Crystal rectifiers and the electron theory

L. E. Darling
State University of Iowa

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"CRYSTAL RECTIFIERS AND THE ELECTRON THEORY"

A THESIS
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L.E. Darling
SUMMARY

This is a study of a device much used in radiotelegraphy, the crystal detector, but about which, curiously enough, little seems to be known.

Two original methods of testing are evolved, and by their aid a great variety of crystal detectors are studied. A new, and apparently heretofore undiscovered aspect of crystal rectification (the arc-like nature of the action going on) is brought to light, and the phenomenon studied in detail.

The conclusion is reached that a crystal rectifier depends for its properties upon an electronic, or at least an ionic, action. The various explanations others have proposed are taken up and analyzed in detail.

A point is made of the assembly of a very complete bibliography on the subject. Leading electrical and scientific journals issued during the last ten years have been gone through with, volume by volume, and the material of consequence listed, and a great deal of it abstracted in detail, in the appendix. The thesis, besides being an analytical article on crystal detectors, is, therefore, a rather complete resume of the material existing on the subject.
This thesis, to judge by the title, is concerned for one thing with an instrument known as a "crystal rectifier." Some general considerations of the subject may be in order.

First of all, what is a "crystal rectifier"?

Even a lay reader is familiar with the fact that there are two general types of electric current commonly met with -- direct and alternating. In the one kind the current traverses the circuit continuously in a given direction; in the other, it rapidly reverses its course, and alternately goes completely around the circuit in one direction and then in the opposite, with the proper kind of apparatus taking place almost as rapidly as we like.

Once given an alternating current, there are instruments which will convert it back to direct. Such instruments are known as "rectifiers". The pulsating, flickering, blueish-white light of the mercury arcs found in moving picture theaters, brings to mind a common example. Ordinary arc-lights possess this property, though to a lesser degree. Curiously enough, it has been found that certain common ores, or cer-
tain mineral crystals, will rectify an alternating current also. It is with these "crystal rectifiers" that we are concerned.

What do the instruments look like? As ordinarily met with, they consist simply of a metallic point bearing upon the surface of a clean mineral crystal in the manner indicated in Fig. I. The crystal is commonly of carborundum, or iron pyrites, or may be any one of a number of other minerals, detailed mention of which is made elsewhere. The point usually consists of a curved, sharpened wire of considerable springiness, whose tapered end bears with more or less force upon the crystal face. The crystal itself is commonly imbedded in a firm, soft alloy, so that a good conducting contact can be made with its under surface. If an alternating current be impressed across the terminals AB (Fig. I, P. 31), and at the same time a direct current galvanometer be attached to the same terminals, a rectified direct current will pass through the galvanometer, causing a resulting motion of its indicator — the amount of such motion being dependent of course upon the strength of the rectified direct current.

The mercury-arc type of rectifier has found its special field for application where comparatively large amounts of power have to be converted, as in street lighting, battery charging, etc. The crystal rectifier, however, has been used so far only in the radio-telegraphic field. Naturally, then, in considering the crystal rectifier, we are going to be more or less involved in the technique of that field.
Just what use has radiotelegraphy for a rectifier, and particularly a crystal rectifier?

To show this, a diagram of the essential connections to a wireless telegraph set is first necessary. (See Fig. III, P. 81). At the left in this figure is shown the receiving apparatus, and to the right, the instruments used in sending.

It would seem unnecessary to go very thoroughly into electrical interactions between various parts of the apparatus shown. Most any of the books listed in the bibliography at the end of this paper are good on these points. Suffice it here to state that the apparatus shown on the right (the sending station) has for its essential function the emission of electromagnetic waves, which travel outwards in all directions through the ether. Striking the aerial of the receiving station, these waves set up therein feeble, but very rapidly oscillating currents. It becomes the problem of the receiving station to detect the presence of these feeble currents.

It is here that the crystal detector comes in. The currents set up in the antenna circuit oscillate so rapidly that a telephone receiver, delicate as that instrument is, will not be affected by them; its diaphragm simply cannot vibrate fast enough to keep up the rapid pace. However, a telephone receiver will readily respond to most any sort of a direct current, however weak or pulsating, because the natural period
of its diaphragm is well above any varying pulls that a direct current can cause. So it becomes necessary to convert the oscillatory current to one of this last-named type.

The crystal detector, it seems, has the ability to do this converting, and therein lies its value to the science. And it may be said in passing, that the value is no small one, either. Though there are other devices which will rectify an oscillatory current of the type here under consideration, they are none of them so common, nor so cheap, nor, above all, so simple. Practically every wireless station in existence — and there are coming to be many of them these days — either depend absolutely on the crystal rectifier for the detection of oscillations, or else keep it as a dependable standby for use when other, and less reliable, detectors fail. The device is much used all over the world, and its efficiency and general simplicity have given it a strong hold on the art.

It is apparent to the reader from the foregoing, no doubt, that some sort of rectifier is a prime essential to any kind of radiotelegraphic communication; otherwise the receiving operator could not hear with his receiver the signals sent out by the transmitting station. Though, as has just been stated, the crystal rectifier is much used device for the purpose, it is, curiously enough, but little understood. This has been true ever since its invention back in 1906.

And now, in the light of all that has preceded, we come to a consideration of the problem of this thesis.
THE PROBLEM

To put it generally, the question here undertaken for solution was to find out if possible why a crystal detector, or rectifier, should have all these peculiar properties just outlined. The crystals are commonly hard and dry, and resemble more or less the broken face of a common pebble, as far as external appearances go -- and the contact points on their upper surfaces are usually nothing more than pieces of ordinary wire, or steel needles, for instance. Why should such simple contrivances possess an ability to rectify an alternating current? What was there about them that could make such action possible?

It was felt that the devices were worth studying, for as has been previously stated, crystal detectors are far more abundant than any other form of rectifier in radiotelegraphy, and of all the apparatus used in the art, are, to judge from the meager literature on the subject, the least understood. Others have looked into the subject and have accomplished some important results, but the work appears to be scattering and without much correlation. It was thought that a resume of the subject as well as some work on a correlated theory of action might not be without value.

In this line, it may further be said that more than half of the published work on crystal detectors deals with rather aimless hunts on the part of various investigators for a crystal which would improve the rectification secured with present minerals -- searches that went on the cut and try method, and which culminated
in little or no delineation of basic principles which might be followed in further investigation. Theories proposed for the action seem to be as many and as various as the colors on Joseph's coat, and as poorly matched and fitted together. This latter effect is due, no doubt, to the fact that published work on the subject is so hard to get at.

And, further than all this, the subject seemed worth studying for another reason. Though crystal rectifiers are a valuable, and much used accessory to radiotelegraphic work, and are little understood, the whole subject of rectifiers in general would seem to merit investigation these days, to judge by current trend in invention -- and a study of one type of rectifier gives one in a way an insight into the workings of them all. Such an insight, in the light of other experiences, would appear to be a valuable thing to have in the advance of any movement.

The electric vehicle, according to current opinions by Messrs. Edison, Steinmetz, Ford, and others, is to be the leading conveyance of the future, even to the exclusion of the gasoline automobile. One of the handiest contrivances for charging the storage batteries on these vehicles is the mercury-arc rectifier, and its development bids fair to be an important adjunct to the rise of such electric conveyances. Rectifiers are being used even in railway work, where large amounts of power have to be handled, to the consequent elimination of the present sub-station, rotary converters, and the like. Dr. Peter Cooper Hewitt (a) has recently

(a) - Elec. World, Nov. 28, 1914. P 1051
announced the invention of a reversed type of rectifier which will work satisfactorily on power circuits. This instrument, according to Dr. Hewitt, will as easily convert direct to alternating current (the "reversed" action mentioned) as will present types perform the opposite function. The Electrical World, in commenting upon the invention, concurs in Dr. Hewitt's view that the device gives promise of revolutionizing our entire present systems of power generation and distribution. By using high-tension direct current on transmission lines, present inductive and capacity effects will largely be eliminated, together with resultant surges and other troubles. Then by transforming the delivered current to an alternating one at the far end of a line by means of one of his devices, all of the present advantages of alternating current in local distribution systems may be retained. Still other, and equally important applications of the device may be expected, as will be noted on an inspection of the article mentioned.

All of the material in the last paragraph or two has been given merely by way of acquainting the reader with the general status of rectifiers, and their present-day position in the electrical field. Dr. Hewitt is not the only one who has brought out new possibilities, though as one of the most recent developments, the work just described may be worth some prominence.

The point is this: In taking up a study of the crystal rectifier as in this investigation, one is not only working with a phenomenon really little known in its own field, but one which lies on a borderland next
a great variety of other scientific oddities of like nature, great use of which promises to be made in a commercial way in the near future. The crystal rectifier consists of really more than a bare metallic point pressing upon a crystal surface — perhaps in it lie some of the most elementary, fundamental ideas and reactions of all nature. Although the device is of great use to the radiotelegraphic field, the principles upon which it operates, and the actions inherent to the instrument itself, may be capable of wider application. A study of the devices may make large returns on the time and effort put in.

We are, then, to proceed on an investigation of the crystal rectifier. In what way was the study taken up?
PROCEDURE, APPARATUS USED, AND SUNDRY COMMENTS UPON THE INVESTIGATION

Naturally, in deciding on methods to be used, one turned to such material as had already been published on the subject, in an effort to acquaint himself with the amount and nature of work already done.

In going over such few articles as the writer could find in the early stages of the investigation, it was noted that a number of experimenters been trying to determine various facts about crystal rectification by impressing across the terminals of the rectifier a 60 cycle alternating current, such as can be obtained from any commercial main. Moreover, they used an ordinary 110 volt (or less) direct current which they alternated at will across the detector by means of a handswitch suitably connected into the circuit.

By such means they determined that a crystal had "unilateral conductivity"; that is, would let a direct current get past it more easily in one direction than in the other. With both alternating and direct current, current-voltage characteristics were run, and the fact determined that as a rule these had a uniformly rising character. Other and perhaps lesser points were settled, and some work done upon the real fundamentals upon which rectification appeared to be based.

The work so done was of course invaluable in
that it brought out fundamental points as to the practical operation of detectors. But it seemed to the writer in such judgment as he had on the subject, that too much and duplicated investigation had been made along such lines, to the neglect of other methods of approach which might bring out still other, and as yet undiscovered effects. Then, too, it seemed that by impressing an oscillatory current of feeble intensity upon a rectifier as is done in radiotelegraphy, and then trying to determine what went on in the process by taking the rectifier out of the aerial circuit and impressing a low-frequency, 110 volt current upon it, that the experimenters were working with rather an anomalous state of affairs; that by working at such low frequency and low voltage, they were perhaps missing many of the effects which might be secured if one tried to test the crystals with an electric current more nearly like that used in actual radiotelegraphic work. At least it seemed that there might be some hope and possibility of developments if such a scheme were utilized. Accordingly, the idea of incorporating a high tension, high frequency current as one of the essential factors in the testing methods to be used, was adopted.

Another idea gave promise of interesting aspects also. It seemed that no one had heretofore taken pains to make any very thorough examination of the point of contact. Most generally, it seemed, the crystal surface was inspected with the naked eye, or at best with a small pocket magnifying glass. Since it seemed
 universally conceded that rectification was a phenomenon that occurred wholly at the point of contact between the metal electrode and the crystal itself, it was reasoned that perhaps one could get closer to the things actually going on there if he had an enlarged view of the region. This brought one to a consideration of the compound microscope; if there were any instrument at all which would aid one in such a minute examination, that device was this type of magnifier.

Therefore, the use of a compound microscope, like the highly oscillatory current idea, was duly incorporated into the testing methods to be used. By experimenting with a great variety of crystals and in most every possible way, using these two devices -- the compound microscope and the high frequency current -- it was felt that perhaps some light might be shed on the object of the search, the "why" of crystal rectification.

So much for the procedure to be used on the testing end of the work. One other idea was adopted, which, to mention it here, may seem a little out of a direct line of thought, yet which had a most important bearing on the investigation as a whole, and by reason thereof merits especial mention at this juncture. The idea adopted related to the position research among magazines and books should have on the general investigation. To the writer it always seemed that a good many articles on scientific or engineering subjects fall short of definite value because they do not give the reader a well-rounded idea of the subject in hand. They
appear—neither to place the subject-matter in perspective with the work of others that may have gone before, nor to differentiate its findings from the general run of ideas on the subject. After reading such articles, one can hardly tell whether they have been worth the exertion or not. Particularly are these things true with articles a little out of one's usual field, where the literature on the topic is not so familiar, nor the general subject matter so well in mind.

Therefore, it was sought to avoid these things in this article as much as possible, if same could readily be done. Though seeming rather a large task perhaps, one could at least make some endeavor in the direction of introducing the reader to the general field, and making clear to him the status of the work in hand. Research through every published article on the subject that seemed to have any direct, or only incidental, bearing on the subject, has been deemed a prime essential to such working up of the thesis; both from the standpoint of placing the reader in the subject, and from the broader angle of bringing to bear on the findings of the experimental work, all the conclusions of others who may have attempted some research on the same subject. Only in this way was it felt that the investigation could have a thoroughness such as to make it worth the exertion of reading, or as to justify a few moments attention from a busy man's time.

Hence, to recapitulate, whatever of worth may be brought out in this investigation will be due to the adoption of the ideas just presented on the experimental side. It will
come from the conception and use of a high-tension, high-frequency current for testing in a way apparently hitherto untried; together with the adoption of the high-power microscope idea with which to get closer to the visible effects attendant upon crystal rectification. On the write-up side, the coordination of the work of others with that resulting from this investigation may be of some value. If it should so happen that the whole maze of ideas and data have been presented with some degree of clearness and continuity, that much is fortunate.

At this point the experimental work is taken up, and an explanation thereof follows on the succeeding pages.
ARRANGING OF APPARATUS USED:

Simple as the two propositions of getting a satisfactory high-tension, oscillatory current for testing purposes, and the mounting of a compound microscope to view the point of contact -- simple as such problems may seem, the practical working out thereof took fully half the time that has been spent upon this investigation, the assembling of previous work and the writing of this paper included.

Three different plans were tried one after the other in an endeavor to get the oscillatory current, two of which failed entirely. As a tentative scheme, it was decided to try out at first the buzzer circuits made use of in wireless telegraphy. In such practical work the buzzer is utilized frequently to test out the adjustment of the detector used. As thus applied, the circuit consists simply of an ordinary buzzer and battery, to one terminal of which an extra lead is attached. See Fig. II, P.81. The extra wire goes to one of the detector terminals, as shown by the wire "W" between Figs. I and II, P.81. Curiously enough the making and breaking of the battery circuit at the buzzer contacts seems to generate feeble oscillatory currents which will traverse the one lone wire and be rectified at the detector, producing a resultant sound in the telephone receiver bridged across the detector as a consequence, or else moving the needle of a galvanometer similarly connected.
As was half expected, the buzzer arrangement is all right for testing the adjustment of a good detector, but does not give strong enough effects to quantitatively test a great variety of crystals of widely varying rectifying powers, as was desired to do in this experimental work; particularly when the rectified current had to be strong enough to produce considerable movements of a galvanometer, as well as to produce a sound in the customary telephone receiver.

It was desired to use both the telephone receiver and the galvanometer for the following reason: By listening-in the telephone receiver one soon gets to judge just what kind of contact his point is making upon the crystal, and can keep a general check upon the things happening in the circuit. But the telephone receiver cannot readily give reliable data on comparative strengths of different rectifications, which made introduction of the galvanometer necessary. The instrument which it was desired to use in this connection was of the D'Arsonval type, a portable device made by the Leeds and Northrup company. It was equipped with various shunts, and had therefore, a considerable range of sensitiveness. It kept its zero excellently, a feature which was hard to obtain with another galvanometer of similar type but much less accurately adjusted, and over which much time was wasted in an attempt to get to work properly.

As the buzzer scheme was not satisfactory, another method had to be tried. Since the end desired was the securing of an oscillatory, high tension current
more or less on the nature of that used in wireless telegraphy, the thought presented itself of rigging up a miniature sending and receiving set, something on the order of that shown in Fig. III (P. 81). Such a plan should certainly give the kind of current desired, it was thought.

But upon testing it was found that this scheme was likewise possessed of the same defects as had been the buzzer circuits. Stronger signals were produced than by the buzzer method of course, but they were still too weak for much comparative testing. Apparently the defect in the arrangement lay in the use of aerials, since there was surely enough energy being sent out by the one-inch spark coil which actuated the sending circuits. The aerial on the sending end appeared to radiate too little energy, and the one on the receiving end appeared to gather in all too little. Therefore the thought occurred that if the aerials were the weak spot in the arrangement, why not eliminate them entirely, and send the oscillatory currents directly across to the receiving end by means of wires as was done with the buzzers previously tried -- thus securing the good points of both arrangements. Accordingly the aerials were eliminated, and the connecting wires substituted in the manner outlined.

This final plan actually secured the ends desired, but only after a long and involved series of trials. A great variety of circuit connections were tried in an effort to get the whole arrangement to operate harmoniously and in resonance, but a good many of them were without avail. Some were apparently sensible, and
according to the theory involved in resonant circuits; others were not. And out of it all a circuit was evolved, which, to look at it, would not appear to have much solid reason for existence. Yet in practice it brought out the effect desired, and in addition, evolved some new and rather different ones. To the reader interested in comparing this circuit with the regulation wireless, the two kinds are drawn out side by side in the page of wiring diagrams given in the appendix. See P. 87.

Here, however, only a brief description of the circuit will be given. Inspection of the picture on the page following, and the diagram beneath it, enables one to place the various parts of the apparatus shown in the photograph, and to see their function. A description of the interactions between the various parts of the circuit, while interesting, would seem somewhat beside the point here, and, as in the case previously mentioned (P. 3 ) only resultant actions will be discussed.

It may be enough then to state that this arrangement, when the several capacities and inductances were tuned into a resonant circuit, would produce a series of fine sparks at the gap shown, the sparks usually being no more than about 1/16" long. At the same time a highly oscillatory current of great energy appeared to be impressed across the detector terminals AB. With the point bearing upon a good crystal, considerable shunt would have to be cut in on the galvanometer circuit, or else the latter would be moved violently clear off the scale. With poor crystals, satisfactory deflections could still be obtained, using however
SHOWING ARRANGEMENT OF APPARATUS USED
ALSO THE FUNCTIONS OF THE SEVERAL PARTS
no shunt at all, or one of high resistance.

This circuit and arrangement of apparatus, then, produced one of the ends desired; that is, evolved a system which could impress a high-frequency, high tension, alternating current across the terminals of a detector, and cause enough of an effect there to enable a great range of crystals and kinds of contact to be tried out, no matter what their resistance or kindred attributes were.

The other aid to experiment — the compound microscope, and its application — will be mentioned in detail later. The point we are most concerned with here is the effects which the kind of circuit just discussed would produce when put to practical tests.

A NEW ATTRIBUTE OF CRYSTAL RECTIFICATION BROUGHT TO LIGHT

Surely enough, and justifying in a large measure the adoption of high-frequency, high-tension currents as best for the investigation to be made, some new and interesting aspects of crystal rectifiers were brought to light. However, as is not infrequently the case, these cropped out in an unexpected manner.

While working with the rectifier, it was found that if the point were lifted off of the crystal while still the high-tension, oscillatory current were impressed across the two, the current was strong enough to
jump the resultant gap. A series of sparks could be
drawn nearly as long as those at the primary spark
gap "S" (Fig. IV, P. 81), which of course was still
sparking, apparently being but little affected by the
change just made in its auxiliary circuit, the
detector. The sparks at "S", it will be remembered,
were only about 1/16" long, and, since those just
evolved at the detector were smaller yet, it will be
noted that they were tiny indeed, as spark discharges
usually go.

A small spark discharge as just mentioned
is nothing particularly novel, but its effects on the:
rectifier circuit were rather startling and unexpect-
ed. When such a rain of small sparks were allowed
to pass between the metal point and its crystal in
the manner just outlined, it was found that the
rectification was MARKEDLY INCREASED by the process.
In fact the galvanometer indication was all out of
proportion to what the crystal had given before with
a plain contact — in some cases, ten to twelve times
as much. Moreover, the surface of the crystal seemed
to be disrupted, or boiled out by the process; the
metallic point, however, appearing to be unaffected
in the operation. In most cases, the direction of the
rectified direct current at the passage of sparks was
the SAME as it had been before when operating as an
ordinary detector.

In all the study of previous work on the
subject which had been made up to this time, no such
effect as this had been noted; apparently the phenom-
C20) enon was new, at least as far as applied to crystal detectors. Surely the discovery might have important bearing the real reasons for crystal rectification, the subject with which, in the last analysis, we were most concerned.

It was here that the microscope previously discussed got in its good work. As has been before mentioned, the sparks with which one was working were very small -- tiny indeed. To look at them with the eye, they appeared as a mere twinkle of light between the point and its closely adjacent crystal. Upon viewing the discharge through a compound microscope, however, it naturally took on larger aspects. Though the microscope had initially been installed merely to see more exactly just what kind of a crystal surface gave the best rectification, it proved an invaluable adjunct to further experiment when this new effect of increased rectification with a spark discharge was brought out. With the microscope, minute differences in the character of a crystal surface could be detected, as well as noting the effect thereon produced by different ways of applying the spark discharge.

But before outlining as briefly as possible how the apparatus had been set up to utilize the microscope and test a wide range of crystals, one other commentary seems appropriate at this place. The London "Electrician", a leading electrical journal in the English field, had an editorial in a recent issue which would seem to foreshadow some such experi-
In the Electrician's issue for Mar. 5, 1915, an editorial on "Radiotelegraphic Methods" appears. After commenting at some length on the fact that in radiotelegraphy "there seems to prevail an almost inevitable law to the effect that a good radiator is a good absorber", and that in consequence "most any principle that can be used in a sending station can also be applied to the receiving station, and vice-versa", it goes on to quote several instances thereof in common radiotelegraphic practice, which however, have little direct bearing here for the most part. One sentence, though, would seem worthy of special quotation. The sentence follows:

"More remarkable still than all these, an ordinary crystal detector, when adjusted by aid of an auxiliary E.M.F. to its greatest sensitiveness for the reception of signals, can then be used for the generation of feeble oscillations by shunting it with a condenser and inductance, just as if it were a minute musical arc, as was first shown some five years ago."

In this article we are not concerned with the fact that a crystal detector can emit feeble electromagnetic waves in the manner mentioned; rather, we are interested in its ability to pick up and rectify these waves. Nor do we care particularly about the "musical"
aspects of any arc-like effect that may be present. It will be noted that the likelihood of crystal detector phenomena resembling those of an arc is indicated, but apparently there has been no experimental proof of such action. To contemplate the ordinary detector, or rectifier, with its hard crystal and simple metallic point bearing down thereon, the prospects for such a device to operate in much the same way as an arc-light do not seem very bright, perhaps. Particularly would such a conclusion be borne out by the appearance of the detector when rectifying ordinary radiotelegraphic oscillations -- such a detector can rectify these waves all day long, day after day with little outward change; at the end of operations one has the same old metallic point and the same crystal -- both apparently no different than at the start. Hence it will be seen that perhaps the Electrician's editor was justified when he used the expression "just as if" when referring to the possibility of crystal rectification phenomena resembling those of an arc, in the quotation given on the preceding page. In the ordinary arc light the electrodes are consumed by the play of the arc; in the detector, the electrodes remain in the same quiescent state all the time when dealing with ordinary oscillations.

But it will be seen that in the "spark phenomena" evolved by the experimental work of this investigation, and which was discussed in detail a few pages
back, are really in effect an excellent proof for the suggestion that arc phenomena and those of the crystal detector are one and the same thing. As mentioned on Page 19 the crystal electrode of the detector was boiled up by the arcing effect, same as in an ordinary carbon arc. Moreover, the rectification secured was increased many times over, and in the same direction, indicating that when a detector operates in the ordinary fashion (with a firm contact and no visible arc) that the action really is the same as in an ordinary arc lamp rectifier.

The full significance of thus pinning down crystal rectification effects to the same class of phenomena as arc-lights and arc-light rectifiers, may not be apparent at once. However, when we come to consider the great variety of explanations which investigators have heretofore offered for the performances of a crystal rectifier, the significance will perhaps be more evident. This matter is taken up in detail on a later page. After settling upon the fact that crystal rectification is much the same sort of thing as mercury-arc rectification, or any other similar sort, an explanation of the fundamental actions at play in crystal rectification is simplified and localized into one class of phenomena about which something is already known.

But first let us look more in detail into the arcing effects obtained with the apparatus used in this investigation, and into the effects brought out by the compound microscope. A brief explanation of arrangement of apparatus and procedure is first necessary.
FORM OF DETECTORS USED AND THE MICROSCOPE MOUNTING

Lest the reader's patience would seem to be tried at this point by what may appear too much of a discussion, it should be stated that only such explanation will be given as will make plain the general conditions under which the crystals and the microscope existed during the tests. A great deal of the data resulting from the investigation hinges on a group of pictures, which appear on a later page. To understand what these photographs mean, and what, in general, the procedure was for the tests, the following explanation is given:

The crystal detector, as used commercially, generally has little more to it than the essentials shown in Fig. I. (P.81) But when it comes to trying out crystals in so many ways as in these tests, very special and flexible apparatus had to be arranged; and there was little precedent to act as a guide. Particularly was this true in the matter of mounting the microscope conveniently to serve the purpose for which it was intended, and still keep up with the varied requirements of different adjustments of the detectors themselves. So both the form of detectors used, and the mounting of the microscope itself, deviates from the usual practice found.
The picture on the page following shows the general arrangement of apparatus as finally set up. The lower portion of the compound microscope is shown in the central background, while in front of it to the right and left may be seen the holders for the movable points. It will be observed that the holder on the left happened to be working with a fragment of crystal as a point at the time the picture was taken, while the one on the right had a needle which served the same purpose. Both holders were connected to a common terminal, and either one could be brought to play upon the crystal at will. If desired, the holder on the left could be arranged in the same way as the other to work with a needle as a point; the whole arrangement in fact being very flexible in these respects so that almost any combination could be assembled at will.

It will be noted that the crystal is held in a small metallic cup, immediately under the microscope, the mineral under test being held in place by the small set screw to the right of the cup. This container is made out of the head of a heavy binding post, as is visible in the picture. The head was bored out on a lathe to form this cup, and in use was filled about two-thirds full with mercury. The mercury permitted good electrical contact to be made with the crystal's under side, at the same time allowing it to be readily turned over for examination on any side.
H and H' are holders for the metallic or other points used; C and C' are the cups or holders for the crystals being tested. C' was not in use at time this picture was taken, but may be seen in operation on a following page. This picture shows two kinds of points, a brass and a crystal, being tried out against another crystal (in the cup C). The microscope may be brought to bear upon operations at any moment.
With the ordinary crystal holder, the mineral is held in place by a lead-like alloy, which must be melted up every time the crystal is shifted in position. Using the mercury instead of an alloy was a handy feature, and made more rapid work possible.

The photograph on the next page shows still another assembly of the apparatus, bringing out its flexibility and adaptableness to various situations. Here each of the holders are fitted with metallic points, and the effect of same could be tried out against most any crystal at will. One mineral and one kind of point could be compared against some other mineral and a different point, if so desired, the comparisons being carried on simultaneously by means of the twin cups for crystals shown. The microscope is standing over the other holder in this picture from what it was in the preceding, showing how it could be swung around its vertical axis and either crystal examined minutely if one liked, making comparisons and the securing of relative data an easy matter. In the background some of the apparatus comprising the electrical circuit may be seen, but this has been treated of already. (See P.17) The lamp shown in the central background was for general illumination of the board and the various galvanometer and meter scales thereon, as well as for lighting up the crystals in their holders. Real dependence for illumination of the crystals
Shows much the same region as the previous picture, but a more general view. Here two metallic points are bearing against two different crystals in the cups C and C'; joint comparison being made as to the effects secured. At the extreme right, the end of the loose-coupler may be seen, while near the left edge of the picture, one end of the D'Arsonval type galvanometer used in the tests is plainly visible.
was placed however, upon a 100 watt tungsten lamp mounted on a special swinging bracket, which could be brought to bear directly upon the holders, producing a strong light for the observations made, and for the photographs.

In the photograph following a more general view of the entire apparatus on the receiving side is given. The various devices are labeled and may readily be made out by comparison with data given beneath the picture.

The photograph shown on the second succeeding page depicts the apparatus on the sending side. This is a more detailed view than can be obtained from the general picture of the whole arrangement given on P. 17-2.

The two photographs just described are chiefly of value in giving one a better idea of the precise nature of the apparatus used. The connection diagram showing the way the various parts are coupled together has already been given (P. 17-3), and may be inspected again if one is rather hazy as to the way they were connected up.
Movable high-power tungsten lamp for illumination of crystals tested is here shown, same being within the shade in the central right-hand side of the picture. The galvanometer "G" is also more plainly used seen at the left. The telephone receiver in test is connected in parallel with galvanometer, and may be seen lying on lower right-hand corner of table.
This may be considered an extension on the right-hand side of the picture shown on P.17-A. It gives in detail the apparatus not shown there. The large, flat, square box at left is the variable condenser ("C"). The neighboring loose coil of wire is the inductance ("L") in series with "C". By adjusting relative amounts of the two in the circuit, resonance could be secured. Voltmeter shown gives battery voltage.
RESULTS ATTAINED
AND FURTHER COMMENTARY UPON RECTIFICATION PHENOMENA

Thus far we have described the crystal rectifier, indicated its importance in the radiotelegraphic field and allied lines of endeavor, discussed the problem here undertaken, described the ideas used as a basis for attack, shown the general plan and set-up of apparatus, and taken up rather briefly one unusual effect brought out by the line of experiment pursued. Now just what tangible data resulted from this line of experiment, and from the investigation as a whole?

The data secured are not such that one can tabulate them in long columns, one after the other, in the manner of accountants. One cannot put his finger on any one item or numeral, and from that propound any lengthy series of alleged facts. Rather the results attained are such as to give one a general understanding and appreciation of the phenomena of crystal rectification. One gets to know in a general way what a given crystal will do under a wide range of conditions; knows the effect of different kinds of points, of varying degrees of contact, and of a great variety of other variables that can enter in. Above all, one gets an appreciation of the crystal rectifier as a rectifier, such that the results of others may in some measure be judged, and classified, and brought into perspective when attempting to evolve a theory that will explain the major effects of rectification phenomena — and that was the ultimate object of this thesis.
The pictures and data hereinafter discussed are intended to be just such as will give the reader in a measure this same point of view. At least it is hoped that from them he can get some insight as to what practical work was done previous to the evolution of a rectification theory, and a co-ordination therewith of the results others have attained. Few observers have ever had a microscope, or any other magnifier of consequence, set up over a crystal rectifier so that general effects could minutely be observed, at least there is but one published work to be found in which mention is made of any such attempts at magnification. And then, too, no other workers have ever had a high-tension, oscillatory current of the kind here used, and have recorded no such finding as was here brought out; namely, that crystal rectification phenomena are not isolated and different from other known kinds of rectification, but depend upon identically the same processes as do arc rectifiers now in commercial use. As far as the writer can find among books and magazines in the field (and an inspection of the bibliography at the end of this article will show that rather an extensive search has been made) -- as far as the writer can find, no other investigation has previously brought to light a phenomenon similar to the "spark" effect discussed on P. 18. This effect of course has a very intimate bearing upon the character of the theory evolved by the whole investigation, and by its novelty and newness, would seem to warrant further attention. Accordingly, a brief, and renewed consideration of this "spark" phenomena is next taken up.

(a) The article referred to is in Vol. 69 1912 Electrician (English) See P. 66. Is rather amateurish in tone, and the effect discussed was old at the time. Only one picture is shown, and that not greatly magnified.
The manner of securing this "spark effect" has already been explained. (See P. 18). The term "spark effect" is used for lack of a better or more descriptive term. Viewed from the standpoint of the nomenclature used in gasoline ignition circuits, the thin blue discharge really was a "spark", for it like the discharge at a spark plug, was obtained from the secondary of an induction coil. However, the discharge seemed to differ in quality from the usual run of such phenomena.

At no time could the spark be made more than about 1/32" or 1/16" long, even though a "one-inch" spark coil was being used as the source of high-tension current. It will be remembered that there was a spark gap in operation on the "Sending End" at all times during the tests, the spark there being only a little larger than the one drawn at the detector in the manner mentioned. The various capacities and inductances of the resonant circuit used seemed to absorb or limit the amount of discharge possible, so that no larger spark could seemingly be obtained.

At one or two places in the previous discussion this spark discharge has been referred to as an "arc", and in truth it would seem to merit such a term, as will perhaps be made more evident from the discussion following. Here, the smallness of the discharge is of interest. Viewed with the naked eye it appeared to be about as large as the tip of the wire or needle which served as one electrode. Viewed, however, through the microscope it naturally took on larger proportions, and other effects were noticeable -- particularly the "arc"-like nature of the discharge.
With the ordinary arc light on a 110 volt circuit, the light given off comes from a vapor stream given forth by one \( \text{electrode} \) (in case of D.C.), and both (in case of A.C.), and a portion of the current which crosses the gap is also carried by this luminous vapor stream — the remainder of course being transmitted by invisible and more or less electronic carriers. But the point is that one or both of the electrodes have to be disintegrated to make maintaining the arc possible. In an alternating current arc, if other electrodes than carbon be used, particularly poorer conductors, it is almost impossible to maintain the arc — UNLESS the potential across the arc be raised. Then it appears that enough current can be forced past the high resistance of the electrodes so that their tips can heat up and presently furnish a vapor stream, thus starting the arc.

Such seemed to be the action in the "sparking" action just mentioned at the crystal rectifier. For the material of one of the electrodes, the crystal, appeared to enter into the arc stream in the same way. Here, evidently, one had a case of a poor electrode, the crystal, which would not ordinarily enter into an arc, but under the impressed high potential could do so. The discharge did not seem to use ions or electrons in the air for a vehicle as in ordinary high-tension spark phenomena using metallic electrodes alone, but carried with it also the material of the crystal itself — and THEREIN appeared to lie the cause of the inordinate amount of rectification secured when such minute sparking was allowed to go on. The metal point used (a steel needle commonly, or many other kinds of similar points) did not appear to enter into the reaction
any more than would the metal of a spark plug's terminals would appear to be disintegrated by a similar tiny discharge. Then, evidently one had a case of an arc-stream being supplied mainly from one electrode alone, the other remaining cold and unaltered by the process. Surely there was something in all this that would seem to shed important light on the fundamental processes going on in crystal rectification; particularly since the rectification secured by this arcing method was all out of proportion to the effects obtained with ordinary firm-contact rectification — many, many times over, and in exactly the same direction.

As has been mentioned elsewhere, tests were run on a great variety of common crystals which have been found to be good rectifiers in current radiotelegraphy practice. Also tests were run on a few previously unused in the science, simply to see if any new ones could be discovered, or any interesting data brought to light. As others have noted, it was found that some crystals would rectify in one direction, and the others in the opposite. That is, some would deflect the indicator on a direct-current galvanometer in one direction, and the others in the opposite; indicating thereby that the direct current produced went in the opposite direction in the one case from that in the other. A possible cause for this is discussed elsewhere.

A few sample tests are listed in the following paragraph. In explanation of the terminology used, a few brief statements should be made. All results are expressed in terms of deflections on the galvanometer's scale. A rectification of 300 for instance means that
the direct current being produced was strong enough to deflect the galvanometer over 300 small scale divisions. A (+) or (-) following the figure given means that the rectification was in the corresponding (+) or (-) direction. Plus direction was when the indicator went to the right, or up the scale, and (-) was of course the opposite. Since it was only desired to get data for purposes of direct comparison between the several conditions and kinds of crystals used, the writer did not go to the trouble of calibrating the galvanometer in terms of micro-amperes, or other standard unit. It was felt that such calibration would be of no more value to the user of the principles evolved, than would deflections in terms of the galvanometer's scale itself -- for crystals vary so in composition, and working conditions are so many, that two investigators working over the same field will rarely agree as to exact quantitative results. It is not quantitative results that are here important -- rather only comparative, for all one was after was to stand one working condition up against another, or series of others, and see which would give the best results of the group. The writer is of the same opinion as are Messrs. Pickard and Powell (See P. 91 and P. 15 where) that quantitative testing by different investigators had better be left alone until crystals and working conditions can be standardized, if two such conditions ever can be realized. Comparative testing by individuals of crystals is all right, it seems to the writer, for then the same conditions and same crystals are being worked with all the time. But comparing the results of one investigator with those of another in exact terms of microamperes or the like, would seem to be valueless as these writers have said. So the galvanometer readings have been used as sufficient for purposes involved.
CHARACTERISTIC RECTIFICATIONS
As Given by This Apparatus

(Crystals most used in radiotelegraphy are grouped near front. Formulae given for the different minerals are from Farringer's "Minerals of Commercial Value". Wiley & Sons. 1897.)

IRON PYRITES - FeS₂
Gave 3400 (-) using a brass point against a flat crystal surface, which was about average of what it would do.

GALENA - PbS
Contact against plain surface gave 900 or 1000 (+). By lifting point off the surface gently and drawing delicate arc, one could get 2000 (+) or more. Galena vapors are heavy and it is difficult to maintain much of an arc. Most one can get is a small sizzling contact.

CHALCOPYRITE - CuFeS₂ - "Copper Pyrites"
Gave about 2000 (+). Very good rectifier and easy to adjust.

ZINCITE - ZnO - "Ruby Zirc" - "Red Oxide of Zinc"
Gave 1600 to 2000 (+). Easy. 1600 seems to be characteristic for the mineral.

BORNITE - Cu₃FeS₃ - "Peacock Ore"
Variable, but (+) in direction. Yellowish and impure specimens give best results seemingly. Hard to get pure blue part to maintain arc. Was evidently acct. resistance of crystal. Plain firm-contact gave but 100 (+) or so. Was evidently working with a poor grade of the mineral as bornite is reported to be fair detector.
MANGANITE – \( \text{Mn}_2\text{O}_3 \cdot \text{H}_2\text{O} \)

Good conductor and sparked very easily. Gave a rectification of 3500 (+) and more without any trouble at all. Smooth glossy surface worked best, and after spicules were worn off of the other kind, it too, worked well.

Chalcosite – Copper Glance: \( \text{Cu}_2\text{S} \)

Clean surface rectifies 3500 (−) with little trouble. Dirty surface and big arc were likely to rect. 600 to 800 (+) without difficulty, though this seems to be due to oxide and is secondary effect.

MARCASITE – \( \text{FeS}_2 \) – Same chem. comp as Iron pyrites, but crystallizes in IV system, while pyrite belongs to the first, or cubical.

Small, crystalline specimen used. Appears to rectify (+) when has big spark, though not very marked. Gives about 500 (−) when in ordinary contact. One characteristic of the mineral is that it seems to give sharp and sudden effects, due, evidently to the rests of small crystals present upon surface.

MAGNETITE – \( \text{Fe}_3\text{O}_4 \) – "Loadstone"

Gave 500 (+) on straight contact, with 2000 (+) and more by drawing gentle arc. Seemed to be pretty good material. Gave effects easily without much adjustment.

NICCOLITE – \( \text{NiAs} \)

On a clean surface and big arc, had tendency to rectify 200 to 300 (−) but didn't last. On oxidized dirty portion could get 1500 (+)
ENARGITE - Cu₃AsS₄ (Ries & Watson Eng. Geol.)

Gave some of best rectifications secured in all the tests. Gave 2500 (–) and more. Easily adjusted. Didn't seem to make much difference what kind of contact was used.

MOLYBDENITE - MoS

Specimen here used appeared to have too much resistance, and wouldn't rectify at all. Molybdenite is commonly reported to be a good rectifier; pieces here used, however, seem to be poor grade.

ARSENO-PYRITE - FeAsS - Mispickel

Seemed to be pretty good. Needed no particular adjustment. 1000 (+) was about its limit.

PYRRHOTITE - Fe₇S₈ - "Magnetic Iron Pyrites"

2000 (+) could be obtained with arcing.
600 (+) seemed to be average.

SPHALERITE ZnS; Franklinite, (FeMnZn)O, (Fe Mn)₂ O₃; Rhöntite, TiO₂; Siderite, FeCO₃; Stibnite, Sb₂S₃; Zircon, ZrSiO₄; Chrysocolla, CuSiO₃,2H₂O; Rhodonite, MrSiO₃; Malachite, 2CuO,CO₂,H₂O; Willemite, Zr₂SiO₄; Quartz, SiO₂; Lepidolite, Complex; Biotite, Mica; Corundum, Al₂O₃; Hematite, Fe₂O₃; Limonite, 2Fe₂O₃ & 2H₂O; Scheelite, CaWO₄; and Halite, NaCl --- were none of them particularly good at rectifying. Most of them would give no effects at all.
In looking the preceding over, the most important thing is to compare the numerical values of the different rectifications, and their direction; that is, whether plus or minus. By this means one can get a good idea of the comparative values of the crystals as rectifiers. These various crystals were each tried out afterward in a genuine wireless telegraph receiving set belonging to the university. This set had a large aerial 100 feet high, and was equipped for regular work. The degree of sensitiveness of the crystals was found to be closely approximate to the rectifications they had given when under the above tests. Hence the testing methods used in this thesis give good criteria as to how given crystals will work out in practice on genuine receiving sets.

The minerals used were all of them from the Geology department of the university, and were just ordinary specimens -- not selected especially for their purity or value to wireless telegraph work. Hence it is not strange that certain ones of them would not give good rectification, as for instance, galena, molbdeneite, etc. The crystals were evidently more or less impure, and in these cases, not representative of their class. The majority of them however were good specimens, and indicative of the general run of conditions to be attained with their use. Geology specimens were used because it was desired to test a wide range of crystals, and only in such work could so many different kinds be obtained.
It will be noted that in general the oxides gave a rectification in the plus direction, while the sulphides were in the opposite. Those crystals with the most atoms to the molecule seemed to rectify best as a general thing. A prime essential to a good crystal was that it be a good conductor, or at least a fair one; else enough potential could not be concentrated in the area immediately beneath the point to cause the crystal to heat up and enter into the reaction.

All of these things would tend to point to probability that crystals break up into ions, which ions have considerable to do with the rectification effects secured. This is exactly the conclusion to which a number of other effects point, and the whole proposition will be taken up on a later page. For, to the writer, it would seem that in this proposition of breaking up into ions, lies the whole basis for crystal rectification.

Mention has been made several times in the forepart of this article that the compound microscope was of considerable use in examining rectifying effects, and in an analysis of surface phenomena. It was said also that pictures would be given to show the class of data the microscope brought out, and the general disturbances attendant upon rectification of such currents as here used. These pictures are now presented for consideration. They are of value in giving pictorial illustrations of the effects just considered.
CONCERNING THE PICTURES

At best these pictures can be but samples. They can only give the reader occasional, glimmering insights to the things one can observe taking place at most any rectification. In use one can constantly shift the microscope around and observe practically all effects that present themselves. One is not limited to one set focus, as in these pictures, nor to one lone area of the field.

The photographs show in a general way the things one observed while getting such data as was listed a few pages back. (P. 36, 37, 38). As can be noted in the pictures, one of the most important functions the microscope performed was in giving the observer exact information as to the kind of surface with which he was working. Many effects that would otherwise seem contradictory could thus be explained and cleared up. For instance, one customarily gets a (-) rectification with iron pyrites. Sometimes, however, the rectified current is in a plus direction. To look at the two areas with the naked eye where such rectifications were secured, little difference could probably be detected. With the microscope, however, one readily see that he was working with a raw surface of the pyrites when he obtained the (-) rectification, while the (+) indication came from the fact that at the moment the needle was pressing upon a minute mass of oxide, or other similar impurity upon the crystal's surface! Plus rectification seems always to be a characteristic of oxides, while minus usually results with sulphides -- and there you have an explanation of the apparently contradictory results with what looked to be the same surface.
Considerable difficulty was experienced in getting the pictures. To provide pictures representative of the usual run of conditions met with while running tests, two minerals were actually run through the various processes and the successive effects photographed. The two minerals used were iron pyrites and galena. These were chosen because they are common types of crystals used in commercial work, and their general characteristics are probably more familiar to the average reader than some of the other minerals tested. Thus perhaps the pictures could be made more interesting.

All pictures of course were taken through the compound microscope and represent the field as an observer would see it while making tests. To get the first group of photographs presented -- those on iron pyrite -- a small "Expo" Watch Camera was placed above the microscope, and the exposures made with its aid. Pictures so obtained seemed to have the happy characteristic of giving fairly uniform definition. Though the magnification was not so great as with the other pictures shown, these on pyrites taken with the small watch camera show practically all of each field in sharp definition. The smallness of the picture obtained, however, was one drawback of some consequence.

Those on galena were taken with a 4x5 plate camera, and show a much larger picture as a natural consequence. The manner of taking the pictures is well illustrated by the photographs given on P. 17-A and P. 43. In the first, the camera is shown swung out of the way so that one could readily focus the microscope in the usual manner, while the second shows the camera swung down ready to take a picture.
SHOWING MANNER OF TAKING THE 4x5 PHOTO-MICROGRAPHS

See also the Similar Picture on Page 17-A, where the Camera is shown swung up from Microscope so that latter could be focused.
It is suggested that the reader use a pocket magnifying glass in inspecting these photographs. In so doing greater detail will be brought out, and the sensation of actually looking through microscope given.

PHOTOGRAPHIC RESULTS AND DATA WITH IRON PYRITE

Violent rectification occurred when an arc such as is shown was allowed to appear at the point of contact. Indicator went clear off galvanometer in the (-) direction. Means that the instrument read 3000 (-) and more.

This photographs the arc without having any auxiliary light turned on so that the crystal could show up out of the darkness as it could in the preceding. Took this picture and the one following primarily to see how the ultra-violet light alone from the arc would affect the photograph film -- merely as a pointer on taking such photographs.

The third picture shows same arc, but here it flashed for but an instant only, to see how it would register on the film. It should be borne in mind that these arcs were obtained between a fine needle point and a crystal surface less than 1/16" away. Arcs are in reality very small and thin, not the blurs these photographs would indicate, nor the bulging kind one obtains at the spark plugs of a gasoline engine, for instance. Arc is here enlarged 60 diameters, or thereabouts.
IRON PYRITES RESULTS

# 2

General view by light of place where sparked before. Neither microscope position nor adjustment of point of contact have been disturbed since the first view shown on the preceding page was taken. So this gives a fair idea of the surface under examination.

This is a picture of same point of contact as before, only microscope has been moved up a little and over to the left, so that now point of contact shows more nearly at central part of field. It will be observed that all these results have been obtained with a needle whose finely-sharpened end has been curved to the arc of a small circle, thus making it a better exploring point. The curve in the needle and its location may readily be observed in all these pictures.

The lower picture is of the same locality and adjustment as the middle one. Taken merely as a check to bring out further detail if another exposure would do it.
IRON PYRITE RESULTS

# 3

This is a higher power view of exactly the same territory as shown in the preceding pictures. It will be noted that the area now shown in the field is only a small portion out of the central part of the preceding photographs -- due to the limited field which the high power could handle. Something is evident here that probably was not very clear in the pictures shown before. That is, that the point started in by pressing lightly upon the sharp crystal edge of the outjutting, cubical formation which fills up most of the left hand side of the picture. An arc has formed between point and crystal until the whole territory immediately beneath the point, together with a considerable section to the lower side and foreground of the picture, has been blotched up and darkened with the products of combustion. Originally, the whole outjutting cube was white in color (or rather, brass yellow) and showed a firm crystal edge clear along its whole projecting edge. Arcing has worn away this edge immediately under the point, and resulted in the blackening-up process mentioned above. The lower picture (Inside the small white circle) shows the "crater-like" formation left in the crystal after the point has been removed.
These are three high-powered views of the same thing shown on the preceding page. The first one is simply a check upon the lower one just given. As was mentioned there the point had been lifted out of its crater and almost removed from the field. It is now located in the upper part of these pictures (Inside of the small circle.) Current was turned on at time lower two pictures were taken, and position of point is made evident by the small sparks shown.

Comparison of the picture at the top of the next page (which is a low-power view of the territory here shown) with a similar low-power view of this neighborhood given at the bottom of the second preceding page will enable one to readily see the relative location of the point now (out of its crater) with the position it had when in the crater. Transferred the point to this new location on a striation edge, because the old and similar one had now become worn to pieces, and even the crater had been so charred as to lose its natural action. At the new locality, a new crater speedily created itself, the rectifying action going on as readily as before.
The low-power view of the territory discussed on preceding page. Shows location of point at present. In almost center of photograph is its old crater, while its new place is clearly indicated. This is the spot that was doing the sparking shown in two lower pictures on preceding page.

This is a low-power view also. Here it was attempted to see what rectification a flat crystal surface would give. So point was placed upon a flat, striated, typically pyrite surface as shown. (Its shadow and reflection in pyrite make lower end of point to be bent into a sharp hook. In reality, however, the point is bearing squarely against the light-colored and rectangular surface shown in central part of picture.) Point was not in thorough contact with the area (fairly firm, however), but apparently ions or electrons from the clean pyrite surface were plentiful, with the result that an arc started easily, and spattered burned pyrite over crystal faces in short order. Lower picture shows the arc. These two pictures, then give some idea of the kind of contact one ordinarily gets with a pyrite surface, and demonstrates how readily the ions available therefrom can provide a path for an arc.
A new attempt at getting a point to rest on a flat crystal surface and give straight rectification was here made. This picture shows very plainly the point resting against the crystal surface. Such an arrangement gives as a general rule about 550 (−) deflection; whereas if the point be raised slightly so that it does not exactly touch the surface, a minute arc may be drawn, and the rectification may go up to 2000−3000 and practically always in the same (−) direction as in this case. If pyrite should give a direct current in the plus direction it will generally be found that one is working with some impurity in the mineral itself, or with a badly oxidized or coated surface.

The upper picture shows the point pressing against one face of a crystal, the lower one shows it in contact with a crystal face at right angles to the one first used. Object was to see if there was any appreciable difference in rectification obtained from the two positions. Was trying out Fleming's idea (See P. 33) wherein he suggests that different faces in a crystal may differ in electron-giving-off power, due to different molecular face which is presented to the needle -- and therefore differences in rectifying powers might be secured. No such effect was noticed.
RESULTS USING LARGE CAMERA FOR PHOTO-MICROGRAPHS

The preceding pictures have been mainly of value in giving a general survey of the effects commonly met with. Because of the smallness of the pictures, a great deal necessarily must remain unshown. To remedy in some degree this defect, the following pictures were taken, using a 4x5 camera. Naturally they show things in greater detail, but are more cumbersome on account of the greater size.

In looking the photographs over it is first necessary, perhaps, to get a perspective as to the subject in hand, or doubtless the first impulse will be to condemn the pictures as a whole or singly, because of the general indistinctness which may seem too prominent a characteristic.

As has been stated elsewhere, the microscope used in this investigation was of the compound variety; equipped with two powers, one about 60 and the other approximately 100 diameters. Use of such high power of course limited the field under observation to a marked degree, and made the proposition of getting all parts of a given field in focus at one time an extremely difficult matter -- particularly with solid objects of irregular surface such as the crystal formations here used were.

To get one's ideas straightened out as to what he is really looking at on the following pages, the picture on P. 51 is first presented. The "19" there shown is the enlarged image through the "high-power" of the microscope of a part of the date on an ordir-
SHOWING MAGNIFYING POWER OF MICROSCOPE

THE "19" FROM THE DATE ON A SILVER DIME
ten-cent piece, or dime. That is, it shows the "19" of the "1915", or "1911", or "1905", or any other date that may happen to be on a dime. If one will extract such a coin from his pocket, and compare the "19" of the date thereon with the "19" here shown, the amount of magnification present in this and the following pictures, will at once become evident. It will be noted, moreover, that the "19" here shown completely fills the field. Inspection of the tiny "19" on a dime shows, then, the area to which one was confined in taking these pictures. Some of the photographs were taken with the "low-power" (60 diameters) of the microscope, in which case a field about twice the width of a "19" on a dime is under observation, or one that would embrace the whole date on the coin, ao "1911", etc. Even with the "low-power", it will be observed that the field under consideration is only about the size of large end of a lead pencil.
The really hard condition to meet in taking large-size photographs of opaque objects through a microscope such as these pictures are, is to get all parts of the picture in focus at the same time. If one gets the needle point in focus, the field upon which it is pressing becomes a foggy blur; while if he gets the field in focus as well as may be, the needle appears in the photograph as a large, indistinct blotch. Such a condition as this last is well illustrated by the picture on P. 56.

The photograph following shows a galena crystal under observation with low-power. The territory viewed, then, is about the size of a lead-pencil end, as was mentioned on a preceding page. It was desired here mainly to show the kind of point used in the following tests -- the point in the act of pressing upon a crystal surface. To do this the territory immediately beneath the point had to be shown out of focus, because of its not being on the same plane as the needle. The nature of field is better shown under high-power in the next picture, so this was not a serious objection. The territory in the upper left-hand corner of the picture here considered (See P. 57) is in fair focus, because of its being higher than the remaining parts of the plane.

The point used in these tests was made of a finely sharpened piece of spring brass wire, the end of same being clearly shown on the opposite page. Since the writer and others have found that the kind of metallic point used makes little difference in rectification effects with crystals, brass was here used
Showing principally how the point of a finely-sharpened needle looks under the microscope. This picture was taken with the "low-power" of the microscope; which means that the needle point is magnified about 60 diameters. When the "High-power" was used, the magnification attained 100 diameters. The picture on next page shows such magnification.

In the background, beneath the point is the galena surface. It is out of focus here because greater distance away from microscope than needle.
because of adjustability to various positions, and lack of the brittleness which characterizes points made of steel needles. Besides many of the commercial detectors in use have a point of brass or German silver and seem to give good satisfaction.

Apropos the mention just made of the many kinds of points tried out, a little further commentary may be in order. The holders, shown in the pictures on P. 25 and 26, and elsewhere, were fitted to take interchangeable points, and the writer made a full set for use in same. The metals used were gold, silver, platinum, lead, tin, copper, zinc, magnesium, brass, iron, aluminum, fuse wire, and many such. Little differences in rectification effects could be noticed, using the different metals. The crystal seemed to be supplying all the carriers for the charges passing between it and the point. Regarding these things extended mention is made later. See P. 67.

The next picture shown (P. 56) is a high-power view of the territory depicted in the preceding picture (P. 54). It will be observed that this photograph deals only with the central portion of the surface shown in the picture just considered, a condition brought about by the limited area which the high-power could handle.

The territory immediately under the point is not in focus, else the point itself would have become hardly distinguishable. The area in the upper left-hand portion of the photograph is in sharp focus, and shows exactly the same conditions, and the same kind of surface, as is under point. Point is actually only about a hair’s width away from the sharply defined portion, so it is seen that picture represents general conditions well.
The end of the needle in this picture is in the lower right-hand corner and appears to be about the size of one's thumb. Galena surface is in sharp focus in upper left-hand corner of this picture, and gives one a fair idea of the usual nature of the mineral's surface.
Fractured Galena shows two kinds of surfaces, that demonstrated by the picture on P. 52 and another type depicted by photograph on P. 58. The nature of the surface is clearly shown. See upper left-hand portion of picture. The various white patches were not in reality white, but colored with all the iridescent hues of the rainbow, and possessed varying degrees of softness and thickness. In some places this kind of a surface would give a rectification of 1040 and more (+). Note that by being in (+) direction, the rectification produced by galena was opposite in sign to that given by Iron Pyrites, the material under test when the preceding set of pictures was being taken.

In one case, with the surface here considered, upon resting point upon a fresh surface, the rectification reached 40 in a hurry, and then hung around 40 and 50. Filmy layer broke through. Then drew a minute arc, and for a moment obtained a small (-) rectification. Putting point down to a sizzling contact with burned spot, obtained 1400 (+). Contrast this reading with the 40 or 50 the crystal would give with a firm (non-arcing) contact. This is simply an instance of the effects discussed on P. 18-19.

The picture on P. 58 is offered to show a typical Galena surface under low power. The shiny, mirror-like exterior of the usual galena crystal is at once recognized, probably -- since such a surface is more characteristic of the mineral than the iridescent, filmy crystal surfaces with which the preceding pictures were concerned.
The characteristic, mirror-like surface of galena is well shown here. The white streak across the middle of the picture is the needle. It is out of focus because of its being nearer the microscope for most of its length than the crystal surface upon which the instrument happens to be focused.
The territory dealt with in the preceding photographs is shown at X (inside the small circle). Since this region happened to be lower down than the rest of the crystal, it is somewhat out of focus in the picture here shown. However, the "crater" formed by the minute arcing previously mentioned is clearly indicated. The appropriateness of the name "crater" is evident perhaps from the appearance of specimen here shown. Other samples of "craters" may be seen within the small circles on P. 60. The name "crater" has been used several times in other parts of this write-up and the pictures here cited may serve to give one some idea of their general appearance.

The rim of a crater is, as a rule, a much better rectifier than the surrounding territory. This is due, apparently, to fact that electrostatic stresses can concentrate there under influence of the impressed potential, which concentration results in great number of ions being given off at the point. This action has an important bearing upon rectification effects secured and will later be demonstrated.

In the picture with which we are just now concerned (P. 58), the point is shown resting firmly against a clear crystal surface. Such a contact gave 400 to 600 (+) rectification. But if one once lifted the point slightly above the surface and let it arc a little, the rectification went up way past the 400 to 600 value. Such a case is taken up in the next photograph.
Point is in lower right-hand corner, same as before. The nicks in the surface (visible all over the area) were caused by the play of the "arc". Material seemed to be drawn up from these nicks toward the metal electrode -- the needle.
Concerning Picture on P. 60.

This is a highpower view of the same locality as is shown in the picture given on P. 58. The picture was taken this time however, after several tiny arcs had been drawn on the crystal's exterior. The needle point may be seen dimly outlined in the lower right-hand corner of the picture, the tapering end of the needle appearing to be about as large as one's thumb. The point has just been moved from the region indicated by the small circle to its present position. As now located, it is bearing upon raw mineral surface, for it has scratched through the ordinary surface material. The scratch created is plainly evident, for the point is at present resting in one end thereof (See picture).

The history of operations performed upon this surface runs as follows:

"Obtained a large rectification in a plus direction (3400) by applying point gently to the clear galena surface previously dealt with (P. 58), and letting the thing arc ever so little. As can be seen in the picture, the arcs scattered a film of half-burned material in some places, and in others seemed to literally tear whole spots directly out from the crystal surface. Observe the speckled appearance in the upper left hand portion of the picture, which is in sharp focus. The whole surface now has that kind of an appearance, though, because of the limitations imposed by focusing requirements, same is not shown in the picture. Observe, however, the change in character of the surface from that shown in the preceding picture. Although the point was applied to but one locality, material from all the territory round about was drawn up, leaving the little pitted areas shown. Perhaps this phenomenon is similar
to the way electrons are forced out of a crystal surface with the lesser potentials used in radiotelegraphy.

The whole surface seemed to be under considerable strain immediately after the arcing operations were carried out, and the point applied to most any area of the surface would give a rectification of 3500 (†) and more. If however, the point was put in the position shown in the picture; that is, bearing through the upper layers of the crystal to the native material beneath, but 300 or 400 (†) would be secured as a rectification. At another place upon the same crystal where there was much galena dust, a rectification of 35000 (Ten times that previously attained, even by the arcing method), was attained. The galena dust was disintegrated by the process, showing that the molecular structure was broken up, and that such breaking up has important bearing upon the amount of rectification secured.

The picture just discussed is the last one taken of a galena crystal. The remaining photograph concerns iron pyrites again, for reasons discussed on the next page.
Needle projects down from upper side of picture, and is resting in a minute depression in a crystal edge. Pyrite striations are visible in lower part of picture. The blotches in lower left portion of picture are bits of other crystal sticking to the pyrite surface, and have nothing to do with the experiment.
VIEW OF A NEEDLE BEARING UPON SHARP EDGE OF IRON PYRITES CRYSTAL

See picture on preceding page. Discussion follows:

In the bibliography to this article in particular, the reader will find frequent reference made to the fact that a crystal will rectify better if the movable electrode be applied to a crystal edge. To show just what the nature of such contact is, this picture was taken.

The point appears to be down in a hollow, but in reality is only in a tiny nick in the crystal edge, caused by a few sparks at the time of making contact. It should be understood that the pyrite surface shown in the picture is one side of a cubical crystal, the side terminating in the ridge shown at the upper part of the picture, and the adjacent side sloping sharply away from this ridge to the background behind.

The long black lines shown in the lower part of the picture are the striations characteristic of pyrite. Note their relative size as compared with the needle point shown above — and the needle was a small one and very sharp, also. These striations would appear to be a valuable characteristic of pyrite, as far as rectification effects are concerned. With weak wireless signals, the potential can easily concentrate upon these tiny lines, resulting in a marked increase in the current density immediately under the point, and resultant increases in rectification secured, due to the greater number of charge bearing ions given off.

This concentration of potential along a fine edge would appear also to be the chief advantage to applying point to crystal in manner shown in photograph and for same reason.
CONCLUSIONS
CONCLUSIONS

And now we come to conclusions. Out of all that has preceded, what definite, tangible findings can be settled upon? Has the investigation attained the object sought? Does one have any better idea of the causes underlying crystal rectification?

A great and diversified mass of data and general considerations has been presented. Out of it all it may not have been easy to tell just what the dominant ideas were, nor what the whole thing meant. We are then, at a stage now where a general sorting-out process may well be taken up — a sorting-out process accompanied by a statement of the conclusions to which the separate findings seem to point.

It seems to the writer that the first and most important thing brought to light is that the disintegration of the molecule of a crystal's surface has a marked effect upon the rectification secured. That is, when the molecule is made to break up under the influence of heat or potential, the resulting ions have a most important action in determining the amount and direction of the rectified direct current produced.

It will be remembered how these effects were brought to light in the experimental work performed. Withdrawing the metallic point only a slight distance away from the crystal surface caused the passage of a "spark discharge", which spark discharge by virtue of its disruptive effects and the heat evolved would break up the crystal surface. (See P. 18 and following.) Particles from the strained portion of the crystal would fly up into the spark stream, making it take on more or less the nature of an arc.
Changing the kind of metallic point used in such tests did not seem to make appreciable difference. (See P. 55) In all cases, when the crystal surface was allowed to break up in the manner mentioned, the amount of rectified direct current was greatly increased. (See p. 19, 57) The action pointed, on the whole, to the fact that the ions produced by the breaking up of the crystal under the influence of either heat or disruptive effect of spark (or both) had a great deal to do with the rectifying action going on at the time. The rectified direct current was in the same direction when the instrument was allowed to spark as it had been before on straight contact, indicating that the same actions were going on, but upon a greatly increased scale.

As far as the writer could find in an extensive search, this was a new aspect of crystal rectifier phenomena. No one had ever come across this effect before. All explanations heretofore evolved for the action of crystal rectifiers had never had this phenomenon to take into account. To judge by the marked effects produced, the action was of the utmost importance to the whole basic actions going on during rectification.

To what then, would this seem to point as a probable explanation for rectification phenomena?

From one such phenomenon alone, it seemed to the writer that one was not justified in drawing any general conclusions. But after consulting the material listed in the bibliography to this paper, and comparing and cross-comparing results in the light of this apparently new discovery it seemed they all seemed to follow a
general law — which law, though different in a considerable measure from those in existence on the subject, would seem a very tenable explanation for the action going on during crystal rectification.

It has been said that the crystal appeared to break up and go into the arc stream — the point remained cool and unaltered. Evidently, then, one had an arc stream being supplied from but one side only. Plainly indicated also, was the fact that one or other of the ions into which the molecules of the crystal's surface broke up was of predominating nature.

A characteristic of ions is that they carry charges. Did it not seem probable then, that in crystal rectification one always had a stream of ions, or other charged particles, emanating from one electrode, the crystal? That of all the ions into which the crystal molecules split up, some one kind were of predominating nature; that is, had the largest charge and store of energy? That these of a predominating nature carried most of the charges across the spark gap that got across at all? That under an alternating current, one half of each wave could travel across the gap with these predominating ions, and the other could not, due to the fact that it opposed the charges naturally possessed by the predominating ions? Or, again, possibly due to the fact that there were little or no charged ions being emitted from the inert metallic electrode at all which could carry these halves of the waves across? Allowing one half of the wave to get across, and the other not, of course produced the rectified direct current in the usual manner with all rectifiers.
There were many evidences in favor of such a theory. In fact, the action seemed to be very like that in ordinary arc-light rectification. Even though the action and effects there present are none too well known, they were far more tangible than the ordinary run of crystal rectifier phenomena. Reading the articles and commentaries on P. 131, 132 here would seem to give strong evidences that previously-known arc phenomena were strangely like that just brought to light with crystal rectifiers, and that they all appeared to work on a common principle.

And then, too, when one took two crystals of the same substance and put them close together, or in contact, the rectification almost ceased. If one put a soft, good-conducting mineral in place of the usual metallic point with the ordinary rectifier, and then allowed the arc to start, the rectification almost stopped, or went in a reversed direction. To what things did these actions point?

One aspect seemed to be brought out very strongly by these things, together with a joint study of analogous cases in the bibliography. (See P. 127, 120 for such cases). That was, that when both electrodes were allowed to enter markedly into the reaction, the rectification was very likely to cease. One could not have both electrodes giving off predominating ions at the same time, and still cause the thing to have a rectifying action. If he did, the ions from each crystal would carry its half of the wave — both halves would get across, there would be no throttling effect, and no keeping back one half of the wave which is so necessary to rectification. Therefore, it seemed to be pretty
well established that one of the reasons a crystal detector was such a good rectifier under ordinary conditions was due to the fact that only the crystal could enter the reaction. The point could not part with its ions under ordinary potentials or heating effects, and the crystal could. Since the ions from the crystal had undisputed sway, they could do all the carrying in whichever way they chose. The main thing the metallic point did was to convey alternating current up to the point of rectification in sufficient quantities.

The title to this thesis is "Crystal Rectifiers and The Electron Theory". As was explained in the summary given at the beginning of this article, such a title was chosen in the interests of terseness, and out of consideration of the fact that electronic theories had been proposed for the action, but not supported by much evidence. The terminating object of the thesis was, then, to consider the evidences accrued as favoring, or not favoring, an electronic hypothesis of crystal rectification. Most every other phenomenon in physics or electrical engineering had been well explained in terms of the electron theory. Would it work out that crystal rectification, also, could be explained in such terms?

As mentioned above, one or two men of high professional attainments have proposed electronic theories of crystal rectification. (See p.137 and 143 here for a consideration of these theories.) However, these theories were only tentatively proposed, and would seem to be lacking in many things. In some ways the evidences secured in the work here performed
would seem to bear out these theories; in others, they
would not.

In the explanation just preceding (P. 60), the
writer used the term "ions", and considered that the
crystal molecules broke up into ions upon disintegrat-
ing. This would appear to be the action when under such
strong potential as was used in the testing methods
here evolved. Heating effects accompanying the passage
of sparks were strong enough enough to produce a con-
siderable melting of the crystal immediately under the
point of contact, resulting in the "craters" shown.
(See P. 60) Inspection of the figure on P. 60 shows
that the disruptive effect of the spark, and attendant
heating effects were strong enough to draw whole areas
out from the crystal surfaces as evidenced by the
pitted areas shown. Certainly something larger than
electrons were entering into this reaction. Perhaps
even molecules, let alone ions, might have entered
into these reactions to a considerable extent.

As has just been said, ions or similar charge-
bearers seemed to do most of the current-carrying with
the instruments and mode of test used in this investi-
gation. But with the weak potentials actually used in
real radiotelegraphic work, it would seem that genuine:
electronic actions do enter in, and that there might
be a good deal in the proposals of Messrs. Pierce
and Fleming, though perhaps not in the exact way that
they respectively outline.

To the writer it would seem that an electronic
explanation, if such be made, should be based upon the
probable varying powers various substances have to give
off electrons, not on the properties of the medium which may separate the two electrodes, as proposed by Pierce (See P. 142). Nor would he think Prof. Fleming's idea as proposed on P. 135 to be entirely correct. The exact differences are taken up in the commentary to that article (P. 137).

But the essence of the electronic idea would appear to be correct. This is in contradistinction to all the other explanations for rectifying action which have been evolved, and which had nothing to do with electrons.

It may be well here to take up some of these explanations, just for curiosity's sake, if nothing else. A theory of rectification proposed by Dr. W.H. Eccle's has received considerable attention from the English technical press, though not recently. His idea seems to be that the passage of oscillations across the terminals of a crystal rectifier, set up very small heating effects at the point of contact. These heating effects so alter the resistance of the auxiliary circuit containing the telephone receiver and battery (which are in series with the detector, the whole forming a closed circuit) that changes in current going to receiver are brought about, the changes causing the receiver to respond with an audible sound. Another (P. 66, Vol. 69 Electrician) explains rectification as sort of diffractive effect.

Thermo-electric explanations have been put forth a number of times, but the work of Prof. Pierce of Harvard University (See P. 141 here) and of others (See P. 165) would seem to settle the fact that thermo-electric
effects and the like, do not have especially to do with rectification, except that they may add to, or detract from other, and more dominating, effects.

Duddell at one time suggested that the action might be due to "compressions resulting from electrostatic attractions." Evidently he had some sort of idea in mind that the point might vibrate in synchronism with one half of the impressed alternating current wave -- causing synchronous contacts upon the crystal, and the cutting in of but one half of a wave all the time, thus giving a pulsating current -- the whole thing being dependent upon electrostatic attraction between point and crystal. The idea was only tentatively suggested at the time, and of course had little experimental proof, and none has appeared since. The principle objection to it is that the weight of the parts involved is too great for such action to occur with the currents ordinarily used. They would not be powerful enough to produce sufficient "electrostatic attractions". Dr. Duddell's idea is interesting, though, for its contribution to the general variety on the subject. Sutton (Electrician, Dec. 16, 1910) had something the same idea apparently, when he suggested a similar action -- due however to "increases in mechanical pressures at contact through thermal expansions produced by the current. Compares action to "Trevelyan rocker effect". Idea seems however, to have had little or no experimental proof since the time considered and was not fundamental.

Suggestions have also been made that the action might be due to capacity effects within material of crystal itself. That is, the separate crystal layers
might act as surfaces in a condenser, and possess a
natural (electrical) frequency of their own. Impress-
ing an alternating current upon such crystals might
produce beats in the current, due to this natural freq-
ularity, the interaction creating a current which went predominately
in one direction, thus giving a "rectified" current
as a result. However, rectification phenomena have
been determined to take place almost wholly at the
point of contact. (See P. A here.) Such a condition
would preclude any action taking place within the crystal,
such as would be necessary with the capacity effects
upon which the explanation was based.

The main trouble with most of these explanations
is that they are not basic enough, even if, in the
case of one or two, it might appear there was something
in the ideas advanced. Still other experimenters have
laid rectification to such vague things as "heating
effects", "rectifying layers", and the like. But such
explanations are of course not very illuminating, nor
satisfactory in general.

This thesis, then, has shown that there is
a great deal to support an electronic, or at least
an ionic, theory of crystal rectification. Heretofore
there have been on the one side all these heterogenous
and mixed-up theories of rectification, with little or
no basis in fact and no inter-relation. On the other
side are the two electronic ideas set forth by
Fleming and Pierce, and these appear to be no more:
than tentative suggestions. If this investigation
has done something toward clarifying the subject, and
coordinating all the ideas into an explanation which
will encompass them all, it may have accomplished a
little, at least, of value.
IN CONCLUSION the writer would like to present for consideration some general principles of rectification which would seem to set forth the known facts about the phenomenon. The principles follow:

(I) Any two electrodes, in contact or not in contact, will rectify an alternating current if certain conditions be fulfilled. These conditions are:
   
   A. The electrodes must be better conductors than the surrounding atmosphere or gas, or else most of the effects produced will be due to that medium, and will in general be weak. See article on P. 121 here for ideas on this subject.

   B. The impressed potential must be strong enough to get past the resistance of the electrodes (whatever they may happen to be) and deliver sufficient current at the point of contact for rectifying activity among ions and electrons to start.

   C. One or other of the electrodes must be at a disadvantage in some way, electrically speaking.
      1. This may be due to the better native ability one electrode may have to give off ions or electrons than the other. See P. 118.
      2. The difference in size of the two electrodes may produce the inequality. See P. 132, 129.
      3. Difference in temperature between the two electrodes may cause ionic or electronic travel to predominate in one direction, facilitating rectification. See P. 131 here.
      4. A current of air or gas may help in the advantage one electrode has over the other. See P. 126 here.

   Many other points about rectification will be evident from an inspection of the numerous articles abstracted in the appendix to this paper. P. 97 and following.
ON ACCOMPLISHMENTS

The observations on crystal rectification just made may seem to have come to rather an abrupt ending. The significance of the whole thesis may yet seem more or less uncertain — and that, perhaps, is the point we are most interested in at this stage. Wrapped up, as we have just been, in the technical end accompanying conclusions, we may have lost in a way a perspective as to accomplishments of the whole undertaking. For the sake of clarifying ideas on this subject, the following observations are appended:

1. Perhaps the most note-worthy results are those on the technical side of the thesis. By the conception and utilization of two new and different testing methods (the high-tension current and the microscope idea mentioned on P. 10 and following) an entirely new effect in crystal rectification has been brought to light and more or less efficiently studied. Heretofore, crystal detectors have been the subject of much speculation (P. 72 and following), and little work connecting their action up with other known phenomena has been done. By securing the "spark effects" (P. 18) with the new type of testing current employed, and by studying these effects in detail with a compound microscope, an explanation of crystal rectification (P. 68 and following) has been evolved which would appear to successfully explain all the phenomena that experimenters have yet noted about crystal rectification.
2. To be more certain of the conclusions arrived at, and as to the status of the whole investigation, emphasis has been placed upon the collection and analysis of all available literature possible on the subject, whether published in this country or abroad. To do this, the articles were not cursorily assembled from one or two miscellaneous indexes, but were obtained from a week-by-week study of journal reviews which have appeared during the last ten years. Some two dozen books bearing on the topic have been reviewed.

3. By thus working out a theoretical basis for the actions going on in crystal rectification, the way is somewhat more plain for the evolution of a better type of crystal detector. Some theoretical basis for procedure in tests is laid down, in distinction to the testing methods now most used -- which seem to consist mostly of aimless trying of one substance against another in the hope that a better combination than those now in use may appear.

4. A study of crystal rectifiers has been of importance practically because of the great use made of the devices in radiotelegraphy. (See P. 4). Much used though they are, the devices have been but little understood, and their actions have been thought to be based upon phenomena wholly unconnected with other known means of rectifying an alternating current. (See P. 72) By establishing the fact that a crystal rectifier can act in the same way as an arc rectifier, the relation between the two is brought out, and the point proven that crystal rectifiers are not things apart nor occult in operation.
Besides being of great value to the radiotelegraphic field, the device known as a rectifier promises to be much used in other fields of electrical engineering in the near future. (See P. 6) Hence, by establishing the fact that crystal rectifiers operate in the same way as other rectifiers, a small contribution may have been made to the coming knowledge of rectification.

The remainder of this paper is given over to an appendix, wherein a wiring diagram, list of apparatus used, and the bibliography are given. The last named consists of a review and analysis of a great many magazines and books bearing upon the subject. To the reader interested in seeing how the theory evolved would be applied to the work others have done, an intimate inspection of the articles quoted in full and the commentaries made thereon, may be of interest. To the reader not so interested, it may be said that the essence of the undertaking has been given in the foregoing, and he will have gotten the gist of the subject if he cares to go no further.
As a finale to all of the preceding, the writer would like to make a few general observations. In preparing a work of this kind, the investigator is left pretty much to his own devices, and such general ideas as he may evolve, have of necessity, to result from his own initiative. Therefore, a brief commentary on the ideas the writer had in this thesis may not be without interest at this point.

There is, without doubt, a certain amateurish note running through the entire article as here presented. The writer does not know that the scheme of things here evolved has been the best. To get some idea of what should constitute a college thesis, a search was made for the ideas practicing engineers, as well as educators, might have on the subject. Though each have without doubt plenty of ideas, few seem to have given written expression thereto. A few articles have appeared in the back numbers of the Society for the Promotion of Engineering Education, and once in a while a consulting engineer will "write a letter to the editor" of other magazines on the subject, and occasionally these officials themselves feel moved to make a few observations. But in general the ideas of the profession on college theses seem rather difficult to get at.

The disposition, more than infrequently, seems to be to regard the undergraduate's thesis with more or less indulgence, and without doubt, rightly so. Though by some mischance or other, he may stumble onto something of value to the profession as a whole, the chances in general are against him — his outlook upon the profession has been to limited, and his general judgment not well enough developed.
These things are without doubt true. So in presenting the subject as the writer has in the foregoing, he is far from sure that he has chosen the best method. It appeared that if the work were to have any value at all, it should be properly placed in perspective with the work others have done before, that the testing methods decided upon should not be such as to retrace ground that had already been well covered, and that the whole subject should so be set forth as to be comprehensible to most any sort of engineer without too much exertion. But as to whether these things have been attained, or indeed, as to whether they would be considered the right premises to the getting up of any thesis, the writer is not so sure.

It may seem hard to follow the conclusions given, and to get the idea in all of the experimental work that has been presented. The many references quoted may seem to mix up, rather than clarify the idea as it was intended to be set forth. The writer does not know. He would like, above all, to let the thing lie a month or two before turning it in, and then revise the thing with a freshened mind and somewhat the perspective that an outsider would have. But time limitations forbid. The subject is a perverse one to write up, the details unruly and hard to get into alignment, but if in the article as here presented the reader has obtained some glimmering idea of the intentions in mind, the writer will have to content himself. Still another going over would, without doubt, result in considerable improvement in presentation, but if even this write-up has some of the elements of clarity, thoroughness, and a glimmering of good sense, the thing will have to be let lie.
APPENDIX
LIST OF APPARATUS USED IN EXPERIMENTS PERFORMED, AND A WIRING DIAGRAM OF CONNECTIONS
APPARATUS USED IN THE INVESTIGATION

GALVANOMETER

Leeds & Northrup make. # 24229. Picture of same is shown at "G" on page 28. Was of the D'Arsonval moving coil type, and would naturally therefore respond only to direct current — which was exactly the end desired.

MICROSCOPE:

Made by Gunlach Optical Co, Rochester, N.Y.
Had a 2/3 and 1" objective, and a 1" eyepiece.
Rated in catalogue as giving 60 and 100 diameters magnifying power with the two objectives. Picture of the microscope is given on p. 28, 29, 29.

RECEIVER

Western Electric "70" with headband. See p. 28 for picture.

LOOSE COUPLER:

Murdoch. Primary had a single slider, and the secondary a six-point switch for tuning. See p. 28.

INDUCTANCE "L" (See P. 29 for Picture)

Coil was about 6" in diameter and 12" high.
Had 17 turns # 12 Al wire.

CAPACITY "C" (See P. 29 for picture)

Made by Electro-Importing Co. A sliding-rod switch on top permitted 9 variations in amount of capacity to be made.

INDUCTION COIL: See p. 29.

Rated at 1" spark on 6 volts. Was operated on that potential all during tests. Used 3-cell storage battery as source.
Circuits Used

Symbols

○ Receiver  ▲ Variable Capacity  ▲ Spark Gap
▲ Detector, or Rectifier
BIBLIOGRAPHY

I.

ABSTRACTS OF ARTICLES ON CRYSTAL RECTIFIERS AND ALLIED SUBJECTS WHICH HAVE APPEARED IN TECHNICAL JOURNALS AND MAGAZINES DURING THE LAST TEN YEARS

II.

REVIEW OF BOOKS WHICH HAVE A BEARING UPON THE INVESTIGATION
IN EXPLANATION OF THE BIBLIOGRAPHY

In presenting the following bibliography, a few words of introduction and explanation are first given.

The bibliography as here presented is divided into two parts, one a review of the journal and magazine articles which have appeared on the subject, and the other a consideration of the books of direct or indirect bearing upon the material handled. The object in either case has been to present as complete a resume of the material available as possible.

The desire for completeness has been due to the belief that no article on a technical subject is adequate without such type of thorough bibliography. It has not been believed to be enough to merely look through one lone index to current literature, as for instance: "Science Abstracts", and to note down articles which, to judge by their titles, may have some bearing upon the subject under investigation. Nor has it been considered sufficient to look through a year or two's back files of one's favorite journal, and consider that an adequate search for, and study of, previous work that has appeared.

It seemed to the writer that such procedure would neither be comprehensive nor thorough enough. Too often, it would seem, are bibliographies compiled in this way. In an experience of some two year's duration in the care of a technical library of considerable size, the writer has found that the average investigator has small idea of the material available on any given subject. His ideas seem usually to extend to a comprehension of "Science Abstracts", or the "Engineering Index", and when he has looked through one or two volumes of these in a search for material, the matter is dropped from further consideration. It does not seem possible to him that any other
article of consequence could be listed elsewhere, or even if such an article were so listed, it appears to him to be out beyond the "point of diminishing returns" in the searching line, and he gives the thing up.

As a matter of fact, "Science Abstracts", the "Engineering Index", and the "Industrial Arts" index, and all such, are totally inadequate when it comes to a thorough resume of the worth-while articles that have appeared upon a given subject. Take it with a subject such as crystal rectifiers, about which little has appeared, the inadequacy of such indexes becomes all the more marked. Taking in a wide range of science and engineering as these indices do, and standard though they are, they cannot help but miss a great deal of importance upon a given subject. Space-requirements alone would preclude that, if nothing else did. So it seems to the writer that an investigator, in depending upon such indices, as a great many do, he is not getting at the real core of valuable material to be had upon a given subject. Sometimes an investigator does not even make good use of the indexes—merely notes down articles from an index, never looks them up, and judges merely by the meaning conferred in their titles that they are fit material to be listed in a bibliography on the subject. Such practice and such methods, are of course of dubious value as far as genuine results to be attained are concerned.

To the writer it seemed that the only real way in which adequate reference material could be obtained from journal literature published on the subject, was to go through the bound volumes of two or three of the leading engineering journals -- volume by volume -- and use the articles which are to be found there. The journals chosen for this investigation were "The Electrical World", an American journal in the electrical field and too well known to need extended description, and the "Electrician", a similar leading electrical journal published in England.
Both these journals make a practice of running, week by week, abstracts of the principal articles of value which appear in current scientific and professional journals. They do not confine themselves to any limited group of periodicals, but embrace the whole field. The "Electrician", being especially close to French and German journals, lists regularly translations and briefs of their articles. The electrical World at the same time covers much the same field, but from the American viewpoint. Between the two one gets a command over the whole range of material that has appeared in most any language on the subject at hand.

The crystal rectifier was invented, or discovered, in the year 1906. Previous to that time, the device had not been applied to radiotelegraphy, or to any other science. Consequently, little material of any bearing on the subject of crystal rectification appears before that time. Accordingly, in going through bound volumes of the "Electrician" and the "Electrical World" those dated 1905 or 1906 were used as a starting point.

In the "Electrical World" and in the "Electrician", most of the material to be found on crystal rectifiers appears in the indices under the following heads—"Wireless Telegraphy", "Radiotelegraphy", "Detectors", "Rectifiers", and "Coherers". Hence these two journals were gone through with volume by volume, and the articles listed under the heads just named inspected, and some of them copied. The two journals have together issued about 40 volumes since 1906, so the work involved was considerable. A list of material to be found in each journal is given in this paper, beginning P. 89 and P. 91.

As a result of this method of compiling a bibliography, it will be noted that a most comprehensive review of the whole field has been obtained. English translations of the material which has appeared in France and Germany are listed, as well as extensive reviews and abstracts of articles appearing in American and English scientific journals.
This method, then, of going through volume by volume the two leading journals in the field, has given a short cut to a thorough resume of material to be had on the crystal rectifier -- whether the articles happened to appear originally in some obscure scientific journal in English, or whether some French or German periodical were the first publishers. "Science Abstracts", or the "Engineering Index", or any other index do not give, nor could give, such an extensive list of material on the subject. It may be said in passing, however, that all of these indices have been thoroughly consulted and all available articles there listed, looked up. Some were already included in the list made up from the World and "Electrician" however, and needed no further cataloguing or explaining.

It is worthy of note that the amount of material available on crystal rectifiers, even after this extended search, is comparatively small. Nowhere near the amount is available as can be had on such common subjects as "power-house", or "dynamo" design, or on "transmission line phenomena", or the like. The references and abstracts listed on the succeeding pages give practically all the material which is available in any language.

Reference to original sources is made easy in the case of any given article listed. Just preceding it is a short paragraph giving the volume number, the page, the date of issue, and any other information at hand, so that from some part of the data at least the original can easily be located.

The value of a good bibliography on a subject is of course well appreciated by all investigators. By a thorough study of previous work, one gets to know the paths over which others have traveled, the results they have secured, and the probable comparative value of these results.
After listing in regular order the material given by the Electrical World and the Electricalian, some of the articles and abstracts named are copied in full on the succeeding pages. Following each article copied is a commentary by the writer, explaining as well as may be the results the different investigators mention—the explanations being in terms of the theory which this paper advocates. By this means a more adequate idea of the theory proposed is obtained, as well as an apparent confirmation of the points it upholds. It appears to be almost impossible to get within such brief consideration as is given on P. 68 and following all points of a theory. This commentary on articles in bibliography then, forms an extension of the remarks given on P. 68 to 74. In addition, this going through the results of others and explaining them, provides a confirmation and check upon the theory proposed.
I.

REVIEW OF THE MAGAZINES AND ENGINEERING JOURNALS.

ALSO A LIST AND ANALYSIS OF A NUMBER OF ARTICLES FROM SCIENTIFIC PERIODICALS PUBLISHED IN THIS COUNTRY AND EUROPE.
NOTES ON MATERIAL IN ELECTRICIAN (LONDON)
From 1905 to the Present

Vol. 56 for 1905-06 Nothing of particular value
Vol. 57 for 1906 and no consideration of Cryst. rect.

Vol. 57 for 1907 Mentions in one or two places that Si
and carborundum had been discovered
to be good detectors. Nothing espec-
ially worth mention.

Vol. 59 for 1907 Abstract of article by L.W. Austin
in Phys. Revw. for 1907 (June). Title
of art. is "High Resistance Contact
Thermo-electric Detectors for Elec.
Waves." Uses a tellurium contact
against a large number of others.

Vol. 60 for 1907-08 But few mentions and these are
better given in Elec. World about
same time. See Elec. World abstracts.

Vol. 61 for 1908 Nothing of particular value mentioned.

Vols. 62 and 63 have not been acquired by the engin-
eering library of the university, and
probably contained little of value
anyway, as detectors had been too
recently discovered.

Vol. 64 for 1909-10 Wellisch P. 736 See P. 121 here
Flowers P. 760 See P. 48 here
Pierce discusses molybdenum and
pyrite / 425 and 718. Practically
same as is contained in his book. See
review P. 141 here.

Sutton & Eccles P. 384. See P. 72 here.
Also: Elec. World Abstract P.

Vol. 67 for 1911 Nothing in particular. See P.
Vol. 68 for 1911-12 Nothing in particular. See P. here.


Vols. 70-71-72 from 1912 to first part of 1914 contain little of value here.

Vol. 74 for 1914-15 P. 326 has article of some importance by A.E. Flowers. See P. 109 here.
NOTES ON MATERIAL IN ELECTRICAL WORLD (U.S.)
From 1906 to the present.

Vol. 48 - 1906 "Carborundum as Wireless Telegraph Receiver" H.J.Round -- P 370

Elemental. Announces the fact that Carborundum is a good detector; that "writer's attention has been called to the fact", but does not know who has discovered the property.

P. 994 - "Carborundum Wireless Detectors" by Greenleaf W. Pickard. Says Gen. H.H.Dunwoody of American DeForest Wireless Telegraph Co, has lately developed this detector. Pickard "has been experimenting" to determine best form of detector to use. Found that crystal operates best when "clamped edgewise between two flat copper terminals." Finds use of potentiometer a good thing, and that crystal works best when "good electrical contact is obtained along edge". "Flat surfaces possess but little conductivity." "Writer is of opinion that many so-called comparative tests of wireless detectors are valueless" account all of them do not use the same, nor standard, methods of producing the oscillatory current.

Vol. 49 - 1907 "Note on Carborundum" - H.J.Round

Gets a light at point of contact, the color of which varied widely. In all cases glow came from negative pole. (#Probably the same phenomenon as heating up of two carbons when starting an ordinary arc-light, though with the electrodes and only the 110 volt potential he was using, a regular arc probably could not be drawn.)
Principle is as follows: If two metals standing far apart in the thermo-electric series be so brought in contact that their contact resistance is sufficiently high, and if the surfaces of the metal are of such nature that heat is not conducted away too rapidly from the point of contact, then the passage of electric oscillations through the junction will produce direct current which may be detected by a galvanometer or receiver in series with the thermo-element. As a pair of materials suitable for the purpose, tellurium and aluminum are mentioned. Silicon may be substituted for aluminum. This sort of detector compares favorably with the electrolytic type."

P 843 — "Wireless Telegraph Receiver"
"Three patents recently issued to Dr. DeForest disclose additional means for detecting oscillations by means of a telephone". Oscillations are made to vary conductivity of a gas maintained in a condition of intense molecular and ionic activity, and having associated and conducting ions. One method was to attach one electrode to a Bunsen burner and hold the other in flame. Gas circuit from relatively cool burner to the electrode in the flame had "asymmetric conductivity" and would therefore rectify.

P 314 records fact that Maj. H.C. Dunwoody patents "loadstone" as a detector.
Vol. 51 - 1908

P. 354 "Flames as Rectifiers" See P. 26 here.
P. 613 " " " " P. 128 "

P. 423 - Mentions patents to G.W. Pierce on rectifiers making use of asymmetrical conductivity of carborundum, oxide of titanium, and telluride of Ag.

P. 147 - Letter from L.W. Austin of Bureau of Standards. Says he has discovered that "Silicon has remarkable unilateral conductivity". "From present evidence, seems that operation is probably a surface phenomena, since it depends so much on position and pressure of contact. When point and Si are well pressed together, the phenomenon practically disappears. (#Note: similarity between the action here mentioned, and the way the excessive rectification mentioned on P. 67 disappeared upon making a thoroughly good contact. ) Says action cannot be thermo-electric account thermo-electric currents are often in reverse direction when joint is heated. Disagrees with G.W. Pickard's patent specification which declares action to be thermo-electric.

P. 1371 L.H. Walter exhibits before Royal Soc. a good detector made of a tantalum point dipped in mercury.

Vol. 52 - 1908

P. 755 - Oct. 3d, 1908

L.W. Austin on Contact Rectifiers. Is extension of previous aluminum-tellurium work. Finds that Si against almost any ordinary metal, carbon against steel, and tellurium against Aluminum, are good detectors. In investigating he uses a D.C. 110 volt current which he reverses at will. Also has a 60 cycle A.C. on hand. Uses a potentiometer to step off voltage desired. In all
cases results go to show that there is a resisting film between conductors. Believes action one due to heat, not to thermo-electric currents.

P. 913 Rectifying effect A.C. arc - J. Sahulka
See P. 131 here.

P. 33 Lieut. ComW. H. G. Fullard U.S.N. describes how an incandescent lamp filled part full with 20% nitric acid can be made to act as a detector. Is electrolytic, and utilizes Pt terminals within lamp for electrodes.

Vol. 53 - 1909


Vol. 54 - 1909

P. 1301 Rvw of A. E. Flowers on Cryst. Rect. Same article is reviewed P. 130 here.

P. 1401 - Editorial states that A. E. Flowers in Phys. Review reaches conclusion that rectification is probably due to electrochemical formation of high resistance film at each alternate reversal of current.

Vol. 54 - 1910

P. 1234 L. W. Thomas gives a discussion of detectors. Not particularly different or new.

Vol. 55 - 1910

Vol. 56 - 1911

P. 1376 - Eccles - Detectors for Wireless Teleg.
Concludes possibly all detectors are fundamentally thermal in action.

Vol. 57 - P. 325

S.M. Powell thinks classifying detectors according to "sensibility" is of little value. Rather he would classify them according to automatic decoherence, adjustibility, tuning, quick acting, sensivity, resist- ance, external effects (vibration and field), ease of construction, and of procuring material.

P 66 - Eccles and Sutton on Trevelyan rocker effects. See P. 73 here.

Vol. 58 - 1911

P. 1602 "Operation of Detectors in Wireless Telegraph Service". Sensitiveness of contact detectors as function of contact pressure. Develops nothing remarkable. A good history of detector development is given in editorial P. 1579.

Vol. 59 - 1912

Nothing especial.

Vol. 60 - 1912


Vol. 61 - 1913.


Vol. 62 - 1913

P. 200 Eccles June 27, 1913. See P. 72 here.
P. 861 Eccles with a new theory. See P. 72 here.
Vol. 63 - 1914


Vol. 64 - 1914.

P 1051 Peter Cooper Hewitt on new form of Oscillator. Mentioned more in detail P. 6, this paper.
CRYSTAL AND SOLID CONTACT RECTIFIERS

A. E. Flowers

A short time ago there appeared an account of tests made by G. W. Pierce on a number of crystal rectifiers; viz., anatase, brookite, and molybdenite. No definite and final conclusions were drawn however, as to the cause of the phenomenon. To determine if possible the cause of the action a series of experiments was carried out by the present author. It seemed that the first and most important thing to do was to find a rectifier of large current-carrying capacity, as the rectifiers previously described were capable of carrying at the most but a few milli-amperes of rectified current. Believing that high resistance was not necessary, the crystals having high conductivity were selected for study. The sulphides appear to be particularly high in conductivity, and iron, lead, and zinc sulphides were tried for current carrying capacity and rectifying properties. Of these, lead sulphide (galena) has by far the highest conductivity, and it showed in several samples very appreciable rectification, single crystals showing sometimes 150 to 200 milli-amperes of
rectified direct current with a 3 volt (effective) alternating current supply. The crystals studied appeared to rectify about half the alternating current. It will be well to emphasize the fact that different samples and different places on the same sample give widely varying results. Samples of molybdenite examined required roughly a 31 volt effective alternating current supply to give 20 to 30 milli-amperes of rectified direct current, and in such cases the a.c. ammeter indicated sometimes 500 or more milli-amperes.

(# Here he mentions using a row of detectors hooked up in parallel, object being to get "larger capacity." Detectors consist of the usual point-and-crystal type, the crystals being set in a long metal trough filled with soft solder "to make absolutely certain contact with the body of crystal." Concludes that "galena was the most promising material among crystals to study in order to find out the characteristics and causes of rectification. "points used in above detector were made of sharpened Cu wires.)

Characteristics of the Galena Rectifier --

In order to analyse the action of the crystal it seemed best to try the effects on a direct E.M.F. A large number of observations were made on different crystals (# Gets a series of volt-amp curves resembling those of Pierce) As to results most important thing was
that they showed definite point at which breakdown occurs which varies with each crystal and setting, and attains a higher value the smaller the current. Breakdown may be made to occur at higher value by breaking current at partial failure and allowing crystal to recover, then applying current again. If current flows too long after breakdown permanent destruction of rectifying properties will result. Considerable currents can be passed from crystal to point without destroying these properties, however. Breakdown seems to be due to the heat produced.

Fact that the reactions are taking place at the surface or in a thin surface film is shown strikingly by measuring the potential difference between Cu point and the surface of the crystal near the point. It is found that practically the whole E.M.F. impressed on the rectifier is required for the potential difference between the copper point and the crystal.

Having found a crystal, author next investigated whether the effects were in any way dependent upon the material of the point used. Volt-ampere characteristics were taken with points of Cu, steel, platinum, lead, zinc, aluminum, brass, solder, and graphite. Characteristics were similar to those illustrated above (# Pierce curves,) and apparently the material of the point


made no difference in the rectification.

Rectification also did not seem to be effected in any way by change in shape of point. Even the substitution of a globule of mercury about 3 mm. in diameter, or of melted lead dropped on the crystal surface and allowed to harden in place so that it made intimate contact with a large surface, gave good rectification. Finally a crystal was selected which showed good rectifying properties. This was mounted in a lead setting and the crystal cut down to a point. When a good rectifying surface has been found, the point may be pressed against it with considerable force without impairing the rectification, and with a great increase in conductivity (in both directions) It was found that a moderate pressure (about 200 g) was sufficient to give steady contact, and in most cases this was the pressure used. A crystal having a rectifying surface was often found to have other rectifying surfaces underneath and parallel when the layers were split off, but scratching or scarring a rectifying surface usually spoiled more or less completely its rectifying properties.

No attempt had hitherto been made to determine the relation between rectification and frequency. A rectifier consisting of a Cu-point-galena-galvanometer-telephone-receiver series arrangement was set up. Speaking into the receiver caused large deflections of the gal-
vanometer, and loud continued vowel sounds would throw the galvanometer off the scale so that the rectified current must have exceeded 7 micro-amperes.

To investigate the effect of electrical discharges, a crystal was mounted and connected to a storage battery. It was found that a static discharge could be passed continuously thru rectifier in either direction without effecting the conductivity of the rectifier or its rectifying properties, whether the rectifier were connected or disconnected from the battery. However, it was found that if the static discharge produced a spark anywhere in its path, the effect for static discharge or any connection of battery is to increase the conductivity in any direction, and to spoil the rectifying property.

The determination of the effect of heat is complicated by the fact that the current that flows when the determination is being made may cause local heating and so intensify and mask the general effect. There may be also electrochemical effects. In general, however, breakdown occurs at lower voltage with an increase of temperature, but the direction is greater for the direction of least conductivity so that the per cent of rectification decreases with increase of temperature. Rectification disappears at a temperature of about 270° C, but is partially regained on cooling, though the parts
of the crystal which carried no current are apparently not affected by heating to 270°C or 280°C under oil and then cooling. It is worth noting that even at 280°C there is a tendency for the current if from point to crystal to decrease, and if from crystal to point to increase, if the current is allowed to flow. It is especially significant that the rectifying property is not entirely destroyed by the continued passage of current in either direction while cooling under oil from this temperature, though the rectification is best when the current is allowed to flow from point to crystal.

Artificial Production of Solid Contact Rectifiers --

An attempt was made to produce rectification in samples of galena that did not rectify naturally by subjecting the crystal to the action of various chemicals. Water and the conducting solutions and acids tried (i.e., nitric acid, alcohol, potassium bichromate), if put on the crystal while the crystal was carrying current usually increased the conductivity, caused breakdown, and spoiled rectification; although such results did not occur when the chemical treatment was not coincident with passage of current. The non-conducting acids and solutions tried (i.e., conc. H₂SO₄, CS₂ and oils) seemed to have little effect.

The copper point was then covered with burning sulphur, the flame blown out and the remaining sul-
phur cooled quickly so that it was left in the amorphous state. A point so treated when set on a galena crystal surface that previously showed no rectifying properties would at first show little conductivity, but the passage of current first in one direction and then in the other produced in a few minutes a fair degree of rectification but in the opposite direction to that found in native crystals. The treatment of a crystal with amorphous sulphur that previously had possessed no rectifying properties and then afterward treating the crystal with current produced rectifying properties similar in all respects to the effect obtained when the Cu point was treated. The effect of the electrochemical treatment with amorphous sulphur of the point set on metallic lead or the treatment of the lead surface itself was much more marked.

It is worthy of note that this contact rectifier showed itself far superior in rectifying properties to any of the crystal rectifiers so far tried, its resistance in one direction being 0.3 to 0.4% of the resistance in the other direction. Its breakdown point was reasonably high, and it showed at one point the partial breakdown and immediate re-sealing or self recovery found with the crystal rectifier. The electrochemical sulphur treatment of the Cu point
while the point was in contact with a piece of lead, produced a rectifier whose point could be removed to a block of brass or other metal and be made to exhibit rectifying properties, but the rectifying film had to be produced first in contact with lead. Attempts to produce the rectifying film by electrochemical treatment of a copper point with sulphur while in contact with brass failed to produce definite results, though good results were obtained by setting the Cu point, after being treated with sulphur, on a small block of graphite.

Rectifiers of this type, when perfected might be used in measuring telephone currents and sound intensities, in detecting feeble electric waves and in charging storage batteries.

CONCLUSION:— It is worth while noting that other workers in this field have emphasized the thermoelectric P.D. of the two materials of the contact rectifier or have emphasized the difference in heat and electric conductivity of the two materials. The rectification cannot be due to thermo-electric force, since this has neither the magnitude nor the direction necessary. The rectification cannot be due to difference in conductivity of the two metals in contact, because graphite, which has a higher specific resistance than lead sulphide, could be used for a contact-making point. There are only two possible
explanations: One is that the film, when once formed has inidirectional conductivity. This seems improbable in solids.

The other explanation is that the film is produced in an infinitesimally short length of time by the passage of a minute quantity of electricity. The tendency of the resistance to rise when the current is flowing to the crystal, the direction of highest resistance, and to fall when the current is flowing from the crystal, seems to give color to this view. The sluggishness of change of resistance sometimes observed at high temperatures and with some crystals also tends to strengthen the probability that the rectifying film is re-formed electrochemically with each reversal. If the film is re-formed at each reversal, then there must be a definite quantity of electricity, however small, required for the production of the film, and one should find that the rectification is less perfect for very small currents or for very high frequencies.
COMMENTARY ON FLOWERS' ARTICLE.

A good evidence for the fact that rectification effects are entirely at the surface with crystal rectifiers is given on P.\(^{10}\), thus opposing the idea that the phenomenon may be due to capacity effects within the crystal as was tentatively suggested at the beginning of this investigation.

The writer likewise found, as does Mr. Flowers, P.\(^{10}\), that the material of which the metallic point was made caused little difference in amt rectification. This is another evidence against Eccles' thermal theories, for surely if the effect were due wholly to changes of resistance with heat at point of contact then the materials so making contact would have an important bearing upon the matter of rectification, and the change of one of them ought to produce appreciable effects upon the rectification.

The comment on page \(10\) on effect of changing shape of point would seem in general true, according to such experience as the writer has had, but there would be a limit to the size of contacts possible, depending upon the potential operating across the detector, and the abundance of ions or electrons on the particular crystal's surface as explained on P.\(^{68}\) here.
The first paragraph on P.102 in regard to passage of electrical discharges was same effect that writer got at first and bears upon the difficulty of getting the exact and are to show same effect as ordinary crystal rectification. Mr. Flowers evidently sent too large and ungainly a static discharge through the rectifier to bring out the effects desired.

Next paragraph mentions "breakdown occurs at lower voltages" with increase in temperature; shows that heat aids in process of giving off charge-bearing ions or electrons, and that it does not require so large a potential to get up to the crystal's capacity at giving off such charged particles when heat has already helped out the process.

Curiously enough, the writer at one time during the course of experiment tried identically the same thing as Mr. Flowers mentions on bottom of page 103; that is, poured various chemicals over his crystals, with the idea in mind however, of supplying a thin layer of ions out of the liquid at the point of contact to see what effect that might have. It was found that a thin enough dampening of the crystals could not be made, because at any degree thereof the whole detector operated more as an electroly than anything else, the results as a whole not being especially satisfactory or indicating anything new or different.
The idea that a film can have "unidirectional conductivity" as mentioned at top P 106, is of course a rather broad statement without any explanation as to mechanism upon which such action may be based.

It is evident that Mr. Flowers has the idea that a "rectifying film" can exist at point of contact, but makes no mention as what it may consist of. The writer's idea borders on the "rectifying film" variety, but makes some mention as to what this film may consist of. See P. 68.


Article on page named is an abstract from "Phys. Rev." and essential points only from abstract are given here.

"CHARACTERISTICS OF CRYSTAL RECTIFICATION"

Alan E. Flowers.

Summary at beginning of abstract:

"The author investigates the effect on the rectification ratio, i.e., the ratio of the average to the effective value of the current in the crystal circuit, of various factors, such as contact pressure, room temperature, frequency, current density, size of contact point, etc. The results show that for small currents the rectification ratio is almost independent of the frequency, but with larger currents tends to become greater with higher frequencies. A small contact area improves rectification."

Mr. Flowers' "Summary and Conclusion" as given at end of abstract:
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.

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 certain minimum value for good rectification.

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

End.
COMMENTARY ON
MR. FLOWERS' "CONCLUSIONS" ON THE PRECEDING TWO PAGES.

1. If rectification tends to be greater at high frequency than at low, it seems to the writer that the effect might be due to the greater stress put upon the molecular arrangement by the rapid alternations resulting in more charge-bearing ions or electrons being given off.

2. The fact that rect. tends to disappear at small currents is another evidence of correctness of the charge-bearing ion idea — it seems to the writer. For with small currents, the electric stress on the molecules would be of course proportionately weak — and in the case of a crystal or other substance which gave off electrons or ions only with great difficulty, this stress would not be enough to produce many electrons about the surface of the mineral, and thus the rectifying atmosphere could not exist. "Low current density" is of course a result of the "large contact area" which he mentions, and sheds light on the reason most crystal rectifiers work best with a fine metallic point bearing upon them — the current density is of necessity high at the point, resulting in the forced raising of a rectifying atmosphere of electrons and ions just beneath the point — which current bearers must necessarily come as a rule
from the mineral used, since a complex crystal will ionize easier and to a greater extent than most any metal, particularly if the crystal be a fair electrical conductor and more or less metallic in nature as most all of the good rectifiers are. It is also evident from these considerations why the writer (and also Mr. Flowers) was unable to detect any difference in the rectification effects secured when the same locality on a given crystal were used, but the kind of metallic point bearing on the vicinity were changed — for as stated above, the crystal was apparently the only thing providing the charged ions or electrons, and it would not make particular difference what mineral were used as the point as long as it were good enough conductor not to interfere with concentration of the electric potential at the point. If, however, the point were heated by some agency to a degree where it would give off charged bodies readily, it, too, would enter into the reaction, and produce appreciable effect upon the rectifications secured. This, it seemed to the writer, was the case with arc light rectifiers — as explained on P. 132.

4. Mr. Flowers' conclusion that "even very large contact areas will rectify well with large current"
seems to the writer in a way as but an inverse statement of the proposition he set forth in (2) above. If one has a large current and a large area, the density at any small portion of that area, would of course be the same as if he had only a small current and a small area in the first place — and the resultant stress among the surface molecules of the crystal would be the same — thus producing an equal rectifying atmosphere, and with same impressed voltage, an equal resulting direct current.

Nos. 5 and 6 seem to be closely connected with the ideas that have preceded.

7. This seems to be a natural result dependent primarily upon the charges that a given group of ions could carry. With arc lights the writer found that it was the power delivered by D. C. that was constant, not I or $E$. Introduction of R into ckt would of course cut down I.
CRYSTAL RECTIFIERS AND WAVE DETECTORS

R. H. Goddard

An account of an experimental investigation with reference to the fact that the resistance to the flow of current across the contact of dissimilar solids depends upon the direction of the current and the use of such contacts as rectifiers and electromagnetic wave detectors. A large number of experiments with currents up to nine amperes suggested the necessity of using contacts of as nearly chemically clean surfaces as possible. By means of a glass apparatus that could be evacuated to a Crooks vacuum, it was possible to break or file the ends of the substances and metals in vacuo, and measure the conductances. Proceeding in this way it was found that tellurium and pure silicon lost most all of their power to produce rectification when cleaned as above in vacuo, in hydrogen, in nitrogen, and in carbon dioxide, but behaved in oxygen as in air. Fused silicon and galena gave rectification in vacuo and in all gases; the former always, the latter often. Galena and natural graphite were found uncertain even under ordinary conditions. Copper filings produced and examined in vacuo and hydrogen did not show the anomalies of conduction manifested...
in air and oxygen. Aluminum and magnesium gave uncertain results. Galena powdered in vacuo by filing showed the same anomalies as in air. The experiment with copper filings supports the theory of Eccles, that the deviation from Ohm's law of the coherer is due to turning of the particles due to electrostatic forces, so that the long axes point in the direction of the current. Although Ohm's law was practically obeyed, there were sudden increases in conductance on raising the voltage. There was little evidence of turning however, unless a film of oxide was present, although Hertz waves greatly increased the conductance. From his experiments the author concludes that rectification is of two kinds, "surface" and body rectification, and that the former takes place with pure elements in an active gas, and the latter with impure elements and chemical compounds, irrespective of the gas present. Many experiments with contacts in air carrying large currents, and contacts in vacuo, showed phenomena which suggested that a film of some sort is necessary in order to have rectification. These experiments, together with an oscillogram of a number of silicon-steel rectifiers in parallel indicated that the action of the solid rectifier, is like that of the aluminum valve, or electrolytic rectifier; that is, a film is formed which hinders the motion of certain ions
with this difference, that, in solid rectifiers the film is broken down by heat or sparking, so that some current usually flows in the direction of higher resistance.

END.
COMMENT ON PRECEDING ( R. H. GODDARD ARTICLE.)

This illustrates another point in the hypothesis of crystal rectification as supported by the writer. In a commentary upon a preceding article (P.&Q.) mention was made of the fact that the metal used in a crystal rectifier as the point electrode seemed to be inert — did not contribute materially to the rectifying atmosphere — and that the complex, and easily split up composition of a good crystal was the main source of ion or electron supply to that atmosphere.

It will be noted that when Mr. Goddard found that if he cleaned Te or Si in vacuum, or in H. or N. (inert gases as here used, where Ta or Si could not oxidize) that they each lost practically all of their power to rectify. That is, he had a metal point bearing against a pure element — two elements against one another. Then according to the writer's view, each would have about equal prospects of giving off charged particles, or at least, their giving off charged particles would be more nearly equal than it would be if one of the materials were oxidized, thus providing a surface compound which could split up to provide the one-sided atmosphere necessary for good rectification. Mr. Goddard notes that the elements in the vacuum mentioned, or in a gas not entering readily
into chemical combination with those elements, that the crystals of same lost "all or nearly all of their power to rectify." The writer ventures the opinion that whatever amount they did rectify was due to the difference in materials at the contact. Though both of them were elements, there must have been some difference in their power to give off electrons, or other charged particles, and in proportion to this difference, the current was rectified. Also, that according to the direction of the predominating stream of particles, the current (electronic, not "current" as commonly thought of) went.

It will be further noted that when put the Si or Te in oxygen "they behaved as in air"; that is, must have provided themselves with an oxidized layer at once, which could split up into the one-sided atmosphere necessary. The writer would not have it drawn as a necessary conclusion from all of the foregoing that an oxidized layer is a prime essential to good rectification. Though all crystals used as rectifiers must have some sort of an oxide layer -- since they are out in the air continually -- it does not seem to him that the oxide is the prime essential. The rectification simply lies in the fact that an oxide is a compound which will split up into charged particles easier than the metal of the point will, thereby carrying a stream of particles which go in one direction only, thus carrying the half of the A.C. wave with
it that happens to be going in the same direction. There being no charged particles to provide carriers for the wave going in the other direction it has to stop or seek some other path. Stopping the one half of the wave all the time, and allowing the other to go through provides the "rectified" D. C. current. From these considerations it does not follow of course that an oxide is a compound that would thus split up most easily, nor that it is the only one which will so split up. It would be an interesting thesis to search for that compound which would split up with the most facility and act best toward the end desired. It would at least provide so theoretical basis for the search in contrast to the aimless trying of one thing against another that now goes on.

It will be further noted from Mr. Goddard's results that elements which are all the time coated over with an uncertain film of something or other gave uncertain results. Examples of such minerals are the Galena, graphite, aluminum, mg. etc., that he mentions. In these uncertain films it would naturally be pretty hard to predict which way the direction of predominating ionic travel would be, and hence the direction of rectification.

The reference to "surface and body" rectification, could, it seems to the writer, be interpreted in another way. The "surface" rectification, if it could be
called such, takes place with the oxide layer on a surface; while what he calls "body" rectification is really also on the surface, but takes place in this case in an atmosphere derived from the molecules of the mineral itself. For instance, if one break a piece of pyrite so that a fresh and conchoidal surface is exposed, the crystal makes an excellent rectifier. Here we evidently have a case of what he calls "body" rectification, but which really occurs wholly at the surface. Pyrite is a "compound" such as he mentions, its formula being FeS2.

The writer would interpret the last reference to the "film's" breaking down in the presence of heat or spark and allowing some current to get through both ways to be due to the fact that either one of these agencies (heat or spark) if too strong, would so raise the temp of the point or mineral bearing upon the crystal that it, too, would enter into the reaction and carry some current in the opposite direction — which would certainly appear to check out well with previous theory.
ELECTRICIAN — Vol. 64 - 1909-10 Continued.
Page 937 - Mar. 18th, 1910. Read before Cambridge
Philosophical Society by E. M. Wellisch B.A.

ELECTRIC DETECTOR FOR ELECTROMAGNETIC WAVES.

During a series of experiments with an ionization chamber containing two parallel Aluminum electrodes at a distance from one another of 2 cm., one of the electrodes being connected to a source of potential, and the other to a Dolezak electrometer, it was observed that, when the gaseous pressure and the electric field were so chosen that the gas was on the verge of breaking down, a very feeble discharge from a Röntgen ray bulb placed in the neighborhood was sufficient to produce an exceedingly large deflection of the electrometer needle. Further investigation of this electric charge produced within the gas showed, however, that the determining cause of deflection lay not in the rays issuing from the Röntgen bulb, but in the electric oscillations set up by the electric waves proceeding from the induction coil which worked the bulb.

Several forms of ionization chambers were then used, and each of them proved sensitive as detectors of extraneous electric waves. The accompanying diagram represents the scheme of connections employed in one of the trials.
In this case the detector consists of a glass tube T (about 4 cm. diam); the electrodes were two parallel Aluminum disks (each 2 cm. diam) at a distance apart of 1 cm. The tube was connected to a Topler mercury pump and a MacLeod gage so that the press of the gas (dry air) could be adjusted and measured.

In the diagram, B represents the battery, one of whose poles is earthed; E the electrometer; R, a high resistance consisting of a conducting glass shunted across the electrometer; C, a variable condenser; and L, a variable self induction. Object of the high resistance R was to cause the needle to return quickly to its zero so that any succeeding impulse might readily be detected.

Effect of extraneous electric impulse is probably to set up electric oscillations in the circuit including the vacuum tube; the electric force in these oscillations when superposed on the electric field in the tube may then suffice to produce a discharge in the gas. It is important to notice that this discharge need not be, and in most cases investigated was not, luminous; its occurrence is manifested merely by the galvanometer...
or electrometer deflection. In this respect the arrangement differs from Zehnder's trigger tube (Wied. Ann. Vol. XLVII 1892 P 77) in which the induced electric oscillations precipitate an electric discharge from an auxiliary battery and thus produce a glow in the tube. Another method for detecting electric waves which depends upon the same principle is that due to Boltzmann (Wied. Ann. Vol. XL 1890 P 399). In the Fleming Oscillation valve induced electric oscillations are detected by their ability to impart unilateral conductivity to the space between a cold cylinder and a hot carbon filament, the conductivity being due to the negatively charged corpuscles emitted from the heated Carbon under the action of a directional electric force in the oscillations.

Comparative tests have been roughly made with the electric detector and the iron filings coherer, and have proved quite favorable to the former; a short period electrometer - a string electrometer - seems especially suited for use in this connection with the present form of detector. It was observed also that in ionization chambers such as those described, distinct deflections would occur under certain conditions of press and voltage in the absence of any waves produced by the induction coil. It is reasonable to suppose that these deflections are due also to electric oscillations.
set up in the circuit including detector. Writer is making further experiments to determine origin of the oscillations if possible.

End of Paper.
This article is listed merely as indicating the possibility that perhaps a crystal detector could be made to operate more sensitively if placed in a vacuum — and this suggests another possible direction in which crystal detectors might be improved.
FLAMES AS RECTIFIERS

A. Cathiard.

A flame in which no solid conductor is suspended may be utilized for rectifying alternating currents. It is necessary merely to use one electrode having a much smaller area than the other. The larger current then passes from the larger to the smaller electrode. The author uses by preference graphite electrodes in a coal-gas flame, the smaller electrode being a pointed pencil 5 millimeters in diameter. An alternating E.M.F of from 2000 to 10,000 is applied at 40 periods per second. The distance between the electrodes may vary from 5 millimeters to 10 centimeters, without altering the phenomenon, and the electrodes may be at different levels. The continuous current obtained is feeble, never surpassing 30 milli-amperes. But it produces distinct electrodeposition in a voltameter. When the current is made stronger it becomes alternating. There is then a bright arc within the flame and a transport of solid carbon. Even when the conduction is unipolar, a feeble luminous arc is seen, whose end moves rapidly about on the larger elec-
trode. When the voltage is reduced the current also decreases and finally the rectification is reversed, giving rise to Hanchel's phenomenon. The author has not yet obtained oscillograph curves from the flame current.

(End of Abstract)
The author showed some time ago that a flame may act as a rectifier for an alternating current of high tension and low intensity. The unidirectional character of the discharge is confirmed by the oscillograph. He now announces that in this case a true disintegration of the cathode is produced. It is accompanied by the appearance of a very brilliant point on the cathode, whereas the anode is merely surrounded by a diffuse violet tuft. If two identical parallel electrodes, say, two cylinders, are mounted in the same horizontal plane, and one of them is immersed in a flame containing no solid conductors in suspension, the electrode so immersed is always the cathode. On transferring the flame to the anode, it becomes the cathode, and at once. The experiment is easily shown with cylindrical rods of homogeneous close-grained carbon, which are especially suitable for anodes.

(End of Abstract)
COMMENT UPON
FLAMES AS RECTIFIERS

He states "the larger current then passes from the larger to the smaller electrode." To the writer this seems an additional evidence in favor of the theory outlined in this paper.

He evidently means "current" in the commonly accepted sense -- not electronic current (which goes in the opposite direction, or from the smaller to the larger electrode.) With the small electrode the impressed A.C. potential is necessarily more concentrated than at the large one, and also the resultant current density is greater likewise. The small electrode would then be under greater stress to give off electrons than the large one, and the resultant electron current would flow from the small electrode to the larger as he implies in the statement above referred to.

Further along he states that when the current becomes stronger, the current passing the rectifier becomes alternating. In such case it would appear that the larger electrode then becomes under sufficient stress to give off electrons also, and to permit some current to go in the opposite direction from that previously furnished by the small electrode alone.

The "brilliant point" referred to in the second
article as being on the cathode, would seem very evi-
dently the place where the charge-bearing particles are
being emitted.
Abstract of an article from ELECTROTECHNISCHE ZEITSCHRIFT, Oct. 1, 1908.

RECTIFYING EFFECT OF AN ALTERNATING CURRENT ARC

J. Sahulka

Under certain conditions an A.C. arc between electrodes of equal composition may have a rectifying effect. For instance, with two carbon electrodes, one above the other, of equal thickness, the lower carbon is always positive, so that the direct current produced has in the external circuit the direction from the lower to the upper carbon. On the other hand with carbon electrodes of different thickness, the thin carbon is always positive. The rectifying effect is due to a difference in temperature of the two electrodes. It is easier for the current to pass through the arc in a direction from the cold to the hot electrode, than in the opposite direction. With two vertical carbons of equal thickness, the lower carbon is always the hotter one, because its cooling facilities are poorer. In two carbons of different thickness, the thinner one is the hotter. Cooling increases rectification, and author has made experiments with a carbon rod against a carbon disk which was rotated. In external circuit direction of D.C. is from carbon rod to carbon disk. Rectifying effect increases with arc length. Easy to obtain a D.C. of 1/7 value of A.C. By special arrangements author was able to increase efficacy, that
COMMENT UPON J. SAHULKA ARTICLE

This would seem another striking proof of the hypothesis put forth in this article as regards crystal rectification — that rectification is ordinarily due to the fact that one of two electrodes in contact or in arc is at a disadvantage in some way, electronically speaking — either by being forced to give off electrons because it is smaller than the other electrode and has therefore a more concentrated potential acting upon it than the other electrode, or else that it consists of a compound (as a crystal) which can split up more easily into charge-bearing particles than can the other electrode.

He states here in several ways that the "current" goes from cold to hot electrode (and therefore that the electronic current goes in the opposite, which would be exactly in line with the evidences before considered.)
The first part of this article is a very good history of the origin and development of the crystal detector, but same not being particularly pertinent to the theoretical aspects of this thesis, it was not copied here. The portion of the article of particular interest runs as follows:

"The writer of this article, however, ventures to put forward a suggestion, merely as a working hypothesis, which is based on modern views of electric conduction. According to the electronic hypothesis of electricity, conductivity for electricity depends upon the presence of free electrons or negative ions or corpuscles, to use Prof. J. J. Thomson's term, in the body. In addition to chemical atoms of the metal there are these free electrons which move between them, or, according to one view, jump from atom to atom. The best conductors are the metals, and their atoms are electrone-positive, and, therefore, have a tendency to lose electrons. Hence in a mass of metal we must suppose that electrons are continually escaping from some atoms and being taken up again by other atoms; but at any instance there is a certain free population of electrons. These free
electrons cannot easily escape from the metal as a whole, because if they did they would carry with them a negative charge and leave the metal positively electrified, which would create a strong attraction, tending to hold the electrons back. Nevertheless, if the metallic mass is highly heated, electrons can escape from it, because their kinetic energy then gives them such a velocity that some at least are flung out beyond the attraction of the mass. If the electrons drift as a whole in one direction through the metallic mass, this constitutes an electric current, and a current is therefore produced in a conductor by any cause which tends to diminish or increase the number of free electrons at any one point, for then they tend to diffuse from the place where the concentration is greatest to a place where it is less, and it is this drift which creates a so-called electric current. Accordingly electric conductivity depends upon the power of electrons to leave the atoms and enter them again freely.

Suppose that the conductor consists wholly of atoms of the same kind; then there is nothing to prevent an equally free drift of the electrons passing from atom to atom in all directions. Suppose, however, that the conductor in question consists of complex molecules, however, of say a metallic oxide or sulphide. The atom of
oxygen or sulphur and the non-metals generally are
electronegative, and tend to take up electrons far
more readily than to give them up. Hence, in a pure
state, such bodies are non-conductors.

If, then, we consider a molecule of say
carbide of silicon, or oxide of titanium, or other
oxide or sulphide, it is quite possible that this com­
plex molecule tends to give up electrons more freely
at some points on its surface and to take them in more
freely at others. It may be likened to a chamber or
vessel with valves in it, some opening outwards, and
others opening inwards. Objects could only enter such
a chamber at certain points and leave it at others. The
same thing may be true of certain molecules; there be
places on them of easy ingress or way in for electrons,
and places of most easy egress or way out. If a large
number of such molecules were arranged irregularly, as
in a non-crystalline mass, electrons could drift through
them equally easily in all directions, because they would
pass from molecule to molecule, taking advantage of
those which were so placed as to afford ingress or egress
in the direction in which they wanted to move. If, how­
ever, the same substance is crystalized, this pre­
supposes a certain regularity of molecular arrangement,
and it is possible that, in the case of some substances,
this results in placing all the points of easy ingress on the molecules to face in one direction. Hence, such a structure would present the peculiarity that, if electrons tried to drift in one direction by trying to pass from molecule to molecule, they would find the points of ingress and egress for electrons on all the molecules arranged in such a manner as to facilitate this drift. But then it would offer great obstruction to electronic motion in an opposite direction, and we should, therefore be presented with the phenomenon of unilateral conductivity. "Rest of article is on his "oscillation valve" of audion type. (Immaterial here.)
COMMENT ON THE HYPOTHESIS AS PROPOSED BY FLEMING.

The idea he advances (P. 35) that the complex molecule tends to give off electrons more freely at one point on its surface than at another, might be allowable with weak currents, but the effect would be swallowed up with strong currents — it seems to the writer. Then too, the writer tried the experiment time after time of putting electrodes on one face of a crystal and then on one at right angles (or other angle) to the first face and see if he could get any rectification differing from that obtained with the first face. Different strengths of current were tried but with little showing. Whatever differences were obtained with the two sides of a crystal were very apparently due to the difference in character of the surface used, as could easily be seen through the microscope. See P. for a picture and explanation of one of trials.

While it might seem very possibly true, as Dr. Fleming states, that with molecules lined up as they are in crystals, different contacts on various sides of the molecular arrangements might offer different amounts of rectification, due to varying ability to give off electrons, it does not seem to the writer that such is the action in ordinary types of crystal rectifiers.

Rather, the writer, as stated many times before,
would think that a crystal's ability to split up into charge-bearing ions or atoms at the point of contact — and the metallic point's non-ability to do so under common potentials, is the real underlying cause of rectification.

Dr. Fleming's idea might hold, working with weak currents as before stated, and in an inert gas or vacuum where pure face of crystal could not be contaminated, but ordinarily such effect would be swallowed up by that mentioned in paragraph above, which therefore is basis of ordinary rectification.
REVIEW OF BOOKS WHICH HAVE A BEARING UPON THIS THESIS.
CONCERNING THE BOOKS REVIEWED

The books here listed played an important part at the beginning of the investigation. Then the writer was trying to get as thoroughly familiar with wireless telegraph circuits as possible, to the end that he might have a well-rounded conception of the function of crystal detectors.

In getting these books together, the same systematic search was gone through with as with the magazine articles. The books were obtained from the Engineering Library, from the Physics Library, and the General Library of The State University of Iowa, and the Public Library of Chicago. This latter institution had twenty or thirty or more on file, only four or five of which are listed here. The remainder were either duplicates of books already obtained from the other libraries, or else too popular in nature to be worth quoting.

The books are each given a brief characterization, for with so many, the general effect is somewhat bewildering, and one often wishes for a brief review to distinguish one book from another. The last five years or so has seen a great influx of books on radiotelegraphy upon the market -- books with much the same names, and covering practically the same ground. Some are excellent, and a number only mediocre. To distinguish such books by the name alone is a rather difficult task -- hence the reviews.

In all cases, the American address of the publishers is given, in addition to any foreign address, should the book come originally from another country. If preface shows a different date than the book itself, the preface date is usually given -- for some book manufacturers, especially the minor ones, have a propensity for dating books ahead.
PRINCIPLES OF WIRELESS TELEGRAPHY -- G.W. Pierce Ph.D.
At the time Asst. Prof of Physics at Harvard Univ.

Has been for a long time a standard work on wireless telegraphy, and may be found in most any public library. Excellent material but somewhat old at the present time; the newer texts seem to be superseding it.

The chapters which begin on P. 140 have a pertinent bearing upon this thesis. Dr. Pierce seems to have been one of the earliest investigators of crystal rectifying phenomena, and his conclusions are still good.

His "Summary of Conclusions With Crystal Rectifiers" follow: (Taken from P 199 and 200 of the book):

(1)
"An examination of the characteristics of contact rectifiers using carborundum, anatase, brookite, hessite, iron pyrites, and silicon, shows that we are dealing with the same phenomenon in the case of all these crystal substances. The various other crystal-contact rectifiers which I have not examined probably act in the same way.

(2) At the contact between the crystal and a common metal, or between two different crystals, or between two apparently similar crystals, there is asymmetric conductivity, permitting a much greater current to flow in one direction than in the other under the same applied voltage.

3. These contacts all have a rising current-voltage characteristic.
4. These crystals all have a large thermo-electric force against the common metals, and the amount and direction of this thermo-electric force is different at different points on the crystalline bodies.

5. The rectifying effect is also different in amount and direction at different points of the crystalline body; the direction of the rectifying effect is often opposite to the effect that would be obtained by heating the contact.

6. Thermo-electricity does not explain the phenomenon of rectification, but the two effects, since both exist in such marked degree in the same bodies, may be related in that both may have their seat in a common property of the material employed. (The following was written in Italics:) For example, if we suppose that a surface of separation between the crystalline body and some other body permits the passage of electrons more easily in one direction than in the other, this would account for the rectifying effect, and would also account for the thermo-electric effect, provided the velocity of the electrons is suitably different at different temperatures.

7. The thermoelectric explanation of the effect, if we had found it to be supported by the experiments, would have correlated the phenomenon of rectification at a solid contact with the body of information that we already have in regard to thermo-electricity, but we should still have by no means a complete knowledge of the action, because our understanding of thermo-electricity is very incomplete.

8. From experiments with thermo-electricity we are familiar with the fact that the energy of an
oscillatory electric current passing through a high-resistance contact is partially converted into heat energy, and that the heat energy so obtained, if produced at a thermal junction, is again partially converted into electric energy, manifesting itself as direct current. It is perhaps, after all, more simple to suppose the alternating current to be converted into direct current without the intermediation of heat; and this seems to be the case with crystal-contact rectifiers. This result opens up a new field for investigation, which may contribute to a better understanding, not only of thermal electricity, but of the much larger question of the mechanism of electrical conductivity in solid bodies."

(End)

COMMENTARY ON THE PRECEDING:

Since it is so easy to confuse various theories which concern the same subject, it may not be out of place to insert here a brief note explaining the differences between the ideas above suggested by Dr. Pierce and those proposed by the writer.

The first five paragraphs he gives have to do with material which was new at the time it was published, but which is not of particular moment here. The suggestion in paragraph # 6 that "a surface of separation between the crystalline body and some other body permits the passage of electrons in one direction more easily in one direction than in the other" would seem to the writer an inexact statement of the conditions which may actually exist at the surface of separation mentioned. Rather the writer believes the property of rectification to be due to the different abilities of the two substances in contact to GIVE OFF electrons
as he has stated at some length in another part of this paper. (P. 17). There is little "permitting" about it, it would seem to the writer; that is, the region between the two bodies in contact has little to do with the hindrance or free passage of electrons — rather this property is inherent in the respective natures of the two substances in contact, and in the precise nature of their individual surfaces. Whichever surface can give off the most electrons will have the predominating direct current going in that direction.

In the remaining sections (Nos. 7 and 8) Dr. Pierce makes some reference to the supposition that "the alternating current is converted into direct without the intermediation of heat, perhaps". The writer would believe that if any heating effects do appear at the point of contact, the same act as catalyzers of the giving-off-electrons effect, and thus promote the rectification secured. In the experimental work the writer has performed it will be remembered how important heating effects were with the small sparks sometimes used. There the heat from the spark assisted in melting up material of crystal and helped keep the space between point and crystal well supplied with ions and electrons, which without doubt had a great deal to do with the inordinate rectification effects secured by the method.

Of all the texts now on the market on the subject of radiotelegraphy, this is one of the newest and best. It is very complete; technical, and yet not so full of mathematics as to be hard reading. All explanations are based on the electron theory; an indication of the modern thought which is everywhere evident throughout the book. The cuts, drawings and typographical makeup of the book are all good. This is in rather sharp contrast to the usual case with English books.

The chapter on detectors presents nothing especially new as bearing upon this thesis, but the whole book is good for a general understanding of radiotelegraphy and the place of detectors in the art.

WIRELESS TELEGRAPH CONSTRUCTION FOR AMATEURS


A much advertised book among the popular magazines of mechanical nature. Good for the kinks it gives on the operation of commercial radiotelegraphic apparatus.
Seems to be pretty well wrapped up with English apparatus and English methods of operation. Presentation of subject is rather perfunctory at times, but gives good pointers upon several occasions as to the practical operation of foreign makes of radiotelegraphic instruments. Book is not essentially popular in nature, but is intended, according to preface, as an instruction book for those in the practical operation of sets. This mission it probably fulfills to a satisfactory degree as far as English practice goes.

WIRELESS TELEGRAPHY AND TELEPHONY — A.F.Collins

A good book for an American operator in commercial work to own. A good compendium of facts on current practice in the art. Subject is presented with considerable punch and conciseness.


Collins was one of the first American writers on wireless, and this is another of his books. More concerned with physical aspects of subject than the one reviewed above.
This is the most comprehensive book on wireless telegraphy -- its history, its apparatus, its theory, and its prospects -- that has yet been put upon the market. Dr. Fleming's "Oscillation Valve" was one of the great contributions to the technical development of wireless telegraphy, and the thorough knowledge of fundamensals which led him to invent this form of oscillation detector, as well as many other important devices, is evident throughout the book. Volume contains over 900 pages. Little mention is made of any type of crystal rectifier, as same had not come into used at the time the first edition was printed and this second edition was evidently not revised to any great degree.

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Book is designed to give a well-ordered idea of the workings of wireless telegraphy to a non-technical reader. Subject is kept well in hand and is not too dilatory on minor points. In common with other recent books on radiotelegraphy, the subject is handled from the standpoint of the electron theory.
INSTITUTE OF RADIO ENGINEERS; Vols. 1 and 2, 1913-14
Society is comparatively new; is organized among
engineers in radio field. Corresponds to A.I.E.E.,
A.S.C.E., Or A.S.M.E. in their respective fields.

Nothing of particular value on detectors of
the crystal type has yet appeared, except possibly
one article on P.59 of the second volume. Paper is
entitled "The Influence of A.C. on Certain Metallic
Salts", by C.Tissot. Article has rather indirect con-
nection here. Is more concerned with coherer phenomena.

EXPERIMENTAL WIRELESS STATIONS --Philip E. Edelman.
1914 Edition. Published by author, Minneapolis, Minn

A First-class book for a beginner at radiotele-
graphy. Full of excellent recipes for getting results
from a miscellaneous collection of apparatus, such as
a novice usually has. A good supplementary book to
any more-theoretical course.

On Page 162 it lists Carborundum, Fused Silici-
on, Iron Pyrites, Copper pyrites, Chalcopyrites, Hes-
site, Zincite, Octahedrite, Stibnite, Galena, Molybden-
ite, Zirconium, Niccolite, Domeykite, Sphalerite,
Pyrrholite, Corundum, Hematite, Cassiterite, Siderite,
Malachite, and Cerusite, as having been used as the
crystals for radiotelegraphic rectifiers. It does not
follow, however, that they are all of equal value for
the purpose.

WIRELESS TELEGRAPHY -- C.L. Fortesque, M.A.; Prof. of
Physics, Royal Naval College, Greenwich, England. 1913.
A small descriptive handbook for a popular reader of
ELECTRIC WAVES - Hertz. Translated from the German by D.E. Jones of the University College of Wales. McMillan & Co, London and New York. 1893

Original publication of this work in the German was one of the milestones in the progress of wireless telegraphy. Volume will always have a historical interest, and it has a technical value still.

ELECTRIC WAVES -- W.S. Franklin, Prof. of Physics at Lehigh University. MacMillan Co, New York. 1909.

Good on getting a conception of wave motion. Intended more for dynamo-electric work than for radiotelegraphy.


A textbook on Electrical Engineering in general as well as on Radiotelegraphy. Prepares Marconi operators for an understanding of Marconi apparatus. Magnetic detectors and the Fleming valve are considered.


Contains over 800 pages, embracing all that the usual yearbooks do in the way of miscellaneous information. Issued annually of course, and worth having as a review of current practice.
THE ELECTRON THEORY -- E.E. Fourrier D'Albe -- 1907.

A much-read book on the subject and uniformly appreciated. To the electrical engineer in practical work for some time, who has not kept up with progress in theoretical lines, the book would prove of undoubted good -- as a short-cut to a comprehension of newer theory. To the writer of this paper at least, the book has proven of an invaluable aid to a more-thorough understanding of electrical and physical units and their interrelations.

CONDUCTION OF ELECTRICITY THROUGH GASES -- Second Ed. 1906. By J.J. Thomson, D.Sc, LL.D., Ph.D., F.R.S.

Long a standard work on the subject, though somewhat old at the present time. The chapter on "Spark Discharge" beginning P. 430 is interesting for the similarity along some lines of the phenomena there listed to the "spark" effects obtained in this investigation.
FOLLOWING BOOKS WERE OBTAINED AT CHICAGO PUBLIC LIBRARY


A book very similar in general nature to the one put out by Stanley, previously reviewed (P. 145). Older book now than Stanley's, hence not of so much use in newer work.


"Long experience in tutorial work makes author hope book will be of service to operators and amateurs." A book much resembling Pender's Prin. of E.E. in general appearance and style, though that book is concerned with a different aspect of electrical engineering than this one on radiotelegraphy. Runs to mathematics to a considerable extent. On the whole, a very good book.


WIRELESS TELEGRAPHY — Ashley & Hayward. Am. School Correspondence. Names most everything, comments intelligently, but doesn't get very technical.