CHARACTERISTICS OF CRYSTAL RECTIFICATION.

By Alan E. Flowers.

IN an article published in the Physical Review[1] some of the peculiarities of the uni-directional resistance between a conducting point and a rectifying crystal surface were described. Most of the measurements were made with direct current and the resistance showed a well-defined tendency to increase with time of current flow in the highly resisting direction and to decrease with time of current flow for the direction of easy current flow. Frequently, upon sudden reversal of current direction the initial resistance corresponded more nearly to the value just previous to reversal than to the final value for this direction of current. In most of the crystals examined some spots rectified well, and nearby portions of the surface rectified but little, if at all, or even gave rectification in the reverse direction. It was also found possible to produce rectifying spots, on the surface of non-rectifying galena crystals by treating the surfaces with hot sulfur.

In view of these peculiarities it seemed desirable to subject crystals to very low and very high frequencies to see if time or energy were required to build up a resisting film upon change of current to the direction giving the higher resistance. Also it seemed desirable to determine the magnitude of the rectification at the high frequencies used in wireless telegraphy.

Two series of tests were carried out. One at Cornell University in December, 1910, was made possible by a grant from the Telluride Association, and another was carried out in the protective apparatus laboratory of the General Electric Company through the courtesy of Mr. E. E. F. Creighton, during the summer of 1912.

In the tests at Cornell University five different sources of supply were used. One of these was the 60-cycle lighting circuit. This was made the standard of comparison in every case. A double pole double throw switch was arranged so that the rectifier could be connected immediately either to this 60-cycle circuit or to the high frequency supply. The usual procedure was to measure the rectification on the 60-cycle circuit, then on a high frequency circuit, and again on the 60-cycle circuit as a check.

[1] 1909, Vol. XXIX., p. 445.

It is worth noting that the readings taken on the 60-cycle circuit in this way check with each other very well indeed, indicating a much greater constancy of rectification on alternating current than was to be expected from the variable values found when measuring the resistance with direct current. This method of checking both before and after the readings on high frequency eliminated chance effects such as, jarring, change of contact pressure, change of contact spot, etc. The contact point in these tests was a blunt ended piece of No. 13 B. & S. copper wire and the pressure on the point was about 250 grams. These values were such that considerable variations of either contact area or contact pressure would affect the rectification but slightly, if at all.

The effective value of the current was measured by means of a thermo-couple consisting of crossed wires of copper and constantan approximately 0.002 cm. in diameter. The current to be measured upon being passed through the copper-constantan crossover raised its temperature sufficiently to produce a thermal E.M.F. and a uni-directional current through a d'Arsonval galvanometer connected to the two ends of the crossed wires at right angles to the current path. A precaution to be observed in the use of this crossed-wire thermo-couple is to see that the crossed wires are well soldered together, otherwise the resistance of the contact causes current to flow directly through the galvanometer when calibrated with direct current or when being used for a partly rectified current. The deflections are then affected by the direction of the current through the couple and one may get a calibration curve that is nearer a straight line than a parabola. In taking measurements with this thermo-couple reversed readings were taken on the galvanometer to eliminate any slight error from this cause.

The average current was measured with a Weston permanent-magnet-type direct current mil-ammeter which gave full scale deflection for 20 milliamperes. For currents of 20 to 50 milliamperes this meter was shunted by non-inductive resistances.

Some of the results of these tests are presented in Table I.

A supply of approximately 2,000 cycles was obtained from an inductor alternator built by the Peerless Electric Company and belonging to the physics department. The wave shape given by this alternator is not known but is fairly smooth. The test results given in Table I. show a rectification ratio on 2,030 cycles very slightly poorer than on 60 cycles. The average difference from a number of such tests amounted to only 1 per cent. and could easily be attributed to wave shape. At the suggestion of Professor Frederick Bedell the effect of widely different wave shapes was tried making use of a complex wave consisting principally of

20-cycle and 60-cycle components which could be combined in different relative phase positions by varying the position of an induction motor rotor used as a transformer. The effective value being kept the same, the wave with the higher form factor should give the poorer rectification. This conclusion was confirmed by Tests Nos. 9 to 17 in Table I. The form factor for the wave given by rotor in position −20 was 1.154, while for the rotor in position 170 the form factor was 1.204. These values were calculated from the equations to the curve. I am indebted to Mr. Anderson, at that time a graduate student in Cornell University, for the use of this variable wave shape apparatus and for the equations to the curve. The difference in rectification was even greater than was to have been expected from the form factors. The effect of wave shape was even more marked on the poor rectifying spots where reverse rectification occurred.

In making the tests with very high frequencies use was made of a 500-volt direct current quenched spark oscillator. The arc played between electrodes lying in a powerful magnetic field and surrounded by

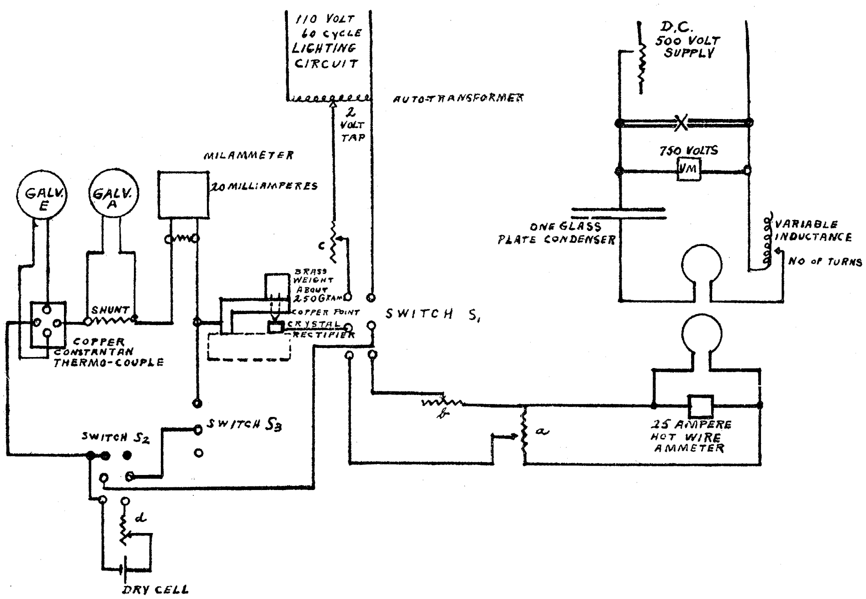

Fig. 1.

Diagram of Connections for Oscillatory Tests at Very High Frequencies.

an atmosphere of illuminating gas. This apparatus had been set up by Mr. F. H. Kroger, then of the electrical engineering department of Cornell University, who very kindly allowed its use for the purpose of carrying out these experiments. A diagram of the connections is shown in Fig. 1.

The arc was somewhat unsteady, consequently a number of readings were averaged in obtaining the results tabulated.

In every case the rectification was found to be better on the oscillating circuit than on the 60-cycle circuit. In several cases this effect was quite pronounced particularly when inductance was placed in series with the supply to the rectifier. The intermediate frequency of approximately 268,000 gave in all cases the best rectification. Tests 21 and 22 show that no disturbing effects were produced by the mere presence of the oscillating arc when the rectifier switch was closed on the 60-cycle circuit. The measuring circuit was inductively linked with the oscillating circuit and well insulated from it but it is possible that in some way leakage may have occurred, and caused part of the D.C. meter deflections. None of the attemps to detect such leakages resulted in discovering anything which caused a decrease in the readings of the meter which indicated effective values or an increase in the readings of the D.C. meter used to get the average or rectified current values.

The results of these tests indicate increased rather than decreased rectification for high frequency oscillating currents. It must be borne in mind, however, that these currents consist of more or less damped wave trains and that rectification varies with the magnitude of the current and the potential difference as will be shown later.

In the tests caried out in the protective apparatus laboratory of the General Electric Company a 60-cycle lighting circuit was again used as a standard to see that no permanent alteration had occurred in the crystal or contact. The high frequency supply was obtained from inductor type alternators giving frequencies up to 100,000 cycles per second for one machine and up to 200,000 cycles per second for the other machine. Some tests were also made using a spark discharge oscillating circuit inductively linked with the measuring circuit.

Effect of Contact Pressure.

It was deemed wise to try the effects of considerable variation in contact pressure to settle definitely the question as to the possibility of variations caused by pressure changes being included in the other effects studied.

Variations of contact pressure on a blunt No. 13 B. & S. copper wire contact between 40 and 550 grams caused very small variations in the ratio of average to effective value of the current when using the 60-cycle supply. The rectification ratio, as just defined, varied between 57.3 and 59.6 per cent., and not more than half of this difference can be definitely ascribed to change of pressure. Another test made later at 100,000 cycles per second showed that the effects of very considerable changes of pressure on the contact-point was negligible when the rectified current was as large as 20 milliamperes. Some observations with very small contact areas and very light pressures will be described later on.

Effect of Room Temperature.

The effect of temperature through a very wide range was described in the article already referred to (published in the Physical Review, November, 1909). The results showed a decrease of rectification with increased temperature; the rectification becoming unstable or disappearing at temperatures between 200 and 300 degrees centigrade. The change for room temperature variations was small and this was checked by a test made during the course of these experiments which showed a decrease from 58.9 per cent. to 57.9 per cent. when the temperature was raised approximately 10 degrees centigrade above the initial room temperature of 22 degrees. This difference is small enough to be negligible in comparison with the effects obtained in the course of this work.

Effect of Frequency.

The small effect of change of frequency is illustrated by the curves in Fig. 2. It is to be noted that a small but measurable increase in recti-

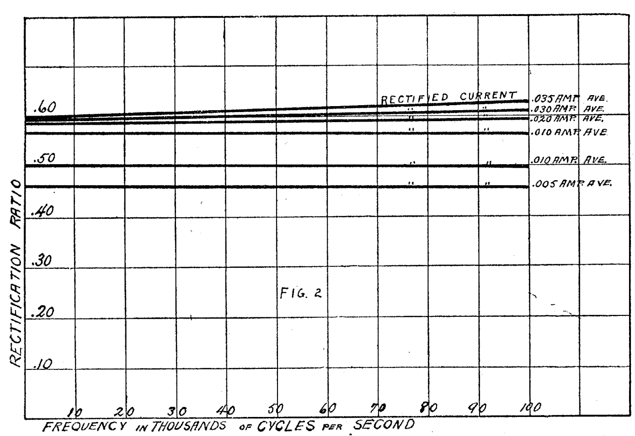

Fig. 2.

Effect of Frequency on Rectification Ratio for Various Rectified Currents.

fication occurred at the frequency of 100,000 cycles for the larger values of rectified current, but that for the smaller currents the rectification decreased slightly. Changes of wave shape may have had some effect, but such effect could not have been large for the alternator was run at low and high speeds for the readings, the current kept constant and hence the reaction of the current on the field must have been almost exactly constant.

Another thing to be noted about the curves is that they show in general a better rectification for the larger currents. The rectification tended to increase with increase of current at 60 cycles per second and a similar effect was found at 100,000 cycles.

Some tests were made with a high frequency supply from an oscillating circuit. The oscillating circuit was excited by a Tesla coil, a sphere spark gap and a high voltage condenser. The oscillating circuit had a frequency of about 120,000 cycles per second as measured with a cymometer and was inductively linked with the rectifier and meters by a single turn air core coil.

The galena crystal which had been giving a rectification ratio of about 60 per cent. on the 60-cycle lighting supply or on the 100,000 cycle alternator gave only 3 per cent. to 5 per cent. rectification on the oscillating circuit. When reconnected later to the 60-cycle supply gave only 35 per cent. to 40 per cent. rectification. These results lead one to think that the high peak in the first wave of the oscillating wave train may have been sufficient to partially break down the rectifying film.

Effect of Current and Current Density.

The noticeable decrease in rectification for small currents led to the attempt to measure the rectification ratio for exceedingly small currents. For these measurements the 60-cycle lighting circuit supply was employed and the value of the alternating curent measured by means of a separately excited dynamometer. The exciting current for the dynamometer was kept constant at 5 amperes and its phase adjusted by means of a phase shifting transformer to give the maximum deflection of the dynamometer. Trial showed that the position of the phase shifter for maximum deflection on the dynamometer was the same for either small or large currents. An instrument of this type really measures the average value of the current without regard to the direction of current flow; consequently the limit of the rectification ratio, as employed here, would be 100 per cent. for complete rectification of a sine wave, while the limit for a sine wave whose effective value was measured would be 91 per cent. This drawback would not greatly affect different readings all taken on the same dynamometer and under the same conditions.

The curve given in Fig. 3 shows that for currents of the order of 1 to 2 microamperes of rectified current the rectification ratio is less than 10 per cent. The same conditions (No. 13 B. & S. blunt copper wire point and 276 grams contact pressure) gave rectification ratios of over 80 per cent. for rectified currents of 500 microamperes. This is shown in

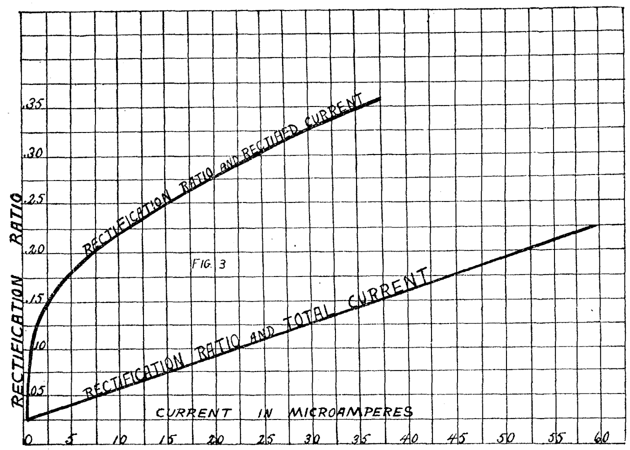

Fig. 3.

Relation of Rectification Ratio and Current at 60 Cycles for Very Small Currents. No. 13 blunt copper wire contact. 276 grams contact pressure. Total current measured with separately excited dynamometer.

Fig. 4 where the results for the whole range of currents are shown in one curve. The rectification ratios in the tests shown in Figs. 3 and 4

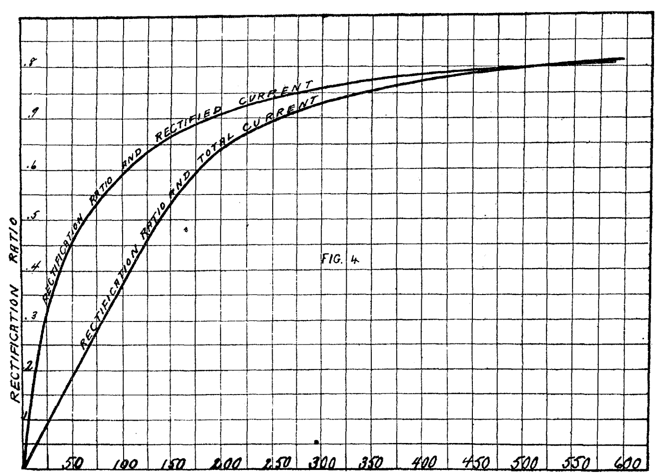

Fig. 4.

Relation of Rectification Ratio and Current at 60 Cycles. No. 13 blunt copper wire contact, 276 grams contact pressure. Total current measured with separately excited dynamometer.

vary as the *square* of the rectified current and as the *first power* of the whole current throughout a considerable range.

Effect of Contact Pressure on Rectifaction of Very Small Currents.

The preceding test which showed that the rectification ratio was very low for small currents suggested that the current density must be a large factor, consequently other tests were made with normal and reduced pressures on the No. 13 B. & S. blunt copper wire point. The tests already described using larger currents had shown but little influence of pressure between 38 and 276 grams. For small currents, however, it was found in this test that quite considerable differences in rectification existed for small rectified currents. The lighter pressure on the point gave an appreciably better rectification, as is shown in Fig. 5.

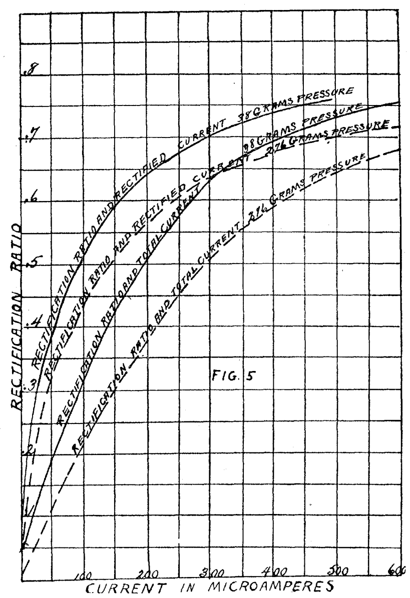

Fig. 5.

Effect of Contact Pressure and Current on Rectification Ratio for Small Currents. 60-cycle supply No. 13 B. & S. blunt copper wire contact. Total current measured with separately excited dynamometer.

Effect of Size of Contact Point.

In order to still further investigate the question of current density tests were made with very fine wires giving small contact areas and with a contact made by a drop of mercury about 3 mm. in diameter. The contact area must bear some relation to the cross section of the wires except possibly in the case of the No. 13 copper wire which was too large to touch over its whole surface area.

The results tend in general to show that, for very small currents at least, the reduction in size of contact points improves the rectification ratio very markedly. It was noted, however, that much larger voltages had to be employed to get the same current.

Fig. 6 shows the results for a 7 mil (0.0178 cm.) copper wire. The

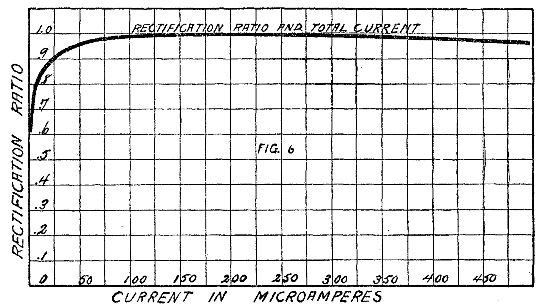

Fig. 6.

Relation of Rectification Ratio and Current at 60 Cycles for a Small Copper Wire Point, .0178 cm. in Diameter. Total current measured with a separately excited dynamometer.

section area of this wire was 2.49×10^{-4} cm., and the curve shows the fairly large rectification ratio of 63 per cent. for very minute rectified currents, *i. e.*, values of 2 to 3 microamperes. For larger rectified currents the rectification ratio was even higher. Even for 0.7 of a microampere this small copper wire gave a rectification ratio of 35 per cent. For currents over 50 microamperes the readings taken gave rectification ratios that indicated practically complete rectification.

A still smaller silver wire 0.0025 cm. in diameter, section area 4.9×10^{-6} sq. cm. while requiring a still higher voltage to give readable currents gave rectification ratios of the very small currents not quite so good as in the preceding test. Another peculiar action which occurred with this extremely small silver wire point was *reverse* rectification on the first application of voltage followed by a sudden decrease in the value of the current, then a change of direction of rectified current to the direction usually found accompanied by very good rectification. On decreasing the supply voltage and thus reducing the current there was a decided tendency for reversal of rectification to proceed of itself as soon as the total current lowered to a value less than 75 to 100 microamperes. Reversed rectification ratios of 35.5 per cent. or more were obtained in this way. In one case 65 per cent. reversed rectification ratio was obtained with 7 microamperes total current. This was obtained, however, by using the smallest obtainable value for the supply voltage.

The current was not stable when using this 0.0025 cm. silver wire and when the results were plotted as in Fig. 7 the curve brings out only the marked tendency to drift towards reverse rectification for low voltages and small total currents.

A check test with a 0.005 cm. copper wire gave results similar to those of the 0.0178 copper wire already described and no reversal of rectification such as was observed with the 0.0025 cm. silver wire.

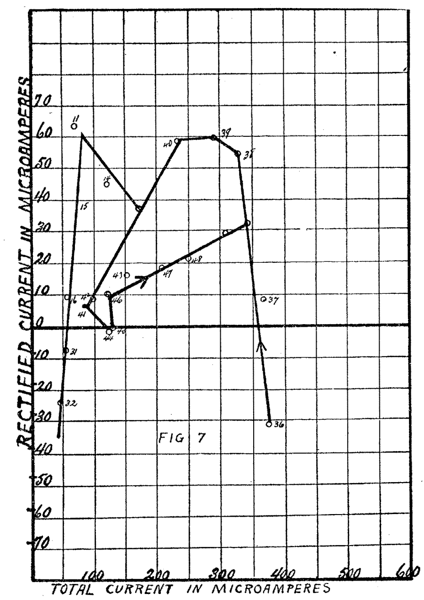

Fig. 7.

Rectification with an Extremely Small Silver Wire Point, .0025 cm. in Diameter. 60-cycle supply. Total current measured with a separately excited dynamometer.

A check test with the large blunt copper point made of No. 13 B. & S. wire gave again results similar to those obtained in the earlier tests under the same conditions. The effect of very large size contact areas giving a very low current density was investigated by the use of a drop of mercury about 3 mm. in diameter, having thus a contact area of 0.07 sq. cm. The results are plotted in Fig. 8.

The highest rectification ratio obtainable with this large contact area was about 10 per cent. and even this required a total current of 60 milliamperes. For currents between 150 and 2,500 microamperes the rectification ratio was less than .1 of 1 per cent. For total currents less than 150 microamperes it was found that the crystal alone gave a direct E.M.F. that affected the galvanometer, giving from 12 to 14 mm.

deflection corresponding to a direct current of 0.12 to 0.14 microampere, so that the apparent rectification ratios rose again to something over 1 per cent. for total currents less than 15 microamperes.

This test gave also an opportunity to compare the readings of the dynamometer with those obtained by the thermo-couple. When in series the current as calculated was 0.00298 ampere for the heated thermo-couple and 0.002455 from the dynamometer reading. The values as

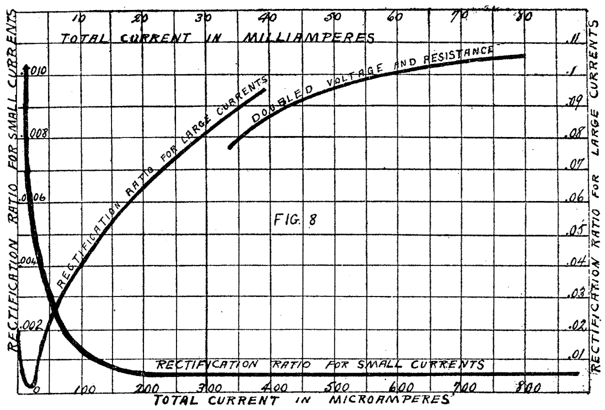

Fig. 8.

Effect of Current on Rectification for Very Large Contact Area. 3 mm. mercury drop contact. Total current measured with a separately excited dynamometer.

read on the dynamometer are therefore smaller than the effective value of the current, and, according to this one check, even somewhat smaller than the ratio of average to effective value of a sine wave. This would, however, tend to make the real rectification ratios *higher* for all the small currents where such low values were found. The validity of this conclusion in regard to the method of measuring the total current is further checked by the higher rectification ratios obtained for currents greater than half a milliampere.

Effect of Frequency and Low Current Density.

If high frequency currents were less well rectified than currents of low frequency such an effect should be most marked with the combination of large contact area, small current, and high frequency. It has already been shown that small currents of normal frequency are but imperfectly rectified when the contact area is large.

Fig. 9 shows the results of tests at different frequencies using the 60-cycle lighting circuit and the high frequency alternator, for several values of rectified current. The rectified current was kept constant and the frequency changed. The effective current was measured in this case with the crossed-wire thermo-couple. These results show, as before, small rectification ratios particularly for the small currents; but the effect of increasing the frequency to 100,000 cycles per second is negligible even for this large contact area and extremely small current density.

The rectification curve for the highest frequency obtainable from the 100,000 cycle alternator lies only a very little below that for the lowest frequency obtainable from the same machine. Both these curves show, however, higher rectification than on the 60-cycle circuit. As far as possible the circuit conditions were kept the same, particularly with regard to resistance, the voltage control being obtained by the use of step-up or

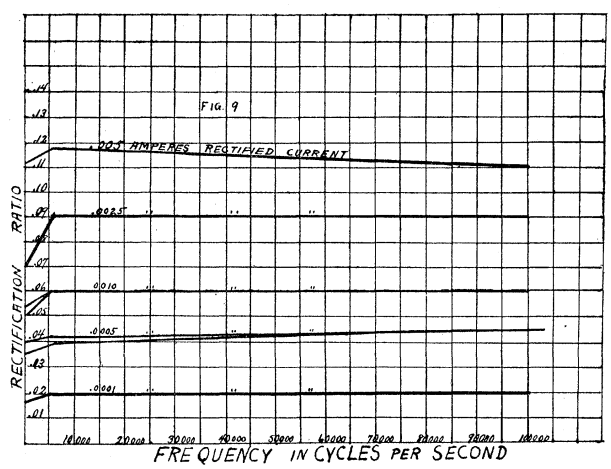

Fig. 9.

Effect of Frequency on Rectification for Small Current and Large Current Area. 3 mm. mercury drop contact.

step-down transformers, moderate changes of field current, and finally by shunt and series rheostats for fine adjustments.

It is also fairly evident from the trend of these curves that larger currents (involving higher voltage) would give very much better rectification. This was proven by later tests which showed rectification ratios of 30 per cent. to 40 per cent. for 2 to 2.5 volts on the crystal rectifier and 1/2 to 3/4 ampere total current. This result is stated here in order to show that the low rectification ratios found with the large contact areas (7 sq. mm.) are due to the low current density and not to accidently touching upon a non-rectifying spot. There is always considerable likelihood with the crystal rectifiers of getting on non-rectifying spots. This particular crystal had been found to have, about 18 months previous to these tests, on its top surface, *one part* which would give reversed rectification. The whole surface at the period of these tests gave rectification in the usual direction. This change is particularly interesting in view of the results obtained by R. H. Goddard and published in the Physical Review for Feb., 1912, Vol. 34, p. 149, showing the absence of rectification on surfaces freshly broken in a vacuum where they would be quite free from oxidizing influences.

Volt-Ampere Characteristics.

The rectification of small currents is better with small contact areas, but this improvement is obtained at the expense of higher applied voltages. In view of this fact further tests were made in which the applied voltage was kept constant. Hot wire voltmeters and ammeters were used in these tests to measure the effective values of voltage and current. The rectified current was measured by a permanent-magnet moving-coil-type meter.

The volt-ampere characteristic when using the blunt No. 13 B. & S. copper point on 60 cycles per second gave a nearly linear increase of rectified current with increase of voltage, but a more rapid increase of total current so that the rectification ratio decreased markedly as the voltage across the rectifier was raised from 1 to 3 volts.

The volt-ampere and rectification characteristics with the very large contact area of 7 sq. mm. obtained when using the mercury drop for a contact gave the fairly high rectification ratios of 30 to 45 per cent. when the total current reached values of .3 to .4 ampere. The better rectification occurred at the high frequency of 180,000 cycles. Possibly the skin effect at this frequency would give increased current density at the outer edges of the drop and so produce a better rectification.

The nominal current density for maximum rectification ratio of 35 to 45 per cent. varies between 5 and 6½ amperes per sq. cm. with this large contact of 7 sq. mm. irrespective of frequency.

A comparison of the tests at 60 cycles per second show nominal current densities for maximum rectification ratio as follows, the maximum rectification ratio corresponding in all case to nearly complete rectification.

Point.	Nominal Current Density for Maximum Rectification.
No. 13 B. & S. copper wire point	7 –
.0178 copper wire point	½ to 5
.005 copper wire point	6
.0025 silver wire point	16

The currents range from 50×10^{-6} amp. for the smallest wires to nearly half an ampere, a range of variation of 1 to 10,000 and the areas vary through a similar range, but even these approximate calculations give only a moderate change of optimum current density.

It is hoped that this work may be followed by other more precise measurements which will make it possible to settle upon definite quantitative values for optimum current density.

If the contact area be very large, the optimum current density may not be reached even when the voltage approaches the critical value, consequently the rectification ratio may be limited to low values.

Effect of Frequency on Rectification at Constant Voltage.

The first tests were made with a No. 13 B. & S. blunt copper wire point under 276 grams pressure resting on the same crystal that had been used in the preceding tests. The high frequency supply was taken from the inductor type alternator and the low frequency standard supply from the 60-cycle lighting circuit. Fig. 10 shows that for these conditions

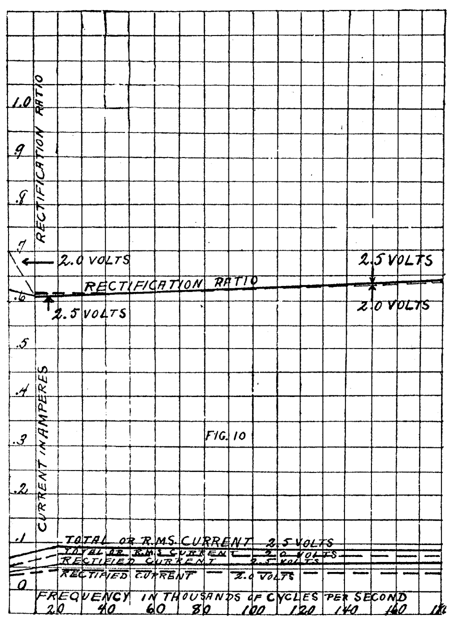

Fig. 10.

Effect of Frequency on Rectification at Constant Voltage. No. 13 blunt copper wire contact, 276 grams contact pressure.

the rectification ratio, the total current, and the rectified current, increaes slightly at the highest frequencies. The best rectification as given in Fig. 10 is 65 per cent. at 180,000 cycles per second.

The resistance of the hot-wire mil-ammeter was rather large (about

16 ohms) and the effect of this resistance in decreasing the rectification was quite marked.

The results at high and low frequency were very similar, as might be expected from the results already given in Fig. 2 but both rectified and total current were somethat greater than at 60 cycles. The difference was greatest at the higher voltages. At 2.5 volts the current values at 180,000 cycles were about 30 per cent. higher than at 60 cycles but the rectification ratio was very nearly the same; 61 per cent. at 60 cycles and 63 per cent. at 180,000 cycles. The numerical values for current and rectification ratio obtained with these hot wire meters should not be given too much weight, because the calibration corrections as given for these meters are rather large and the ammeter measured also, necessarily, the current required by the voltmeter for its deflection and this correction to the ammeter readings had to be applied in all these tests. The voltmeter

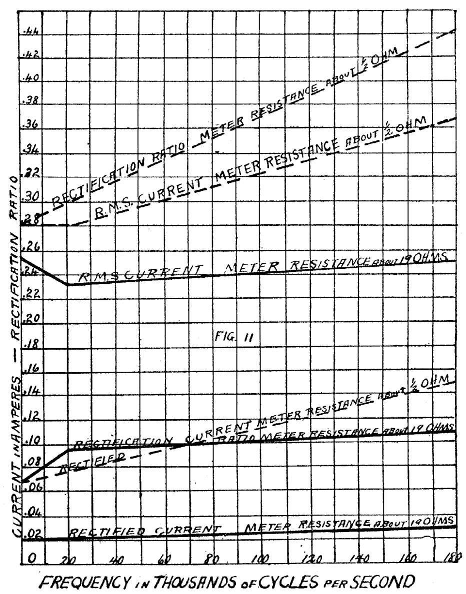

Fig. 11.

Effect of Frequency and Meter Resistance with Large Contact Area and 1.8 Volts on Rectifier. 3 mm. mercury drop contact. Meter resistance 19 ohms and ½ ohm.

was connected directly across the rectifier thus excluding meter drops. These drawbacks do not affect the value of the *comparisions* on low and high frequency.

In order to get the combined effect of low current density and high frequency other tests were made at constant voltage using the same crystal but with the contact consisting of a mercury drop about 3 mm.

in diameter resting on the top surface of the crystal. Part of the results in terms of current and rectification ratio are plotted in Fig. 11 (for 1.3 volts across rectifier) to show the effect of frequency at constant voltage.

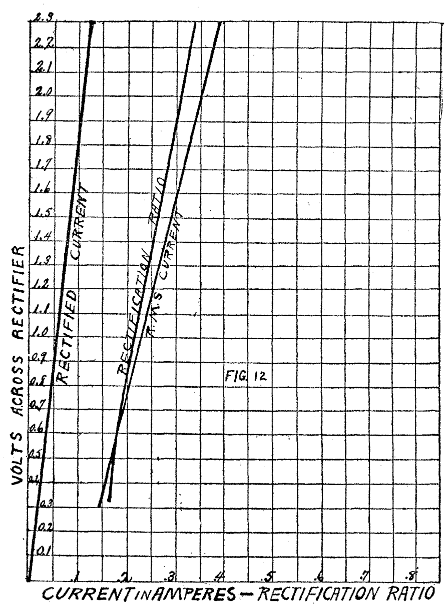

Fig. 12.

Low Frequency Volt-Ampere and Rectification Characteristic with Large Contact Area. 3 mm. mercury drop contact. 60-cycle supply. Meter resistance ½ ohm.

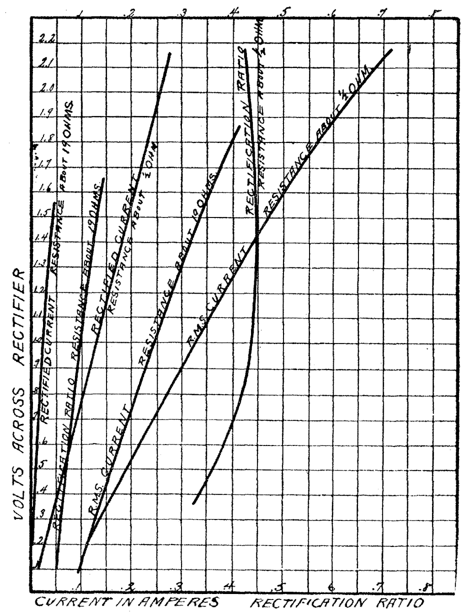

Fig. 13.

High Frequency Volt-Ampere and Rectification Characteristic with Large Contact Area, at 180,000 Cycles per Second. 3 mm. mercury drop contact.

The effect of reducing the circuit resistance by making use of low resistance meters is very marked, particularly on the rectification ratios. The shorting of two meters, one the hot-wire mil-ammeter (0.25 ampere full scale deflection) having 16 ohms resistance and the D.C. mil-ammeter (0.20 ampere full scale deflection) having 2.5 ohms resistance thus reduced the resistance of the circuit 18.5 ohms; that is, from about 19 ohms to about 0.5 ohm. This reduction in resistance made a moderate increase in the total current but a very great increase in the rectified current and consequently in the rectification ratio. Apparently the difference is not due to the elimination of the inductance of the D.C. meter the resistance of which was small (2.5 ohms), but is largely due to the elimination of the reistance of the small scale hot-wire mil-ammeter which had a resistance of 16 ohms as determined by test during the course of these experiments. This conclusion is based upon the values obtained

Table I.

Effect of Frequency and Wave Shape on Rectification.

	Date of Test.	Rectifier.	Frequency Cycles per Second.	Current. Effective Value Milli-amp.	Current. Average Value for Current Milli-amps.	Rectification Ratio.
1.	Dec. 21, 1910	M	60	8 to 38		.544
		P	60	21.9		.568
2.	Dec. 28, 1910	P	60	41.5	25.75	.619
		P_1	2,030	40.4	24.90	.616
3.	Dec. 29, 1910	P_1	60	34.35	19.6	.571
4.			2,020	34.35	19.47	.567
5.	Dec. 29, 1910	M	60	21.4	13.7	.640
6.			2,150	21.4	13.4	.626
	Set Contact on Area for Reversed Rectification.					
7.	Dec. 29, 1910	M_1	60	45.4	1.5	.0331
8.			2,150	43.1	.45	.0104
	Effect of Wave Shape.					
9.	Dec. 29, 1910	P_1	60	28.6	18.4	633 standard
10.			20+60	30.28	18.7	.618 flat-topped wave
11.			20+60	30.28	14.5	.479 peaked wave
	Effect of Wave Shape Using Spot Having Reversed Rectification.					
12.	Dec. 29, 1910	M	60	47.5	.8 Unsteady	.01685
13.			20+60	46.6	.4	.00858 flat-topped wave
14.			20+60	46.5	.25	.00538 peaked wave
	Effect of Wave Shape with Point Reset for Usual Direction of Rectification.					
15.	Dec. 29, 1910	M	60	28.35	18.55	.654 standard
16.			20+60	8.20	5.35	.652 flat-topped wave
17			20+60	9.73	5.00	.513 peaked wave
	High Frequency Supply from Quenched Spark Oscillating Circuit.					
21.	Dec. 30, 1910	M	60	59.4	35.23	.5935
22.			60	58.9	34.97	.5955
23.			268,000	36.95	28.18	.763
24.			60	56.	33.40	.597
24′.			60	36.9	21.60	.586
25.	Dec. 31, 1910	M	60	49.02	29.56	.603
26.			678,000	52.18	32.70	.626
27.			268,000	37.50	28.60	.7688
28.			60	50.81	30.66	.603
29.			60	30.62	18.48	.604
30.			268,000	25.52	18.70	.7326
31.			678,000	26.31	18.56	.7053
32.			678,000	32.56	20.42	.638
33.			678,000	54.13	32.55	.605
34.			60	29.95	18.24	.6088

TABLE I.—*Continued.*

High Frequency Supply from Quenched Spark Oscillating Circuit.

	Date of Test.	Rectifier.	Frequency Cycles per Second.	Current. Effective Value Milli-amp.	Current. Average Value for Current Milli-amps.	Rectification Ratio.
35.	Dec. 31, 1910.	M	268,000	25.02	18.45	.7375
36.			678,000	27.27	17.98	.661
	Air Core Induction Coil in Series with Supply to Rectifier.					
37.			60	29.79	18.17	.6103
38.	Dec. 31, 1910	M	268,000	17.68	17.44	.986
39.			678,000	14.09	9.46	.6744

when first one and then the other of these two meters was short-circuited. In this connection it should be stated that the hot-wire voltmeter was connected directly across the terminals of the rectifier so that none of these changes of ammeter resistance could affect the accuracy of the values taken for the potential difference across the rectifier. In all cases the A.C. ammeter readings have had subtracted from them the values corresponding to the current through the voltmeter. The values for these corrections to the ammeter readings were obtained by a separate experiment. The magnitude of these corrections is well brought out by the data recorded in Tables II. and III.

The results in Table II. and in Fig. 10 have been corrected for voltmeter current but the values *given* for the hot-wire A.C. ammeter calibration errors have not been used in calculating the results. In Table III. and in Figs. 11, 12, and 13 the effect of the voltmeter current and also the calibration errors of the ammeters have been allowed for. There is some doubt as to the values that should be used for the calibration corrections. The omission of the calibration corrections gives somewhat larger values for the effective current and lower values for the rectification ratio, particularly for the smaller currents.

SUMMARY AND CONCLUSIONS.

1. The rectification at high frequency tends to be greater than at low frequency with the larger currents, and but very little different for small currents.

2. For very small currents the rectification tends to disappear, particularly for large contact areas and low current densities.

TABLE II.

Volt-ampere. Rectification Characteristics at Low and High Frequency.

Galena Crystal M, No. 18 B. & S. with Blunt Copper Wire Point and a Contact Pressure of 276 Grams.

Rectified or Direct Current.		Total Current.		Voltage on Rectifier.	Voltmeter Current, Amp.	Net Current through Rectifier, Amp.	Rectification Ratio.
No. 3,815. .020 Sc., 2.5 Ohm, Amp.	No. 263, .5 Sc., .08 Ohm, Amp.	No. 5,535, 2 Scale, .26 Ohm, Rdg. Amp.	No. 47,201, .25 Sc., 16 Ohm, Rdg. Amp.	No. 47,203 5 Scale, Volts.			
60-cycle Lighting Circuit Supply, Meter 3815.							
.0073	.0075	?	.032	.5	.015	.017	.430
.0127	.013	.1 est.	.054	1.0	.031	.023	.550
.0205	.0205	.1 est.	.085	1.5	.0475	.0375	.547
Meter 263.							
Shorted	.024	.1 est.	.090	1.5	.0475	.0425	.565
	.035	.2 est.	.128	2.0	.0625	.0655	.534
	.045	.2	.161	2.5	.080	.0810	.555
	.036	?	.130	2.0	.0625	.0675	.533
	.025	?	.091	1.5	.0475	.0435	.575
	.0165	?	.062	1.0	.0310	.0310	.533
	.036		Shorted	1.0	.0310		
	.059			1.5	.0475		
	.085			2.0	.0625		
	.118	.28 est.		2.5	.080		
.0193	.019	?		.5	.016		
180,000-cycle Supply from Inductor Alternator.							
.0122	.012		.044	.5	.015	.029	.421
.0189	.018		.064	1.0	.031	.033	.572
Shorted	.019		.063	1.0	.031	.032	.594
	.024		.078	1.2	.0355	.0425	.565
	.031		.099	1.5	.0475	.0515	.602
	.041		.129	1.8	.056	.073	.562
	.046		.143	2.0	.0625	.0805	.572
	.052		.161	2.2	.069	.092	.565
	.057		.175	2.4	.076	.099	.576
	.060		.180	2.5	.080	.100	.60
	.053		.165	2.2	.068	.097	.547
	.047		.146	2.0	.0625	.0835	.573
	.033		.106	1.5	.0475	.0585	.564
	.021		.070	1.0	.031	.049	.428
20,000-cycle Supply from Inductor Alternator.							
.012	.012		.044	.6	.018	.026	.462
.0163	.016		.060	1.0	.031	.029	.562
Shorted	.018		.067	1.0	.031	.036	.500
	.028		.099	1.5	.0475	.0515	.544
	.036		.125	1.8	.056	.069	.522
	.043		.144	2.0	.0625	.0815	.527
	.050		.165	2.3	.0725	.0925	.541
	.0545		.179	2.5	.080	.099	.55
	.043		.145	2.0	.0625	.0825	.521
	.030		.103	1.5	.0475	.0555	.540
	.020		.070	1.0	.031	.039	.645?

TABLE II.—*Continued.*

Check on 60-cycle Lighting Circuit.

Rectified or Direct Current.		Total Current.		Voltage on Rectifier.	Voltmeter Current, Amp.	Net Current through Rectifier, Amp.	Rectification Ratio.
No. 3,815, .020 Sc., 2.5 Ohm, Amp.	No. 263, .5 Sc., .08 Ohm, Amp.	No. 5,535, 2 Scale, .26 Ohm, Rdg. Amp.	No. 47,201, .25 Sc., 16 Ohm, Rdg. Amp.	No. 47,203, 5 Scale, Volts.			
10	.010		.040	.5	.015	.025	.40
15	.015		.056	1.0	.031	.025	.60
Shorted	.016		.060	1.0	.031	.029	.552
	.026		.093	1.5	.0475	.0455	.572
	.037		.132	2.0	.0625	.0695	.532
	.046		.165	2.5	.080	.085	.541
	.037		.135	2.0	.0625	.0705	.525
	.026		.095	1.5	.0475	.0475	.548
	.021		.063	1.0	.031	.032	.656
	.0105		.044	.5	.013	.031	.339
	.021		Shorted	.5	.013		
	.037			1.0	.031		
	.060			1.5	.0475		
	.093			2.0	.0625		
	.120			2.5	.080		
	.099			2.0	.0625		
	.041			1.0	.031		

3. The rectification ratio for small currents is nearly proportional to the square of the rectified current and nearly proportional to the first power of the total or R.M.S. current.

4. Even very large contact areas will rectify well with large currents.

5. The rectification *ratio* for very small currents may be improved by the use of very small contact points but a much larger potential is required to get the same amount of current.

6. The current density must be equal to or greater than a given minimum value for good rectification.

7. Resistance in series with the galena crystal rectifier greatly decreases the rectification ratio even for the same potential difference on the terminals of the rectifier.

OHIO STATE UNIVERSITY,
November, 1913.

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Table III.

Volt-ampere and Rectification Characteristic at Low and High Frequency.
Galena Crystal M. 60-cycle Supply. 3 mm. Mercury Contact.

Direct or Rectified Current.		Total Value or Effective Value of Current.				Potential on Rectifier, No. 47,203, 5 Scale, Volts.	Voltmeter Current, Amp.	Net Current through Rectifier.	Rectification Ratio.
No. 3,815 (Weston), .020 Scale, 2.3 Ohms, Amp.	No. 263 .5 Sc., .2 Ohm.	No. 5,535, 2 Scale, .26 Ohm.		No. 47,201, .25 Scale, 16 Ohm.					
	Amp. Rdg.	Amp. Rdg.	Amp. Value.	Amp. Rdg.	Amp. Value.				
1	2	3	4	5	6	7	8	9=4 or 6-8	10
.015	.015	.250	.22	.208	.223	1.0	.030	.220	.068
.0196	.020	.300	.27	.239	.260	1.3	.040	.199	.100
Shorted	.031	.220	.190	Shorted		.5	.015	.175	.177
this meter	.050	.280	.250	this meter		1.0	.030	.220	.227
	.080	.410	.360			1.5	.046	.314	.254
	.113	.510	.460			2.0	.062	.400	.283
	.135	.650	.610			2.5	.079	.530	.255
	.113	.450	.390			2.0	.062	.330	.347
	.080	.400	.340			1.5	.046	.294	.272
	.052	.320	.280			1.0	.030	.250	.208
20,000 Cycle. R = 19.16 Ohms.									
.0021	.002			.067	.055	.1	.003	.052	.0403
.0033	.003	?		.084	.075	.15	.007	.068	.0485
.0074	.0075	.1		.132	.129	.3	.009	.120	.0616
.00955	.0095	.1		.161	.163	.5	.015	.148	.0645
.01640	.0170	.23		.213	.228	1.0	.030	.198	.0828
.01780	.0180	.24	.21	.217	.234	1.1	.033	.201	.0886
.02000	.0200	.26	.23	.233	.259	1.2	.037	.222	.0901
R = 16.66. Voltage rose because D.C. meter was short-circuited.									
Shorted	.0250	.30	.27	.248	.283	1.38	.042	.241	.1037
	.0190	.26	.23	.228	.251	1.20	.037	.214	.0889
Shorted this meter, making the resistance of the meters .66 ohm. This reduction of resistance increased the meter readings until the supply was readjusted.									
	.127	.47	.41			1.73	.053	.36	.353
	.043	.22	.19			.5	.015	.175	.246
	.063	.29	.26			1.0	.030	.23	.274
	.079	.33	.29			1.2	.037	.25	.316
	.093	.40	.34			1.38	.042	.30	.310
	.098	.42	.37			1.50	.046	.32	.306
	.123	.48	.43			1.73	.053	.38	.324
	.113	.48	.43			1.90	.059	.37	.307
	Tapped lightly								
	.127	.49	.44			1.9	.059	.38	.334
	.130	.50	.45			1.73	.053	.40	.325

TABLE III.—*Continued.*

20,000 Cycle. R = 19.16 Ohms.

Direct or Rectified Current.		Total or Effective Value of Current.				Potential on Rectifier, No. 47,203, 5 Scale, Volts.	Voltmeter Current, Amp.	Net Current through Rectifier.	Rectification Ratio.
No. 3,815 (Weston), .020 Scale, 2.5 Ohms, Amp.	No. 263, .5 Sc., .2 Ohm.	No. 5,535, 2 Scale, .26 Ohm.		No. 47,201, .25 Scale, 16 Ohms.					
	Amp. Rdg.	Amp. Rdg.	Amp. Value.	Amp. Rdg.	Amp. Value.				
1	2	3	4	5	6	7	8	9=4 or 6–8	10
	.143	.55	.51			1.90	.059	.45	.318
	.151	.58	.53			2.0	.062	.47	.321
	.108	.45	.39			1.5	.046	.34	.318
	.069	.33	.29			1.0	.030	.26	.265
	.042	.23	.20			.5	.015	.18	.233
180,000 Cycles.									
.0058	.006			.117	.112	.2	.006	.106	.0557
.0116	.0115	.180	.15	.161	.163	.5	.015	.148	.0784
.0195	.0195	.25	.22	.223	.244	1.0	.030	.214	.0911
Shorted this	.0275	.30	.27	.250	.287	1.24	.038	.249	.1104
meter	.0150	.20	.17	.183	.189	.50	.015	.174	.0862
	.022	.27	.24	.223	.239	1.0	.030	.209	.1052
	.026	.28	.25	.244	.277	1.2	.037	.240	.1083
	.184	.50	.45	Shorted this meter		1.45	.045	.410	.445
	.081	.26	.23			.6	.018	.21	.385
	.125	.36	.31			1.0	.030	.28	.449
	.137	.40	.34			1.1	.033	.31	.442
	.149	.43	.38			1.2	.037	.34	.438
	.078	.25	.22			.6	.018	.20	.390
	.124	.37	.32			1.0	.030	.29	.428
	.135	.40	.34			1.1	.033	.31	.436
	.147	.43	.38			1.2	.037	.34	.432
	.178	.49	.44			1.4	.043	.40	.445
	.204	.55	.51			1.6	.049	.46	.443
	.234	.62	.57			1.8	.056	.514	.455
	.257	.69	.67			2.0	.062	.61	.422
	.275	.75	.72			2.2	.068	.65	.423
	.303	.87	.86			2.5	.079	.78	.389
	.258	.71	.67			2.0	.062	.61	.423
	.208	.59	.54			1.6	.049	.49	.425
	.185	.51	.46			1.4	.043	.41	.452
	.157	.45	.39			1.2	.037	.35	.448
	.129	.40	.34			1.0	.030	.31	.416
.0190	.019	.25	.22	.220	.239	1.0	.030	.209	.091
.0121	.012	.20	.17	.176	.181	.5	.015	.166	.073
.0061	.006	.1 Est.		.121	.116	.2	.006	.110	.055