THE General Radio EXPERIMENTER

VOLUME XIX No. 12 MAY, 1945

ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

VACUUM-TUBE AND CRYSTAL RECTIFIERS AS GALVANOMETERS AND VOLTMETERS AT ULTRA-HIGH FREQUENCIES

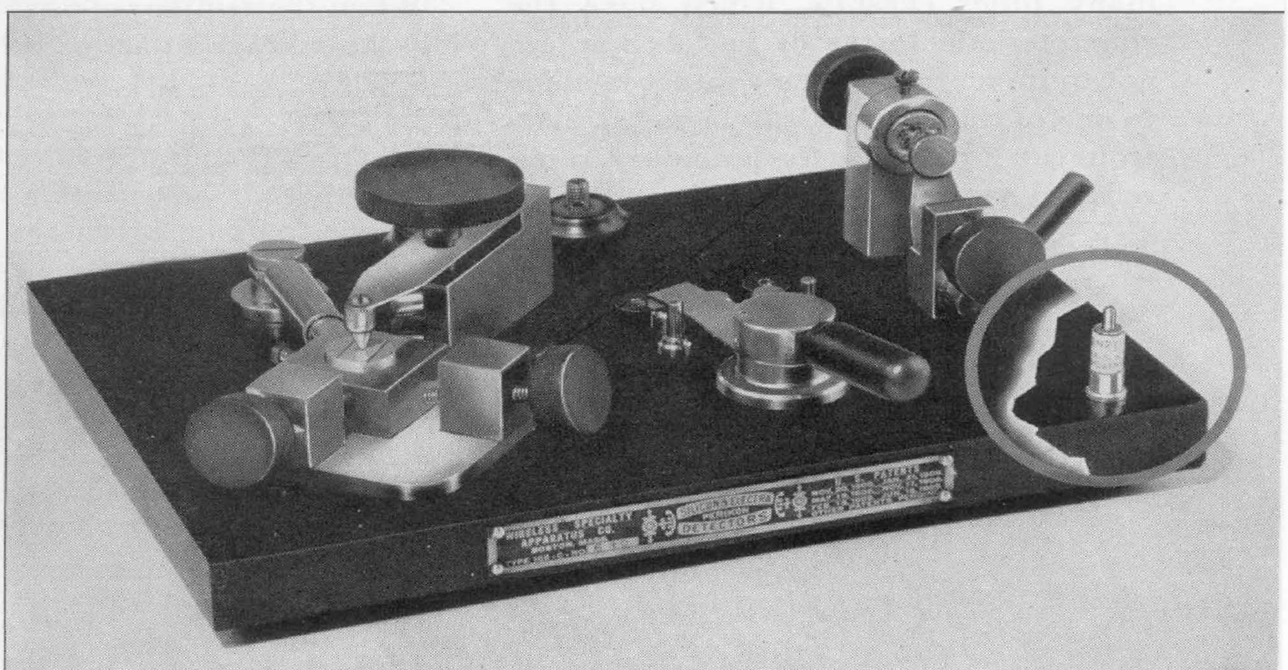
Also IN THIS ISSUE

● **UNTIL RECENTLY,** the crystal detector of radio's early days has had little, if any, commercial use since the introduction of mass-produced vacuum tubes. It has, however, always found considerable application in ultra-high frequency research[1] and lately has again become commercially available.

Today's crystal units are more stable and more uniform than those of 30 years ago, although in neither respect are they as yet comparable

[1]G. C. Southworth, "Beyond the Ultra-Short Waves," *Proc. I.R.E.*, Vol. 31, No. 7, July, 1943, pp. 319-330. G. C. Southworth, "Hyper-Frequency Wave Guides — General Considerations and Experimental Results," *Bell System Technical Journal*, Vol. 15, No. 2, April, 1936, pp. 284-309. W. L. Barrow, "Transmission of Electromagnetic Waves in Hollow Tubes of Metal," *Proc. I.R.E.*, Vol. 24, No. 10, October, 1936, pp. 1298-1328.

FIGURE 1. Crystal detectors of 30 years ago and (in circle) a present-day unit. Older types were cumbersome and adjustable. Modern units are small, and the adjustment is sealed.



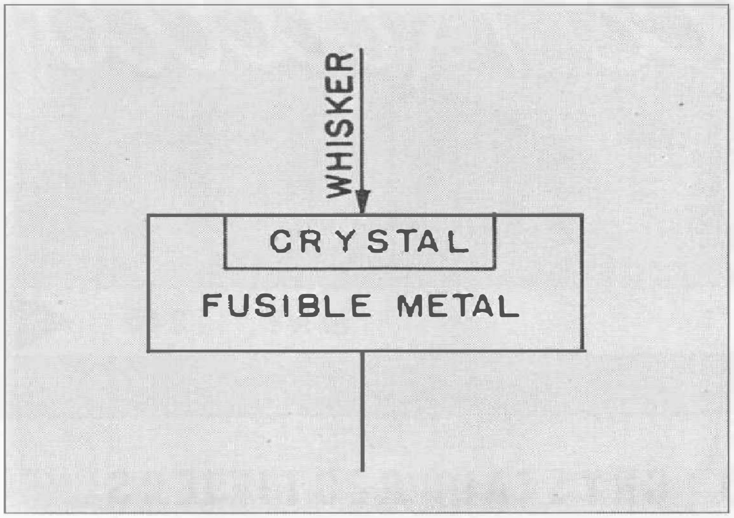


FIGURE 2. Simplified diagram of the construction of a crystal rectifier.

to vacuum tubes. They perform well as detectors and mixers in u-h-f circuits and offer considerable promise as rectifying elements for high-frequency voltmeters. The capabilities and limitations of the crystal as a voltage measuring device can best be shown by a consideration of its characteristics and a comparison with those of the vacuum-tube rectifier.

Nature of the Crystal Rectifier

The crystal rectifier depends for its non-linear behavior on the very interesting properties of the class of materials known as semi-conductors.[2] This class includes silicon, iron pyrites, galena, and many other crystals, which have the characteristic luster of metals but are not quite metals. When contact is made to one of these crystals by a metal, electrons can flow across the boundary, often referred to as the barrier layer, more readily in one direction than in the other, and this behavior is used for rectification. As rectifier elements, the units are usually constructed with the crystal held in a fusible metal alloy, which serves as one terminal of the rectifier. The other terminal is a "cat whisker," such as a fine tungsten wire, which touches the crystal as shown in Figure 2.

[2]K. F. Herzfeld, "The Present Theory of Electric Conduction," *Electrical Engineering*, Vol. 53, No. 4, April, 1934, pp. 523-528.

Owing to its inherent simplicity, the crystal rectifier can be made in a unit of extremely small physical size. Very small vacuum tubes also have been constructed for use at high frequencies,[3] but the need for an evacuated space surrounding the diode elements makes its manufacture extremely difficult in any size smaller than the familiar acorn tube.

Resonance Effects

The main reason for reducing the physical size of a rectifier is to increase the lowest resonant frequency of the circuit formed by its elements. Below this resonant frequency the voltage that appears at the rectifying element, which is the plate-to-cathode space in the diode and the barrier between whisker and crystal in the crystal rectifier, is greater than the terminal voltage because of series resonance between the lead inductance and the capacitance across the rectifying element.

When the rectifier is used for measuring the voltage at its terminals, a cor-

[3]B. J. Thompson and G. M. Rose, Jr., "Vacuum Tubes of Small Dimensions for Use at Extremely High Frequencies," *Proc. I.R.E.*, Vol. 21, No. 12, December, 1933, pp. 1707-1721. Leon S. Nergaard, "Electrical Measurements at Wave Lengths Less Than Two Meters," *Proc. I.R.E.*, Vol. 24, No. 9, September, 1936, pp. 1207-1229.

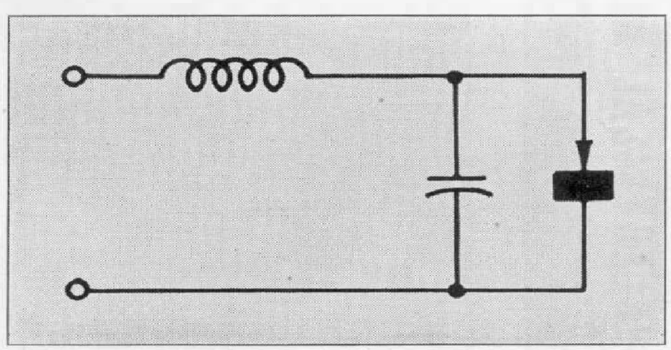


FIGURE 3. Diagram showing the resonant circuit formed by lead inductance and shunt capacitance of a crystal rectifier.

rection must therefore be made for resonance. As the frequency of the applied voltage approaches resonance the required correction becomes greater, and near resonance the accuracy of measurement becomes very poor because the large correction cannot be accurately determined.

A more serious effect of resonance, for which no numerical correction can be made, is the emphasis of harmonics as compared to the fundamental. When the applied voltage contains harmonic components that are in the vicinity of the series-resonant frequency, the indicated voltage may be almost completely determined by those components even though the fundamental component is appreciably lower in frequency than that of resonance and is many times as large in magnitude at the voltmeter terminals as the sum of all other components.

The resonant frequency can, therefore, be considered as a first upper limit to the frequency at which a given rectifier can be used as a voltmeter. Commercial diodes are available with resonant frequencies in the vicinity of 1500 Mc, and the resonant frequencies of commercially available cartridge crystals are considerably higher. Crystal rectifiers can readily be built with resonant frequencies still higher than those of the commercially available crystals. Thus, in this respect, the crystal rectifier has a marked advantage over the diode.

When a rectifier is used as an indicator of relative voltage level, that is, as an r-f galvanometer rather than as an absolute voltmeter, the resonant frequency is not so important a limitation, for resonance does not produce by itself any effect on voltage ratios. However, harmonic components in the vicinity of resonance may cause considerable error, and the reduction of stray pickup becomes more difficult at frequencies near and beyond the first resonance.

Transit-Time Effects in Diodes

Another reason for reducing the size of a diode rectifier is to reduce the effects of the finite time of transit of the electrons from cathode to plate. When the period of the applied voltage becomes comparable to this transit time, the vacuum tube characteristics are modified from the low-frequency ones. While for some specialized measurements tubes with adjustable transit time are used, the resultant systems are inherently frequency dependent. In the very useful diode peak-type voltmeter, such as the General Radio TYPE 726-A Vacuum-Tube Voltmeter, the effect of transit time is to reduce the indicated voltage for a given applied voltage as the frequency of that applied voltage is raised.[4] This behavior might be characterized as a reduction in rectification efficiency. Furthermore, since transit time depends on the applied voltage, this reduction is dependent on voltage level, with the result that voltage ratios are not preserved independent of frequency. This behavior is a serious limitation for the diode rectifier, not only for its use as a voltmeter but also as a galvanometer where accurate measurement of ratios may be important even though the absolute level is not. For acorn-type diodes, the reduction in rectification efficiency is noticeable at 30 Mc for voltages of the order of one-half volt or less, and at 500 Mc at the same voltage level the reduction is of the order of 30%.

The effect of transit time in a crystal rectifier is negligible for its present appli-

[4]L. S. Nergaard, *loc. cit.* Ivan G. Easton, "Radio-Frequency Characteristics of the Type 726-A Vacuum-Tube Voltmeter," General Radio *Experimenter*, Vol. 15, No. 11, May, 1941, pp. 1-5.

cations, but another limitation appears whose effect is similar to that of transit time.

R-C Effect in Crystals

The crystal rectifier with its semi-conductor crystal and metallic whisker is a barrier-layer rectifier like the copper-oxide rectifier and has in common with that rectifier a decrease in rectification efficiency with increasing frequency.[5] However, owing to the whisker-type of contact and the nature of the material, the frequency limitations of the crystal are not nearly so serious as those of conventional copper-oxide rectifiers. In fact, the frequencies at which there is an appreciable drop in rectification efficiency for a suitably constructed crystal unit can be thousands of times the corresponding frequencies for copper-oxide instrument rectifiers.

As an illustration of the decrease in rectification efficiency, Figure 4 shows the results of some measurements made

[5]Joseph Sahagen, "The Use of the Copper-Oxide Rectifier for Instrument Purposes," *Proc. I.R.E.*, Vol. 19, No. 2, February, 1931, pp. 233-246. Karl Maier, *Trockengleichrichter*, München, R. Oldenbourg, 1938, pp. 52f, 198f, 261, and 283ff.

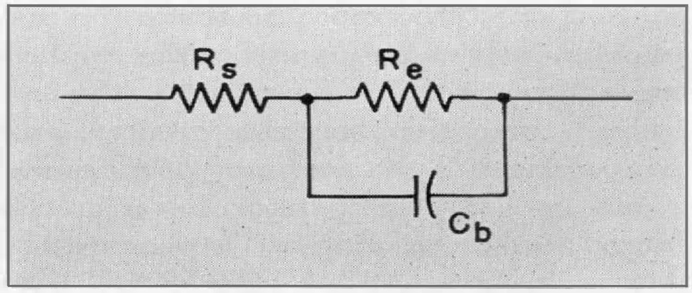


FIGURE 5. Equivalent circuit for interpreting the R-C effect of the crystal rectifier. The resistance R_e of the barrier layer is non-linear.

on an iron-pyrites crystal rectifier. The crystal in its holder had its lowest resonant frequency at about 3500 Mc. The input voltage to the crystal rectifier was standardized by means of a bolometer, and the effective voltage indicated by the crystal as a function of frequency was noted. The result shows a marked drop in the indication of the crystal as the frequency is raised.

The equivalent circuit shown in Figure 5, developed by Schottky and Deutschmann,[6] can be used for interpreting this decrease in rectification efficiency. In this circuit R_e represents the non-linear resistance of the barrier layer of the whisker-crystal junction, R_s represents the resistance of the semi-conductor between the barrier layer and the fusible metal alloy that holds the crystal, and C_b is the capacitance that exists directly across the barrier layer. At high frequencies this capacitance tends to shunt out the non-linear element so that only a fraction of the

[6]W. Schottky and W. Deutschmann. "Zum Mechanismus der Richtwirkung in Kupferoxydulgleichrichtern," *Physikalische Zeitschrift*, Vol. 30, No. 22, November 15, 1929, pp. 839–846. O. Zinke, *Hochfrequenz Messtechnik*, Leipzig: S. Hirzel, 1938, pp. 100 ff. W. Meyer and A. Schmidt, "Messungen an Sperrschichtgleichrichtern," *Zeitschrift fur technische Physik*, Vol. 14, No. 1, 1933, pp. 11–18.

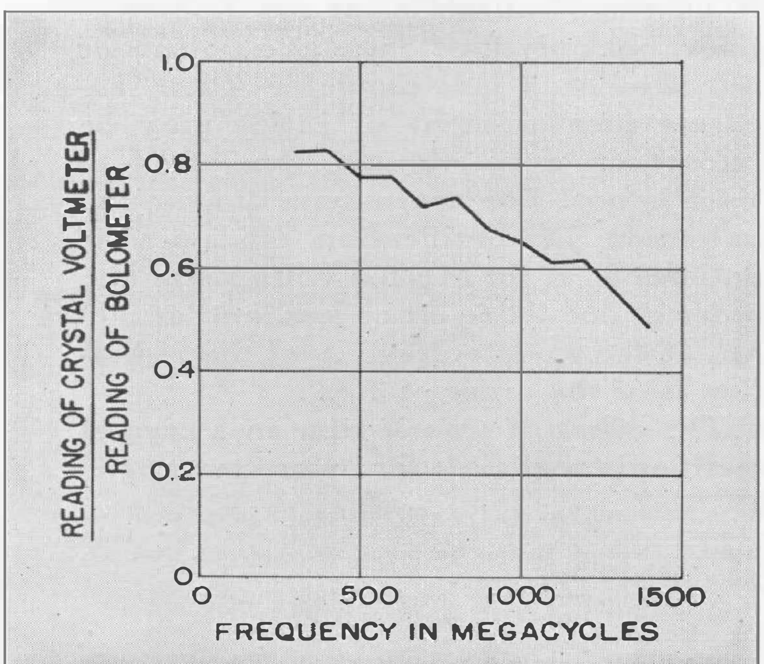


FIGURE 4. Plot showing decrease in rectification efficiency of an iron-pyrites rectifier as a function of frequency.

energy going into the crystal unit appears in the non-linear element where the rectification occurs. The result is a reduction in rectified output at high frequencies compared to that at low frequencies for the same energy input.

It is important to note that the above reduction results from the increased current flow in the resistive element R_s with a resulting increase in dissipation of energy where it is of no value. A capacitance across the complete unit and an inductance in series do not upset the energy relationships, because of their non-dissipative nature. Thus they do not inherently affect the rectification efficiency, even though they do modify the impedance relationships and the relative voltage appearing at the barrier layer compared to that at the input terminals.

A rough measure of the relative energy contributing to the rectification as a function of frequency is given by

$$\frac{1}{1 + (\omega C_b)^2 R_e R_s}.$$

Since R_e is nonlinear, the expression indicates only the order of magnitude and the general nature of the variation of rectification efficiency with frequency. The relative rectified voltage varies with frequency approximately as the square root of the above expression.

Consequently, for small departures from uniformity the reduction in output varies as the square of the frequency. The departure is in a direction opposite to that for resonance, and the two effects tend to cancel at low frequencies, so that the apparent resonant frequency is raised. However, since the barrier-layer resistance depends on the voltage level, the amount of the reduction in rectification efficiency is a function of the voltage, and hence, even in the crystal, the measurement of voltage ratios is not completely independent of frequency.

Fortunately the magnitude of thin reduction in rectification efficiency can be kept small by proper design of the crystal unit and by the choice of the rectifying material. The commercial 1N21B-type crystals are much better in this respect than is the crystal whose characteristic is shown in Figure 4. Actually this crystal was one of the poorest of a large group measured, and the 1N21B-type crystal exhibits no appreciable reduction in rectification efficiency up to 1000 Mc and in many cases even higher frequencies. This frequency is far higher than that at which transit-time effects begin to appear in diodes.

Reverse Rectification in Crystals

Although the rectifier action in crystals is normally expected to be confined to the whisker-crystal junction, rectification also can occur in the junction between the crystal and the other contact.[7] This rectification is in the opposite sense to the desired one, and might be called a reverse rectification. Normally the resistance of this second contact is very small compared to that of the whisker contact so that the desired rectification dominates. But when the

[7] J. T. Kendall, "The Rectifying Property of Carborundum," *Proc. Phys. Soc.*, Vol. 56, Pt. 2, No. 314, March 1, 1944, pp. 123-129.

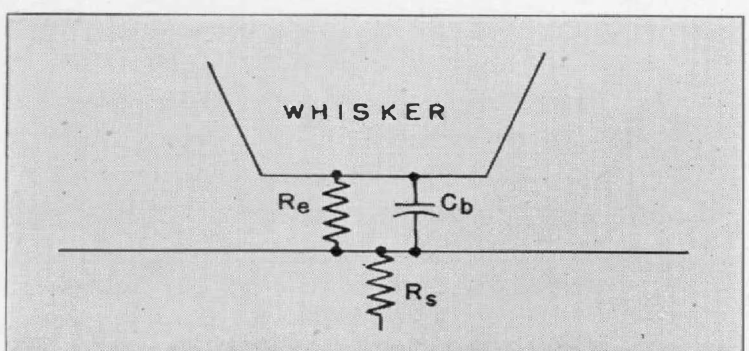


FIGURE 6. Simplified sketch of the whisker-crystal contact greatly enlarged to show the location of the elements of Figure 5.

crystal is merely embedded or soldered in its retaining cup, the reverse rectification may be very important.

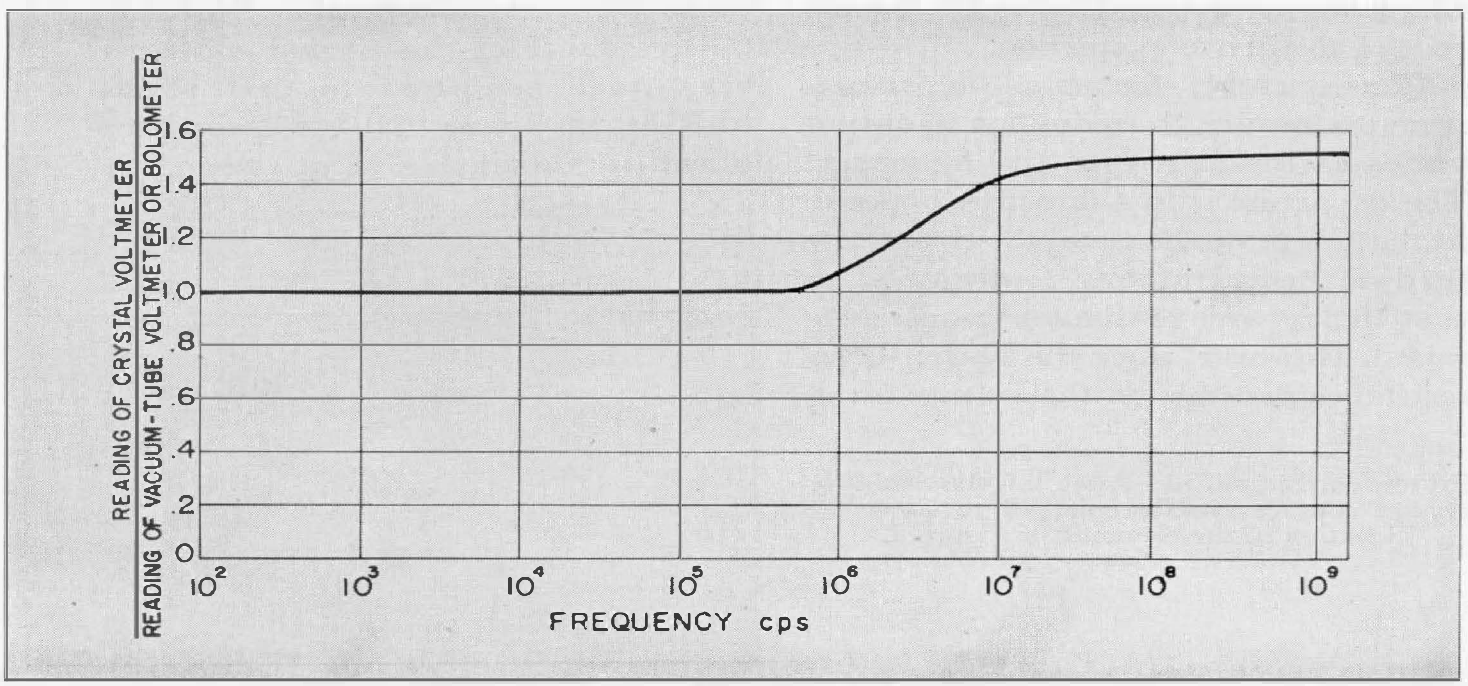
The effect of this rectification at the second contact is highly dependent on frequency. The capacitance across the contact is so large that its reactance rapidly becomes very low compared to the impedance of the main rectifying contact as the frequency is raised. This causes the voltage across the second contact to decrease and the contribution from its rectification to disappear as the frequency is raised. Thus one would expect to observe an increase in rectified output for increasing frequency for a crystal with a noticeable reverse rectification. This behavior is exhibited in Figure 7, which shows the results of some measurements on an iron-pyrites crystal used as a voltmeter.

Even more marked effects of reverse rectification have been observed. One crystal had an output which was reversed from the normal at low frequencies (the reverse rectification dominating), but normal rectification at high frequencies. Another showed no appreciable rectified output at low frequencies but had fairly good output at high frequencies. Most crystals show only a moderate effect from reverse rectification, and the reverse rectification can usually be made negligible by plating the crystal before mounting or by fusing the crystal in place. The 1N21B-type crystal seems to exhibit no appreciable effects of reverse rectification.

Other Limitations

In addition to the frequency characteristic, other factors must be considered in determining whether or not the crystal is satisfactory for use in a given application. One of the most important of these is input impedance. At high frequencies the crystal and the diode have comparable impedances. The input capacitance of a probe containing a crystal unit is usually comparable to that of one using a diode. While the input conductance of a diode voltmeter can be made very low at low frequencies, the conductance increases with increasing frequency, and at ultra-high frequencies the conductance becomes nearly as great as that of a very good crystal unit used as a peak voltmeter.

FIGURE 7. Frequency characteristic of an iron-pyrites rectifier showing the increase in output that occurs as a result of the large capacitance across the second contact.



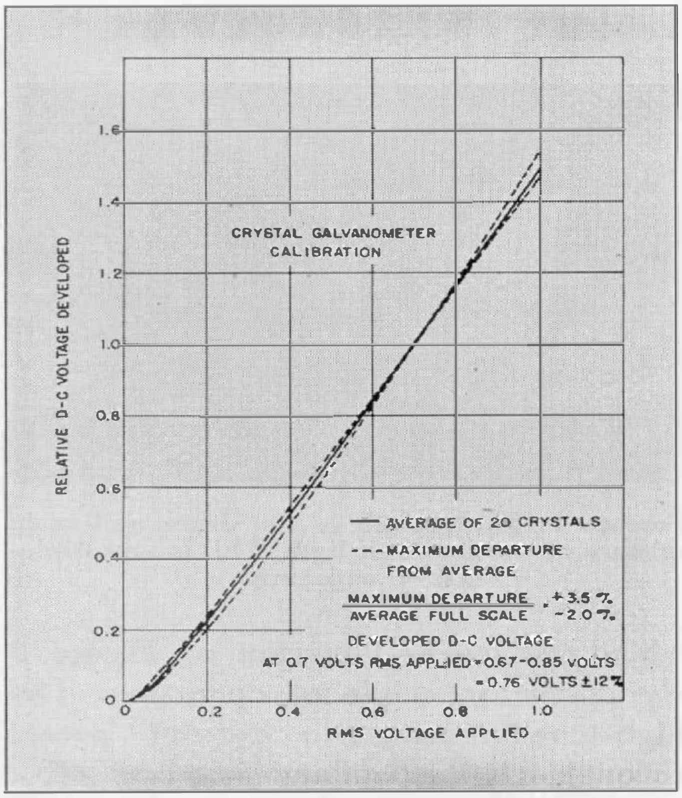


FIGURE 8. Plot showing the average characteristics of 20 crystals and the maximum departure from average. The output is taken as unity for 0.7 volts, r-m-s, input.

The crystal unit is seriously limited in voltage range, with a 1-volt r-m-s limit for a 1N21-type unit as a peak rectifier. When the crystal is overloaded its characteristics are changed, so that great care must be exercised in many systems to avoid permanently damaging the crystal contact. Higher voltage can be measured, however, by using capacitance multipliers.

The characteristics of crystal rectifiers are somewhat dependent on the operating temperature, so that they should be calibrated at approximately the ambient temperature at which they will be used.

One important disadvantage of the diode compared to the crystal is the need of maintaining a constant cathode temperature to assure constant thermionic emission. Consequently, the crystal, because it requires no heated cathode, has a considerable advantage in simplicity, and can be used at lower voltage levels.

In any measurement system which uses vacuum-tube or crystal rectifiers the uniformity of characteristics of different units of the same type is an important consideration. If replacement of a unit necessitates recalibration of the measuring device, the general usefulness of the device is impaired. Vacuum-tube diodes, particularly the high-frequency types, are not so uniform as is often desired, but even so they are appreciably better in that respect than are the commercial crystal units. For instance, the replacement of the acorn diode in the TYPE 726-A Vacuum-Tube Voltmeter does not appreciably affect the calibration of the voltmeter with its 2% accuracy rating. If a crystal rectifier is used in a similar circuit, however, the indication of the meter is appreciably dependent on the particular crystal used. Figure 8 shows the average characteristics and maximum departure from average of a group of 20 crystals of the same type used in a peak-reading voltmeter. The extent of the variation in rectified output is appreciable. Furthermore, since the shapes of the curves are different, a single calibration-check point will correct only approximately for the variations among the crystals. Thus for accuracy of the order obtained with the diode voltmeter a complete calibration must be made for each crystal.

The overall stability of modern crystal units is remarkably better than the arrangements used in the early days of radio communication and further improvement can be expected. While lack of uniformity between crystals is at present an important limitation as compared to diodes, this disadvantage is outweighed by their better high-frequency characteristics. — ARNOLD PETERSON

SPARK TIMING WITH THE STROBOLUX

AT THE AERONAUTICAL RESEARCH LABORATORY of the University of Kentucky, research on aircraft engine fuels is carried on under the sponsorship of Pratt and Whitney Aircraft. During a long series of tests on an engine to evaluate its performance with a given type fuel, it is necessary to have an exact knowledge of the degree of spark advance with which the engine is operating.

Using the General Radio Strobotac and Strobolux, Professor A. J. Meyer, director of the laboratory, and his associates have developed a spark-indicating system that gives accurate and dependable results. Figure 1 is a stroboscopic photograph showing the indicator dial,

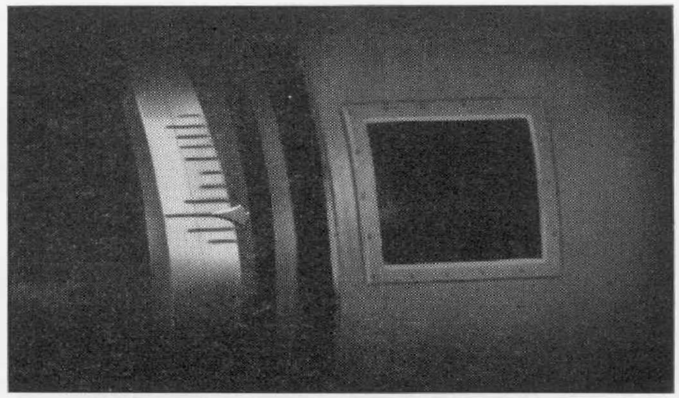


FIGURE 1. Photograph of the drum and scale taken with stroboscopic light. This is a multiple-flash exposure.

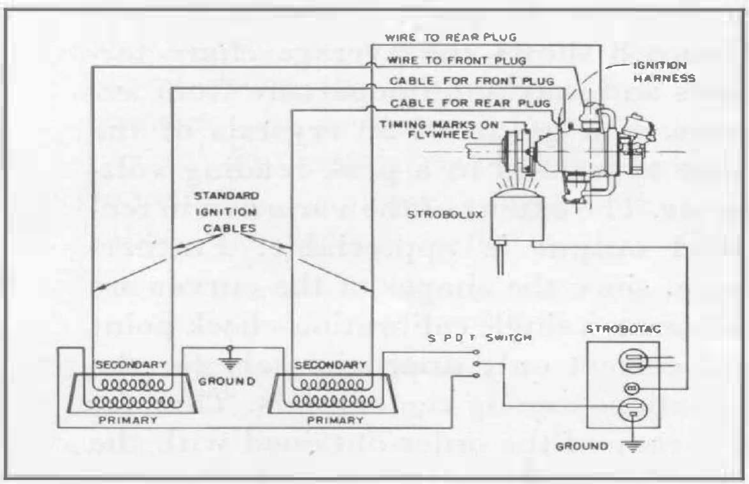


FIGURE 2. Diagram showing connections for the spark indicator.

while the wiring diagram of Figure 2 shows the principle of operation. The high-tension magneto current passes through the secondary winding of a standard automotive spark coil, while the primary winding is connected to the contactor terminals of the Strobotac. The Strobolux is flashed from the Strobotac circuit in the normal manner. Its lamp illuminates the fly-wheel, which carries a scale. When the light flash initiated by the ignition spark occurs, the angular position of the fly-wheel at that instant can be accurately read from the scale.

In Figure 2, connections to both front and rear plugs are shown, with a switch in the low-tension circuit to select either plug.

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