there are exactly two unimodular matrices $P=\|P^{A'}{}_B\|$ and $-P$ which satisfy

$$g^\sigma = P\bar{g}^\tau \bar{P}^{-1} L^\sigma{}_\tau = Pg'^\tau \bar{P}^{-1} L^\sigma{}_\tau, \qquad (2.2)$$

where the prime denotes the transposed matrix. The last of these equations follows from the fact that

$$\bar{g}^{\sigma A'B} = g^{\sigma B'A}$$

and hence

$$\bar{g}^{\sigma A'}{}_B = g^\sigma{}_{B'}{}^A.$$

When dealing with complex vectors in the space of the x^σ the last form of Eq. (2.2) should be used.

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An Improved Method of Making Permanent Electrets and Factors Which Affect Their Behavior

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A method is described for making strong, smooth, and uniform electrets. The study concerns both the mixing of the carnauba wax and rosin of which the electret is made, and the manner of cooling in the electric field. The electret was cooled in a heavy iron cylinder placed in an oil bath whose rate of cooling was controlled automatically. Electrets were made for which the time of cooling ranged from 30 minutes to 10 days. Observations made on some 35 electrets seem to justify the following conclusions: (1) Electret behavior depends markedly upon details of preparation of the carnauba wax-rosin mixture. The time required for reversal of the electret's charge is increased by mechanical mixing of the components, by heating to a high temperature for a short time, or by heating to a somewhat lower temperature for a longer time. (2) Extending the cooling time in the electric field beyond a day produces little effect. Below this there exists a range of cooling times vital to the behavior of the electret. Those cooled in the open air in the customary manner reverse sign in a shorter time than do those cooled within the cylinder. X-ray photographs show a structural difference between these. (3) Alignment of crystals, as judged from x-ray studies, has little to do with the final charge density attained by the electret. Many samples which are electrets show no alignment. (4) The behavior of the carnauba wax-rosin electret is that of carnauba wax physically modified by the presence of the rosin.

PERMANENT electrets composed of carnauba wax and rosin acquire a final charge which is of sign opposite to that which one expects on the basis of an ionic or polar hypothesis; that is, the face of the electret adjacent to the positive electrode during the manufacturing process finally assumes a positive rather than a negative charge. Crumrine[1] and Gemant[2] have suggested that such behavior might be expected if one of the constituents of these electrets were piezoelectric. Some force mechanism would have to exist to produce the observed charge. This force might arise because of strains set up in the wax during cooling. If we accept this concept, then we might expect these strains, and hence the electret charge, to be affected by the rate at which the wax is cooled during manufacture of the electret.

Preliminary to investigating how the charge on the electret is related to the manner in which the wax mixture is allowed to cool during manufacture, some effort has been directed towards a method of securing smoother, more uniform samples. Our experience has shown that the details of preparation have a greater effect upon the subsequent behavior of an electret than the literature would lead one to believe.[3] Therefore, the purposes of this investigation were: (1) to devise a method of making smooth, uniform electrets; (2) to obtain information as to what effect the details of preparation have upon the behavior and structure of the electret; (3) to observe how the final charge on the electret

[1] K. Crumrine, Master's Thesis, University of Kansas (1933).
[2] A. Gemant, Phil. Mag. 20, 929 (1935).
[3] J. V. Eguchi, Phil. Mag. 49, 181 (1925).

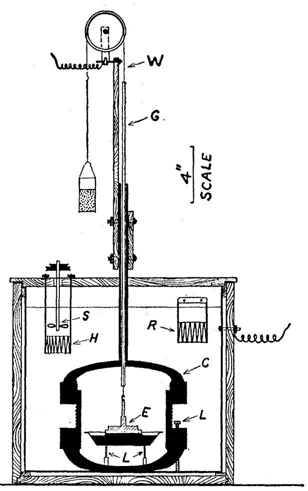

FIG. 1. C, heavy iron cylinder immersed in an oil bath; H, heater; S, stirrer; R, resistance thermometer; L, leveling screws; E, upper electrode; G, glass tube; W, flexible wire supporting and making electrical contact with the upper electrode.

and the rate at which this charge is acquired, depend upon the manner of cooling in the electric field.

THE METHOD OF MANUFACTURE

The behavior of permanent electrets has been shown to depend upon the kinds and relative amounts of materials in their composition.[2] The strength of the electric field in which they are cooled has also been shown to be significant.[1, 2] All electrets in the present study were composed of equal weights of rosin and carnauba wax, and were made with a field strength of approximately 8000 volts per centimeter. To control the rate at which cooling took place in the electric field, an oil bath as shown in Fig. 1 was used. A resistance thermometer, bridge with continuously variable galvanometer contact, photo-cell, and relay system, made it possible to extend the time required for cooling to 24 days.

Tin seems most satisfactory as an electrode material; it showed less evidence of electrochemical activity than other metals which were tried. The bottom electrode was a tinned pan; the top electrode was a solid tin disk, turned on a lathe, and polished with carbon tetrachloride and rouge. A new pan was used and the top electrode repolished, for each electret made. Since the melted wax wets the tin, it is possible, by counterbalancing the top electrode slightly in excess of its weight, to cause that part of the electret in contact with the electrode to be elevated. (See Fig. 1.) In this way the electret is left free to contract when it cools, without the inevitable cracking that occurs when the electrode is imbedded. The temperature of the oil bath was not allowed to exceed 90°C; at higher temperatures the tin showed evidence of chemical action. For the same reason the mixture was not poured into the tinned pans at temperatures above 90°.

The oil bath was kept at 90° for twelve hours after lowering the top electrode onto the surface of the melted wax. This prolonged heating at 90° seemed to have no significant influence upon the behavior of the electret; it was found necessary to produce electrets having no air pockets in the surface next to the top electrode. The bath was allowed to cool to 75°C at a rate determined by surrounding temperatures. Below 75° the cooling time was controlled automatically; it could be made as long as 24 days. The electric field was applied automatically when the temperature dropped to 75°; if it were applied at 90° the resulting electret inevitably cracked at the periphery of the top electrode.[4] The electret was removed from the cylinder at or below 24°C. If it were removed at a temperature much higher, the top electrode would stick. The electrets were kept in the pans in which they were made. These pans were provided with lids of such design that the top face of the electret was shorted to the bottom face when the lid was closed. Avoiding the use of tin foil as an electrode leads to much smoother electret surfaces; avoiding its use as a wrapper minimizes effects introduced by handling. An air-tight cabinet with dryer was used for storage.

RESULTS AND CONCLUSIONS

A series of electrets was made in which successive samples of the series were heated to successively higher temperatures during melting. As the carnauba wax and rosin going into a particular electret were melted together, the

[4] This cracking was peculiar in that it appeared to follow the fringing lines of electric force as they leave the edge of the upper electrode. It is not clear just what causes this.

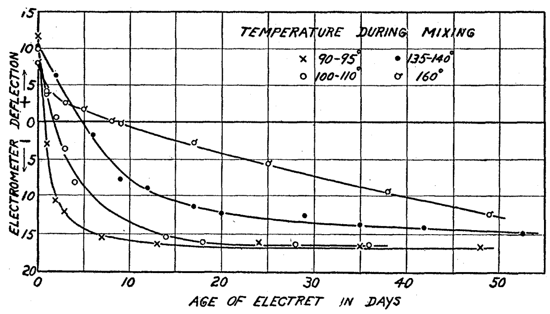

FIG. 2. Showing the effect of the temperature maintained during mixing upon the subsequent behavior of the electret. The cooling time for each of these electrets was one day. A positive electrometer deflection indicates that the face of the electret bears a charge opposite in sign to that on the electrode adjacent it during manufacture. Although these observations were made without the use of a guard ring, further measurements with a guard ring showed the same relative behavior. The final charge density attained by these electrets is essentially the same as that attained by electrets made in the usual way.

temperature of the melted portion was held at that temperature characterizing this given electret until the last bit of solid carnauba wax or rosin had melted. The curves in Fig. 2 illustrate the effect of the temperature maintained during melting upon the subsequent behavior. There are two conclusions that can be drawn from these curves. First, all samples attain approximately the same final surface density of charge; and second, the time required for reversal[5] in sign of charge becomes less and less as the temperature maintained during melting is lowered. Further investigation has revealed that the reversal time approaches a lower limit which is that characteristic of an electret of pure carnauba wax. There is evidence that either prolonged heating or vigorous stirring of the wax at lower temperatures accomplishes to a lesser degree what is here accomplished by higher temperatures during the initial melting. These facts suggest that the subsequent behavior of the electret depends upon the thoroughness with which the components are mixed, and that heating contributes to this mixing. Chemical action may play a part, but x-ray evidence to be presented indicates that the effect is mainly one of physical mixing.

In order to study the way in which the characteristics of the electret depend upon the rate at which it is cooled in the electric field, it was necessary to adopt a standard method of preparing the wax which could be duplicated with sufficient accuracy to insure otherwise identical electrets. The wax was prepared by heating it at 135° for two hours. Constant moderate stirring assisted in establishing a uniform temperature throughout. Results having to do with the effect of the manner of cooling in the electric field will, for convenience, be classified as follows: (a) those for electrets cooled in the iron cylinder, and, (b) those for electrets cooled in the open air. When cooled inside the iron cylinder the electrets are smooth, uniform, and strong. The two parallel faces are as smooth as the electrodes with which they were in contact. Samples of such electrets have been made for which the cooling times ranged from 30 minutes to 10 days. The shortest cooling time attainable by allowing the oil bath to cool normally was a little over a day. Electrets were made in 10 days, 4 days, and 1 day without having to resort to rapid cooling schemes. These electrets yield rather consistent evidence that the time for reversal of charge becomes longer, and the final density of charge becomes smaller, as the time of cooling in the electric field is increased. The differences are so small, however, that they can scarcely be considered significant. A more perceptible trend of this character was evidenced by electrets which were cooled by cold oil added immediately after the hot oil had been drawn off at 75°C. These more rapidly cooled[6] electrets reversed in a shorter time, acquiring essentially the same final charge in a shorter time. If, on the other hand, one adds ice water instead of the cold oil, thereby reducing the total cooling time to 30 minutes, the samples do not become electrets at all. This was the only manner of cooling which did not yield an electret of some character. The three samples so made did not reverse during a $3\frac{1}{2}$-month period after manufacture; and they gave no indication that a reversal would ever take place. Finally, electrets cooled inside the iron cylinder require a much

[5] It appears that this time of reversal depends also upon the rosin, since electrets made from another batch had reversal times, when well mixed, of about 4 weeks instead of the 8 days shown in Fig. 2.

[6] These electrets cooled from 75° to 37° in one hour. They remained in the cylinder approximately a day, until the oil bath had reached room temperature.

longer time to reverse their sign of charge than those cooled in the open air, using the same electrode system without the inclosing iron cylinder. Those cooled in the cylinder were free from cracks and strong; those cooled in air were full of cracks and easily broken. The authors see no reason why cooling in the cylinder and cooling in the open air should produce results so radically different, or why cooling the cylinder with ice water produces no permanent electret. The phenomena are no doubt connected with the temperature gradient within the cooling electret. Information regarding this might be obtained through use of thermocouples imbedded in the cooling wax.

In addition to investigating the behavior of the charge on the electret, a simultaneous x-ray study was made by removing a small core from each one and examining the diffraction rings immediately after the electret's manufacture and again after the reversal of charge had taken place. For the electrets composed of rosin and carnauba wax and cooled in the open air, results were obtained corroborating the work of Ewing.[7] The present work, however, shows a diffuse ring inside those described by Ewing.[8] By securing the diffraction patterns for pure carnauba wax and for pure rosin, it was ascertained that the three sharp rings described previously belonged to carnauba wax, while the inner diffuse ring had a contribution from both rosin and carnauba wax. The fact that the diffraction patterns for the two component materials are not modified by thoroughly mixing the components, indicates the absence of a predominant chemical combination. A notable difference exists for all electrets cooled inside the cylinder in that they all show entirely uniform diffraction rings. This is true even for electrets of pure carnauba wax. Both types, the one showing uniform diffraction rings, the other showing marked variations in intensity, make equally good electrets. Crystalline orientation seems to have no effect upon the final strength of an electret. Significant is the fact that when pure carnauba wax is cooled in the open air, the diffraction pattern indicates a more nearly complete alignment of crystals than does that of any other type of electret. (See Fig. 3.) The intensity distribution in the diffraction rings of one pure carnauba wax electret was found to change noticeably during a 5-month period; there was no observable change in electret behavior.

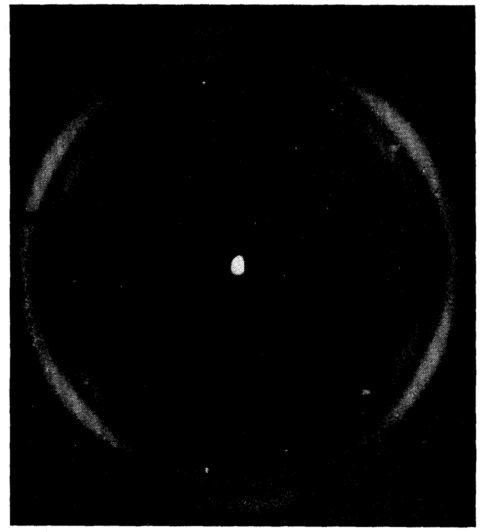

FIG. 3. X-ray diffraction photograph of an electret of pure carnauba wax cooled in the open air. The x-ray beam was perpendicular to the previously applied electric field. This field was directed horizontally across the photograph.

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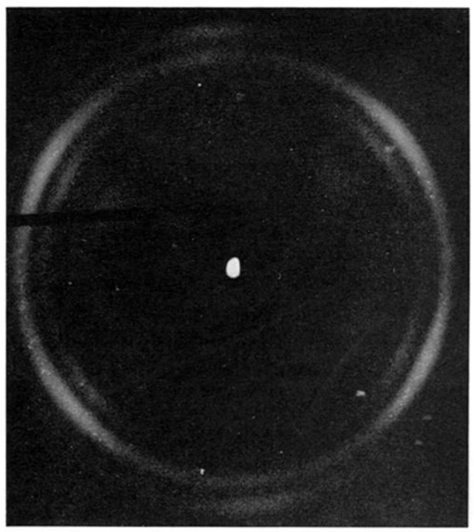
[7] M. Ewing, Phys. Rev. **36**, 378 (1930).

[8] Ewing found three sharp rings, and found that for electrets all these rings varied in intensity in a simple symmetrical manner.



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