varied over a wide range in such a reversible cycle. Both these facts point to area change as the cause of the change of resistance with force, since we know that the elastic deformation of a contact would produce a change in contact area of the required type, and also since we might expect a measurable change in the temperature coefficient of resistance if the state of strain within the contact region were markedly altered. Although the mean stress within the contact area alters somewhat with the contact force, even when the area changes in accordance with elastic theory, this effect is relatively small.

These conclusions concerning the nature of the contacts and the mechanism of resistance change with contact force are in line with the assumptions underlying Gray's equation. Accordingly a study was made of the slopes of the reversible resistance force cycles for both single contacts and aggregates.

The technique used for the study of aggregates was similar to that employed for the single contacts with the exception that the lower contact C_1 consisted of a shallow cup with a conducting bottom and containing a large number of loosely packed granules several layers deep. The upper contact was made by cementing a large number of granules to the bottom of a conducting plate, the cement being such as to give a low resistance contact.

The experiments showed that for any reversible cycle the relation between the resistance and force was of the form

$$R = K\,(F)^{-n} \qquad (4)$$

in the case of both single contacts and aggregates. The exponent n varies somewhat from cycle to cycle when the force limits are the same and its average value depends on the force limits.

The largest values of n were obtained with the aggregates under such conditions of force limits as to indicate that the elastic straining of the aggregate during the cycle was relatively large. A maximum mean value substantially independent of the force limits over a wide range closely approaches 7/9, which is the maximum value consistent with equation (2). This indicates that with sufficiently large strains the aggregate may be made to act as though it were a single contact between spheres having rough surfaces obeying the laws assumed in the derivation of equation (2). On the other hand, for relatively small strains the value of n diminishes to values smaller than the theoretical minimum 1/3 consistent with equation (2). The measured values of n for single contacts are in general less than 1/3 and may become very small if the contact forces are large. These departures from theory appear to be associated with internal contact forces or cohesion which render the contacts relatively insensitive to changes in the applied forces. The existence of cohesion was readily demonstrated by the fact that the contacts always required a finite force to break them even when no current had passed through the contact.

All the experimental results are therefore consistent with the theory of area change due to the elastic deformation of the contact material. Furthermore, the realization of the theoretical maximum value of n in the case of the highly strained aggregates indicates that in a granular mass deformed elastically not only do the contact areas change in the case of those contacts already established, but that new contacts possibly between other granules may be made and broken in a reversible cycle.

OBITUARY

MEMORIAL TO JAMES MELVILLE GILLISS

THE Secretary of the Navy has forwarded to the Ambassador at Santiago, Chile, a bronze bust of the late Lieutenant James Melville Gilliss, U. S. Navy. Mrs. Louise Kidder Sparrow, of Hyannis, Massachusetts, was the sculptress. Congress on June 9, 1930, passed an act providing an appropriation to procure for presentation to the Chilean National Observatory,

5 Unpublished.

6 *Z. tch. Phys.*, 3: 290–294, 320–326, 349–357, 1922.

7 *Wiss. Ver. a. d. Sieman's-Konzern*, 7: 217–271, 1929.