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SELENIUM:

ITS ELECTRICAL QUALITIES AND THE EFFECT OF LIGHT THEREON.

BY WILLOUGHBY SMITH.

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ITS ELECTRICAL QUALITIES, AND THE EFFECT OF LIGHT THEREON.

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By WILLOUGHBY SMITH.

FROM the many inquiries which have reached me since I first called attention to the effect of light upon the electrical qualities of Selenium, I am induced to enter more fully into details than I otherwise should have done.

In 1817 Berzelius discovered a new and rare elementary substance, which he named Selenium. It is obtained in small quantities from iron and copper pyrites, the smoke from the furnaces of silver Works, the deposit in the leaden chambers at sulphuric acid Works, and it has also been discovered in the metallic copper of commerce. It appears in two modifications, one soluble and the other insoluble in bisulphide of carbon. That soluble in bisulphide of carbon has been called "Red Selenium," "Amorphous Selenium," and "Glassy Selenium." That insoluble in bisulphide of carbon has been called "Black Selenium," "Granular Selenium," "Metallic Selenium," and "Crystalline Selenium." Solid amorphous Selenium is a bad conductor of heat and a non-conductor of electricity. At the ordinary temperature it remains unchanged for years. It is brittle, easily scratched and powdered, its surface red-brown and of a metallic lustre, and its fracture of a brown-glass colour, dark lead-grey, and shining.

Solid "crystallized" Selenium is a conductor of electricity, has a granular, lead-grey surface, and a finely granular, dull fracture. The change from the "amorphous" to the "crystalline" state is effected by exposure to a high temperature. Requiring some bars of "crystalline" Selenium for high resistances, I obtained seventeen from a gentleman who had previously supplied me with similar bars; but not requiring them for immediate use, I embraced the opportunity to experiment with them, and the results are such, that I hope they will prove at least interesting to the members of this Society.

The bars were placed in a wooden box thirteen and a half inches long, six inches wide, and one inch deep, with vulcanite sides and wooden cover. Through each side of the box the ends of nineteen binding-screws projected. The ends of each bar had a short length of fine brass wire in metallic contact with it. Each bar was suspended in the box by the brass wires being attached to the ends of the two binding-screws entering the box opposite each other. These bars were marked consecutively from A to R, omitting J, and their dimensions were as given in Table 1.

No. 1.

Mark	Diameter in inches.	Length in inches.
A	·092	1·5
B	·093	1·817
C	·092	1·55
D	·066	1·433
E	·096	1·8
F	·093	1·467
G	·095	1·3
H	·092	1·917
I	·094	1·833
K	·066	1·667
L	·066	1·017
M	·092	1·567

Mark.	Diameter in inches.	Length in inches.
N	·091	1·783
O	·094	1·967
P	·092	1·783
Q	·066	1·117
R	·091	2·483

Not one of the bars was uniform in diameter throughout its length. Several measurements of each were made, and the mean recorded. The temperature inside the box was ascertained firstly by a standard thermometer, the bulb of which was placed in the centre of the box under the bars, and the tube of which projected through an aperture at one end of the box; and, secondly, by the resistance of a length of silk-covered copper wire, which was distributed over the bottom of the box, with its ends attached to terminals, one on each side of the box. The length of the wire was so adjusted that its resistance should be one hundred ohms, while the thermometer registered 63° Fahrenheit. The room in which the experiments were made was 15×16·5×10 feet. The table in the centre of the room was 8·9×4 feet. All solar light was excluded, and the room was but dimly lighted by one ordinary "fish-tail" gas burner, suspended four feet above the centre of the table. The box containing the bars was so placed on the table that the light fell on the centre of it at an angle of fifty degrees. The resistance of each bar was ascertained by the deflection method; that is, a deflection was obtained from a constant electromotive force passing through a known resistance, and then the known resistance was replaced by the Selenium bar, and the deflection noted; and from these two measures the resistance of the bar was determined One hundred Menotti cells, having a resistance of twenty ohms per cell, were used, and an astatic mirror-reflecting galvanometer, the resistance of the coils of which was 6,200 ohms. The box had been closed for three hours previous to the commencement of the test. Table 2 gives the resistance of each bar in megohms. The black figures show the resistance while light was excluded, and the red figures the resistance when light was admitted. The same arrangement will apply to all the tables to which I shall have to refer.

No. 2.

Mark	Megohms.	Megohms.
A	303·6	211·4
B	4.385	4·172
C	229·3	163·
D	46·43	34.44
E	591·3	370·
F	281·	197·3
G	667·	361·5
H	27·86	21·62
I	31·05	26·16
K	52·33	41·
L	739·9	535·1
M	61·10	42·09
N	47·83	34·31
O	150·3	119·9
P	19·17	17·54
Q	0·0099	0·0082
R	0·002919	0·002923
A	303·6	199·8

Each reading was taken after the current had been on one minute, commencing with the bar marked A and proceeding consecutively to the one marked R.

During the test with the light excluded, the temperature increased from 61° to 63° Fahr.; but this appears not to have interfered with the values, as, on the completion of the test, the bar marked A was re-tested, and its resistance was precisely the same as at first. During the test while the light was admitted, the temperature increased from 63° to 65°, and on re-testing the bar marked A, its resistance had fallen to 199·8. This, however, was not all due to change of temperature, but to the time it had been exposed to the light. The effect of light is gradual, and the lower its intensity the slower its effects.

It will be seen that the resistance of each bar is lower while under the influence of light, with the exception of the bar marked R, and that appears to have increased; but its resistance was too low to give satisfactory results, and therefore no reliance is placed in any values obtained from it. There being such great discrepancies in the resistance of the bars, the gentleman who supplied them was asked if he could assign any cause for it. He replied that they were all made from the same sample, and that probably the difference in their resistance was due to some of them having been heated longer than others.

The two following tests were made with a view to ascertain the effects of difference of temperature on their electrical resistance. The box containing the bars was covered with an iron case 17·5 inches high, in the top of which was a square aperture large enough to admit the light from a "bat's wing" gas burner suspended immediately over it, and so regulated as to keep the temperature as near 100° Fahr. as possible. The connections could be made and the light admitted or excluded by manipulating the lid of the box, without removing the iron case or in any way interfering with the arrangements.

The temperature had been kept at 100° Fahr. for an hour before the commencement of the test. The results are given in Table 3.

No. 3.

Mark.	Megohms.	Megohms.
A	373·1	183·4
B	4·719	4·185
C	283·1	152·8
D	51·75	33·19
E	633·3	287·4
F	320·9	163·7
G	654·9	237·7
H	42·97	26·59
I	31·67	24·81
K	48·62	35·65
L	687·6	377·5
M	92·56	46·06
N	65·04	33·78
O	123·4	78·9
P	11·19	8·997
Q	·1449	·1318
R	·003105	·003156
A	356·5	162·6

During the test while the light was excluded, the temperature gradually increased from 97° to 100° Fahr., and the resistance of bar A decreased from 373·1 to 356·5. During the test while the light was admitted, the temperature increased from 98·5° to 99°, and the resistance of bar A decreased from 183·4 to 162·6 megohms. Seven days intervened before the following test was made, the box having been kept closed during that time. The arrangements were the same as in the previous test, with the exception that the bottom of the iron case was kept standing in a freezing mixture. The temperature was kept at 44° Fahr. for one hour before commencing the test. The results are given in Table 4.

No. 4.

Mark.	Megohms.	Megohms.
A	406·2	131·
B	5·731	5·014
C	291·7	110·7
D	54·09	27·57
E	758·1	213·5
F	353·9	122·3
G	962·7	194·5
H	29·9	18·16
I	36·06	22·92
K	61·32	35·39
L	934·7	367·5
M	69·76	30·86
N	52·9	25·74
O	188·8	85·96
P	25·67	16·6
Q	·150430	·120340
R	·003106	·003136
A	406·2	133·7

During the time occupied by the test while the light was excluded, the temperature increased from 43·7° to 46°; but the resistance of bar A remained constant, and was precisely the same on completion as at the commencement of the test. During the time occupied by the test while the light was admitted, the temperature increased from 51·5° to 59·5°, and the resistance of bar A increased from 131 to 133·7 megohms.

It will be seen that at the low temperature light has a much greater effect in reducing the resistance of most of the bars than it has at the highest temperature.

After the above experiments the bars were excluded from light for twenty-four hours, and then again tested under the following conditions. The box containing the bars was placed on a wooden frame two feet four inches high, in a yard sixteen feet wide, bounded on the south by the wall of a high building, and on the north by a similar wall, but not quite so high. The east and west aspects were comparatively open. The longitudinal position of the bars was north and south. The weather was what in common parlance would be termed "a dull, cold afternoon." There was a light breeze from the north-east, dirty white coloured clouds were comparatively stationary overhead, but in the west were gathering large clouds resembling in appearance and density the atmosphere generally seen rising from large manufacturing towns. The sun was not visible, but the varying density of its light, caused by the clouds passing between it and the bars, was distinctly marked by the alteration in the electrical resistance of the bar under test at the time. To be sure on this point, a small artificial cloud, made of finely-combed wadding, was passed from north to south about two feet from, and at an angle above, the box. Although it was difficult to perceive any shadow caused by the interposition of the wadding, still each movement of the same affected the deflections on the scale of the galvanometer in a more marked degree than the actual clouds had done. My assistant intercepting the light while passing the end of the box to adjust the cloud was also noticed to affect the deflections. Thus the shadow of a man, although not visible to the naked eye, was found to interfere with the mechanical laws which govern the motion of ordinary matter. The results of the tests are given in Table 5.

No 5.

Mark.	Megohms.	Megohms.
A . . .	314·7	53·92
B . . .	5·58	3·918
C . . .	227·5	44·03
D . . .	44·85	16·13

Mark.	Megohms.	Megohms.
E	554·8	76·79
F	284·8	50·52
G	648·5	77·41
H	24·93	10·66
I	34·05	15·48
K	53·32	23·13
L	738·3	141·2
M	53·92	15·53
N	41·19	13·09
O	154·8	49·48
P	24·24	12·8
Q	·13258	·09794
R	·003157	·003157
A	314·7	59·25

During the time occupied by the test while light was excluded, the temperature imperceptibly decreased from 44·5° to 43·8°. The resistance of bar A remained the same throughout the test. During the time occupied by the test in which the light was admitted, the temperature fell from 43·7° to 43·2°, so that during the whole time occupied by the tests, which was ninety-five minutes, the temperature only varied 1·3°. The apparent dull solar light had a much greater effect on the resistance of the bars than the apparent bright artificial light from coal gas.

The above test was repeated at noon on a hot midsummer day, with a clear atmosphere and the rays of the sun falling direct on to the box. While light was excluded, the temperature remained at 108° Fahr., and the resistance of the bar marked A remained constant throughout the test, which occupied twenty minutes. During the test with the light admitted, the temperature increased from 112·5° to 121°, and the resistance of the bar A decreased. The intercepting of the light by the artificial cloud during this test had an immediate and powerful effect on the resistance of each bar. The results of this test are given in Table 6.

No. 6.

Mark.	Megohms.	Megohms.
A	369·1	54·41
B	4·928	3·046
C	283·5	49·8
D	49·8	25·93
E	611·2	82·57
F	319·1	51·44
G	619·3	64·03
H	50·33	14·07
I	32·57	14·62
K	47·54	20·07
L	687·1	116·2
M	103·4	19·82
N	67·72	15·11
O	108·2	32·35
P	8·33	4·318
Q	·1675	·1229
R	·003374	·003303
A	369·1	51·44

This test was repeated under precisely the same conditions between eleven and twelve on a dark night, and the resistance of each bar remained constant; the removal of the lid of the box making no perceptible difference. But when the dim light from an ordinary dirty street lamp, at an angle of 26°, and a distance of twenty-one feet, fell on the bars, the resistance gradually decreased as shown in Table 7.

No. 7.

Mark.	Megohms.	Megohms.
A	537·7	505·2
B	6·965	6·81

Mark.	Megohms.	Megohms.
C	387·9	357·7
D	64·29	56·75
E	999·3	892·6
F	478·9	433·7
G	1209·8	1069·1
H	42·17	38·47
I	41·79	39·97
K	63·41	63·85
L	1121·2	1044·8
M	96·78	85·13
N	69·65	60·89
O	192·3	181·7
P	23·1	23·1
Q	·18763	·16418
R	Unsteady	Unsteady
A	537·7	483·9

During the test while the light was excluded, the temperature remained constant at 57° Fahr., but while the light was admitted, the temperature gradually fell from 56·3° to 55°. While under the influence of the light, the resistance of the bar A very gradually fell from 505·2 to 483·9 megohms. The resistance of each bar was higher in this test than it had been before, but from what cause could not be ascertained.

The above test was repeated about the same time one night, when the dim light from the waning moon appeared to equal in density that given by the dirty street lamp in the previous experiment. The result was as given in Table 8.

No. 8.

Mark.	Megohms.	Megohms.
A	427·3	410·3
B	6·061	5·869
C	316·5	301·1
D	53·29	50·95

Mark.	Megohms.	Megohms.
E	753·9	718·8
F	383·2	369·4
G	843·0	827·9
H	35·8	33·47
I	38·64	37·85
K	59·83	58·32
L	697·2	692·0
M	80·63	75·39
N	57·24	53·6
O	168·6	159·9
P	18·89	18·62
Q	·16383	·14007
R	·003324	·003312
A	425·4	399·7

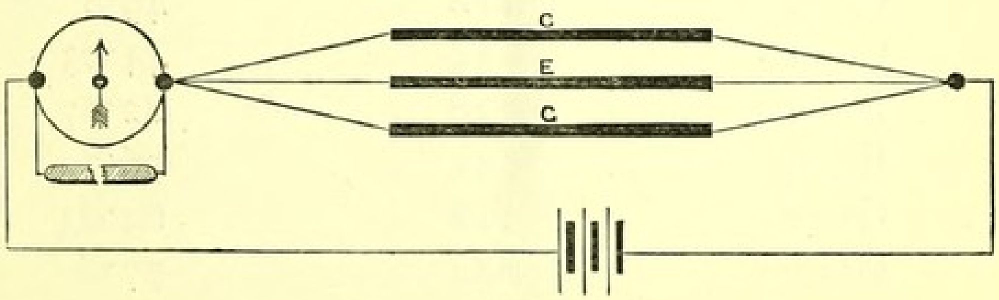
During the test while the light was excluded, the temperature gradually fell from 63° to 60° Fahr., and the resistance of bar A fell 2 megohms. During the test while the light was admitted, the temperature fell from 59° to 57°, and the resistance of the same bar fell 11 megohms.

The following experiment was then made, which clearly shows that the resistance decreases gradually while the bar is under the influence of a dull light, and increases as gradually to its normal condition when the light is excluded. The bar marked A was the one used in this experiment. The light was admitted for seven and a half minutes, and the deflection at the end of each half minute recorded. Then the light was suddenly excluded, without in any way interfering with the test, which was continued until the resistance had returned to its normal condition, which, as shown by the figures in Table 9, occupied seven and a half minutes, being the same time as it was under the influence of the light.

No. 9.

Minutes.	Deflections.	Minutes.	Deflections.
·5	272	8·	279
1·	273	8·5	278·5
1·5	274	9·	278
2·	274	9·5	277·5
2·5	275	10·	277
3·	275·5	10·5	276
3·5	276	11·	275
4·	276·5	11·5	275
4·5	277	12·	274
5·	277·5	12·5	274
5·5	278	13·	273
6·	278·5	13·5	273
6·5	279	14·	272·5
7·	279·5	14·5	272·5
7·5	280	15·	272

With a view of ascertaining to what extent the resistance of the bars would be affected by the eclipse of the moon on the 23rd August last, three of the bars, marked respectively C, E, and G, were joined in parallel circuit, and included in the circuit of fifty Menotti cells and an astatic mirror-reflecting galvanometer. The box containing the bars was placed on the roof of a high building, so that the moon's rays fell direct upon it during the whole time of observation. The connections were as given in diagram marked 10, and, with the exception of short-circuiting the galvanometer to check its zero, were not altered during the test.



Minute readings were noted. At 8·15 p.m., when not under the influence of light, the deflection was 171 divisions, and the temperature 68° Fahr. At 8·16, after one minute's exposure to the moon's rays, the deflection had increased to 179 divisions. From 8·16 to 9·15 the deflections were alternately rising and falling, owing to the varying power of the light caused by clouds of varying density passing quickly between the moon and the bars. But at 9·15 the deflection was 190 divisions. From 9·15 to 10·17, about two minutes before totality, the deflections gradually decreased to 185 divisions, and the temperature to 50°. From 10·17 to 11·24 the beam of light remained apparently firmly fixed on the scale at 185 divisions, and the temperature had fallen to 49°. At 11·24 the deflections began to gradually increase, and continued to do so until the end of the observations, which was at 2·15 a.m. on the 24th, when the deflection was 235 divisions and the temperature 43° Fahr.

If the previous tests of each of the three bars used in this experiment be referred to, it will be seen that when exposed to solar light at temperatures of 118° and 44° Fahr. respectively, the resistance of C and E decreased with a decrease of temperature, following the law of a metal (as copper), but the resistance of G increased with a decrease of temperature, following the law of a dielectric (as gutta-percha). Table 11 gives the actual figures.

No. 11.

Mark.	Temperature.	Resistance in megohms.
C	118	49·8
C	44	44·03
E	118	82·57
E	44	76·79
G	118	64·03
G	44	77·

While under the influence of artificial light, ordinary coal gas, they behaved as a metal, as shown in Table 12.

No. 12.

Mark.	Temperature.	Resistance in megohms.
C	100	152·8
C	44	110·7
E	100	287·4
E	44	213·5
G	100	237·7
G	44	194·5

When excluded from light and the temperature obtained from solar heat, C and E behaved as a metal, but G again followed the law of a dielectric, as shown in Table 13.

No. 13.

Mark.	Temperature.	Resistance in megohms.
C	118	283·5
C	44	227·5
E	118	611·2
E	44	554·8
G	118	619·3
G	44	648·5

But when excluded from light and the temperature maintained by artificial heat, ordinary coal gas, they each behaved as a dielectric, as shown in Table 14.

No. 14.

Mark.	Temperature.	Resistance in megohms.
C	100	283·1
C	44	291·7
E	100	633·3
E	44	758·1
G	100	654·9
G	44	962·7

If the correction for temperature were applied to each bar, the results obtained during the eclipse would be more marked than they are. In the experiment during the eclipse the deflections obtained are given. The resistance corresponding to the deflection is as given in Table 15.

No. 15.

Deflections.	Resistance in megohms.
171	265·3
179	253·5
190	238·8
235	193·1

So that the action of reflected solar light reduced the resistance about 26 per cent. When the shadow had quite passed from view at 1·10 a.m. the deflection was 207, and went on increasing to 235. As the light at 1·10 appeared to be as bright as at 2·15, the impression is confirmed that while under the influence of light time affects the results.

I think there can be no doubt but that the action of light alters the electrical properties of crystalline Selenium, but not permanently, for when the light is withdrawn the Selenium slowly returns to its normal resistance. Solar light has a much greater effect than artificial light. The action of the light appears to be analogous to the polarisation of a dielectric (gutta-percha) while under the influence of an electric charge; as with gutta-percha, so with Selenium, after the removal of the cause of polarisation it gradually de-polarises and returns to its normal condition. I have no doubt but that properly prepared Selenium, while under the influence of an electric current, would be what is much needed, a very sensitive photometer, by which light alone would produce mechanical motion so as to mark upon a scale a direct reading of its intensity. By way of experiment I constructed one as follows: In a closed wooden box twenty-two and a quarter inches long, six and three-quarter inches wide, and ten and three-quarter inches deep, blackened within, were placed, in grooves cut in each side of the box, thirty ground glass slides, six and a quarter by five inches. Unfortunately they were not so uniform in thickness as I could have wished. The distance between each slide was half an inch. On the inside of one end of the box were placed in parallel circuit the three Selenium bars marked respectively G, E, and D, the connections of which were attached to two terminals fixed in vulcanite, one on each side of the box. Between the glass slides and the bars was a wooden slide, which, when its lower edge rested on the bottom of the box, excluded all light from the bars. In the other end of the box was an aperture to admit the rays from the light under experiment. The slides were so arranged that they could intercept the light or be lifted from its path. After the current from one hundred cells had flown through the bars and the galvanometer in metallic circuit for one minute, and before the light was admitted, the deflection on the scale of the galvanometer was noted. A gas flame from an ordinary burner, adjusted, as far as the eye could judge, to half its illuminating power, was placed opposite the aperture at the end of the box. The glass slides were so adjusted that the rays from the gas would have to pass through nine of them before they could affect the bars. At the end of the minute, the light was admitted by lifting the wooden slide in front of the bars, and after the bars had been under the influence of the light for one minute the deflection was again taken. The light was then excluded by dropping the wooden slide, and when the deflection had returned to within a few divisions of the first reading the experiment was repeated with the gas flame, as far as the eye could judge, at double its previous illuminating power. The results were as follows:

With the light excluded	.	322 divisions.
With the *half* light	. .	340 ,,
With the light excluded	.	326 ,,
With the *full* light	. .	358 ,,

So that in the first experiment the power of the light was 18, and in the second 32.

The experiment was repeated, and nearly the same results obtained, as will be seen by the following figures:—

Dark	. .	329 divisions.
Half light	.	347 ,,
Dark	. .	329 ,,
Full light	.	360 ,,

Or as 18 to 31.

And here I will leave the question of the effect of light, and pass to what no doubt will more directly concern the members of this Society,—the introduction of Selenium, such as would be constant in its resistance, and in every way suitable for use where even great accuracy of measurement is required. Hitherto the use of Selenium has been very limited, owing to its want of uniformity in electrical resistance, not only in different samples, but in the same sample. The time of annealing, or "crystallizing," as it is termed, and the temperature at which it is annealed, have a great effect on the degree of resistance; that is to say, if a high resistance is required, the annealing must be for a much less time, and the temperature lower, than if a low resistance is required. But if too long a time is allowed, or the temperature carried too high, the resistance becomes too low, and far from reliable; and if too short a time, the resistance is very high, and again not reliable. But by careful attention to both time and temperature, the amount of which will depend on the proportions of the Selenium to be annealed, there is no difficulty in producing it, so that when it has settled to the normal temperature its resistance will remain constant. The results of my experiments with the samples which I have prepared myself, have more than surpassed my expectations. Properly prepared Selenium follows the law of a dielectric (gutta-percha) as to temperature. I have made a series of special experiments, and from the results have compiled Table 16, in which is given the relative resistance for each degree from 100° to 40° Fahr., assuming the resistance at 100=1.

No. 16.

Temp.	Resistance.	Temp.	Resistance.
100	1·000	81	1·565
99	1·024	80	1·602
98	1·042	79	1·641
97	1·073	78	1·680
96	1·099	77	1·720
95	1·125	76	1·761
94	1·152	75	1·803
93	1·179	74	1·846
92	1·208	73	1·890
91	1·236	72	1·935
90	1·266	71	1·981
89	1·296	70	2·028
88	1·327	69	2·077
87	1·359	68	2·126
86	1.391	67	2·177
85	1·424	66	2·229
84	1·458	65	2·282
83	1·493	64	2·337
82	1·529	63	2·392

Temp.	Resistance.	Temp.	Resistance.
62	2·449	50	3·250
61	2·508	49	3·328
60	2·567	48	3·407
59	2·629	47	3·489
58	2·692	46	3·572
57	2·756	45	3·675
56	2·822	44	3·744
55	2·889	43	3·834
54	2·958	42	3·925
53	3·028	41	4·019
52	3·101	40	4·115
51	3·175		

I have tested the resistance of properly prepared Selenium with various battery powers, commencing with one hundred cells, and increasing the same number each test up to one thousand cells. The current was reversed in each test, and remained on for ten minutes, the resistance being taken at the end of each minute. In each case it remained very constant throughout, and did not show signs of being affected in temperature by the high power as an ordinary resistance coil would have been, especially if of the same resistance. In using high resistances, especially with high powers, more than ordinary care must be taken to guard against surface conduction. Having obtained the desired resistance, care must be taken that it be kept well protected from the effects of light, or it will not remain constant. Hitherto experiments in which high resistances were required have almost been out of the question, owing to the great expense of resistance coils. This will be readily understood when I mention that the cost of *one* megohm, constructed of platinum-silver wire, is about £80. Now, I have reason to believe that resistances equally as reliable can be supplied in selenium, from one to five hundred megohms, for about thirty shillings each. I have instructed Messrs. Elliott Brothers how to prepare them, and I believe they are willing to supply them at something like that price. The full importance of these cheap high resistances will be more fully realised when we have a good system of underground wires; for I have reason to believe, from the results of experiments I have made, that by a judicious arrangement of high resistances at various junctions in a long subterranean line the speed would be much increased. This, however, is a subject rather foreign to my present paper, but one which I may at some future time ask permission to bring before the Society.

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