ART. XX.—*On the Electrical Resistance of Glass, Quartz, Mica, Ebonite and Gutta-percha*; by OGDEN N. ROOD, Professor of Physics in Columbia University.

IN the August number of this Journal for 1901,* I published an account of an electrometer intended for measuring very high electrical resistances, and at the same time described a set of units of resistance that had been made with its help, the highest of which reached to 14,000,000 of megohms. Since then, with a similar set of high resistances, measurements of the external and internal resistances of certain insulating substances have been undertaken, which may not be without interest, in spite of the fact that they are to be regarded as first approximations. The reason of this limitation is to be found, not in any especial uncertainty in the resistance of the units employed, but in another direction, viz: metallic connection with substance under experiment is necessary, but mere mechanical contact is not sufficient to abolish contact-resistance, which is apt to be quite large, and various expedients were adopted to remove this troublesome difficulty. The best of these appeared to be the application of an amalgam of tin and mercury, of the consistence of soft butter, to the parts in question, but others were also employed; as, for example, in the case of gutta-percha, it seemed fair to cement the tinfoil to it with a liquid solution consisting mainly of gutta-percha, while in the case of ebonite, a metallic powder was attached to its surface by a very weak solution of shellac, and this again overlaid by tinfoil. Another source of error lies in the *time* of exposure to the electrical current, as the resistance of the substance through which it flows is apt to increase with the time. The initial resistance, or more properly the average resistance during the first stroke of the electrometer, was in each case noted, and an effort was made to adjust matters so that this should be about one minute, but very often it differed considerably from this amount of time, a drawback which could only be remedied by a large amount of extra labor and expenditure of time. It is owing then to these two factors that the measurements given below are to be regarded as first approximations. On the other hand, no difficulty was encountered in causing the current to pass through glass, quartz, mica, gutta-percha and ebonite, or to flow over their surfaces.

Mode of experimenting.—Mr. H. C. Parker determined for me the resistance of five small units in the ordinary way, and

* This Journal, vol. xii, p. 91.

these were used to build up a large set of high resistances similar to those described in my article already alluded to. All this was done twice, and during these operations, the resistances of the insulating substances under experiment were determined, as far as possible, immediately. In the case of surface conduction, tinfoil was cemented on the ends of the strip and fringed with a line of metallic powder. For internal conduction, metallic surfaces were fastened to opposite sides of the plate, which was provided with a guard-rim of tinfoil, cemented with a solution of gum arabic and glycerine all around its edges, and grounded to prevent surface electricity from reaching its opposite side; a precaution which in the case of quartz and ebonite is not necessary, quartz giving the same result with and without the guard-rim, and the surface conduction of ebonite in dry weather is again still smaller than that of quartz.

In order to compare together the results obtained, those for surface conduction are reduced to the *calculated* resistance that would be offered by *one* surface of one square centimeter between the terminals. For internal resistance, the *calculated* resistance of coatings one square centimeter in area, with a thickness of one millimeter of substance between them, is given. A set of one hundred dry cells was employed in each case; its electromotive force was 150 volts. The striking distance of the electrometer was one millimeter, except in the case of very high resistances, where it was reduced to one-half or one-quarter of a millimeter.

Internal resistance of quartz.—The thickness of the plate was 1.71^{mm} , the metallic coatings, each, one square centimeter in area. Calculating the resistance for a thickness of 1^{mm} , I obtained, on

Feb. 19th	860,000	Ω	Hyg. 18°
" 22d	910,000	"	" 27°

The coatings were composed of an amalgam of tin and mercury.

Internal resistance of glass.—Very numerous measurements were made on plates of ordinary glass, and on others colored by oxide of cobalt, and even one plate of glass 6.2^{mm} in thickness was employed. The current traversed all of these with a certain facility, but the resistance of the cement used to attach the coatings increased from week to week, and consequently it is not worth while to give any figures at present. The internal and external resistances of two excellent Leyden jars of recent German make were also measured; in both cases the external resistance was very considerably greater than the internal; hence, in use, the main leakage would be through the sub-

stance of the glass. It would, therefore, seem undesirable to obtain capacity by thinness of wall.

Internal resistance of gutta-percha.—Two sheets of gutta-percha were employed, their thickness being 2.79^{mm} . Tinfoil was cemented on them with a solution of gutta-percha, and the results were fairly constant as seen below, where the actual figures obtained are given :

No. 1	6,030,000	Ω	Feb. 19th	Hyg. 18°
" 2	6,270,000	"	" "	" "
" 1	5,240,000	"	" 24th	" 27°
" 2	6,640,000	"	" "	" "
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	6,050,000	"		

Calculating this for a surface of one square centimeter and a thickness of one millimeter, we obtain, $18,500,000 \Omega$.

Internal resistance of ebonite.—Three plates of this material were used, one having a thickness of 2.29^{mm} ; the other two were only $.5^{\text{mm}}$ thick. The coatings were made of a metallic powder backed by tinfoil, all of which probably did not insure the best possible contact.

Reducing the results to the standard of one square centimeter of surface and a thickness of one millimeter, we have

No. 1	76,400,000	Ω	Hyg. 32°
" 2	45,200,000	"	" "
" 3	45,000,000	"	" "
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	55,000,000	"	

Internal resistance of mica (muscovite, beautiful large sheets).—The thickness of No. 1 was $.122^{\text{mm}}$; Nos. 2 and 3 had a thickness of $.32^{\text{mm}}$. The coatings were made in the same way as with ebonite. Reducing to an area of one square centimeter and a thickness of 1^{mm} , I obtained for

No. 1	100,000,000	Ω	Hyg. 32°
" 2	190,000,000	"	" "
" 3	110,000,000	"	" "
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	133,000,000	"	

From this it would seem that the internal resistance of mica is somewhat greater than that of ebonite, though, as will be shown later on, its surface resistance is much smaller.

Surface resistance of plate glass (window glass, commercial).—This proved to be unexpectedly regular, in spite of some variations in the hygrometric condition of the air. Two plates were employed, each having a length of 23.7^{cm} between the terminals. The actual figures obtained on three different occasions are as follows :

No. 1	3,400,000	Ω	Feb. 19th	Hyg. 18°
" 2	3,600,000	"	" 22d	" 27°
" 1	3,700,000	"	March 3d	" 32°
" 2	3,600,000	"	"	" 32°
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	3,570,000	"		

Calculating this for *one* surface of one square centimeter between terminals gives 1,590,000 Ω .

Surface resistance of cobalt glass.—From previous experiments it was known that the surface resistance of cobalt glass is considerably greater than that of the ordinary varieties of window glass, and the results given below confirm this idea. Four strips were used, with an average length between terminals of 4^{cm}. The experiments were all made on the same day, the hygrometer indicating 34 per cent of moisture. The actual figures obtained are:

No. 1	24,400,000	Ω	Hyg. 34°
" 2	21,700,000	"	" "
" 3	24,400,000	"	" "
" 4	21,700,000	"	" "
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	23,000,000	"	

Calculating this for *one* surface of one square centimeter between terminals gives 22,000,000 Ω .

Surface resistance of mica.—Four slips of mica were used; the distance between terminals was 2.5^{cm}; the actual figures were:

No. 1	29,900,000	Ω	Hyg. 35°
" 2	25,600,000	"	" "
" 3	39,400,000	"	" "
" 4	31,600,000	"	" "
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	31,600,000	"	

Calculating for *one* surface of one square centimeter, we obtain 50,760,000 Ω .

Surface resistance of gutta-percha.—Two slips of the material were used, the distance between terminals being 1^{cm}. The actual figures were:

No. 1	17,500,000	Ω	Feb. 20th	Hyg. 17°
" 2	18,900,000	"	" "	" "
" 1	13,000,000	"	" 28th	" 35°
" 2	7,700,000	"	" "	" "
" 1	18,800,000	"	March 3d	" 32°
" 2	19,500,000	"	" "	" "
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	16,000,000	"		

Calculating the mean for *one* surface of one centimeter between terminals, we have 432,000,000 Ω .

Surface resistance of quartz (crystal).—The distance from terminal to terminal was 1.5^{cm} ; the actual figures were:

76,000,000 Ω	Feb. 20th	Hyg. 17°
75,000,000 “	“ 27th	“ 34°

Calculating the mean for one surface of one square centimeter, we have 521,000,000 Ω .

Surface resistance of ebonite.—Two strips were used; the breadth of gaps was in one case 5.5^{mm} , in the other 6.2^{mm} .

Calculating the resistances actually obtained, for one surface of one square centimeter we have

No. 1	1,107,000,000 Ω	Hyg. 34°
“ 2	2,940,000,000 “	“ “
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	2,000,000,000 “	

These results are sufficiently discordant; those with quartz are scant, but damp weather prevented additional observations.

In closing this article, I give two determinations of the resistances employed in the investigation, for the purpose of showing the degree of accuracy readily obtainable in the process of building up high units by my method. The two operations were separated by an interval of about a week; the units were one year old.

53,760	53,830 Ω
71,860	72,370 “
81,400	80,500 “
244,000	241,000 “
220,000	205,000 “
297,000	292,000 “
389,000	384,000 “
1,161,000	1,163,000 “
585,000	554,000 “
1,565,000	1,504,000 “
1,401,000	1,380,000 “
2,246,000	2,193,000 “
2,891,000	3,140,000 “
2,203,000	2,193,000 “
3,707,000	3,432,000 “
2,990,000	3,130,000 “
3,070,000	3,130,000 “
1,958,000	1,803,000 “
7,808,000	8,194,000 “
7,902,000	8,460,000 “
8,720,000	8,540,000 “
5,584,000	5,560,000 “
8,120,000	8,194,000 “
6,780,000	6,906,000 “

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