The General Radio Experimenter

Vol. IV, No. 9

February, 1930

PIEZO-ELECTRIC QUARTZ PLATES

By Charles E. Worthen

UNTIL the terminology for describing piezo-electric quartz plates becomes standardized, it is practically necessary that every paper on the subject be preceded by a glossary. Different investigators use different terms, and it is sometimes difficult to keep them straight even when one is working with them every day. The article that follows was originally intended to serve as an introduction to a catalog description of the mounted quartz plates sold by the General Radio Company, but it is hoped that enough information has been included to make it useful for reference when comparing nomenclatures.

The crystalline quartz which is used in piezo-electric oscillators is found in various parts of the world, the greater portion of it coming from Brazil. It is one of some seven crystalline forms of silica, but it is the only one that possesses marked piezo-electric properties. While other varieties exhibit them, the kind ordinarily used ("low" quartz) is the best. It has a structure similar to that shown in Figure 1, although in the natural state its shape may be imperfect, some pieces having no flat surfaces at all. For explanatory purposes, we assume that the crystal has a regular hexagonal cross section, but the shape has no definite bearing on its piezo-electric properties.

Regardless of its geometrical shape, a quartz crystal has four axes of symmetry, which means that if the crystal is rotated about any one of these axes, two or more positions are found where the same properties recur. The first, called the optic axis, extends through the crystal in the direction indicated in Figure 1 by the line ZZ. The other three are separated by an angle of 120° and lie in a plane perpendicular to the optic axis. These are known as electric axes because along the direction in which they lie the maximum piezo-electric effect is observed. If the section of the crystal perpendicular to the optic axis were perfect in cross section, the electric axes would be lines joining diametrically opposite vertices. The electric axes are indicated in Figure 1 by the lines XX, $X'X'$, and $X''X''$. In addition to these it is also useful to consider another set of axes designated by YY, $Y'Y'$, and $Y''Y''$. These lie in the same plane with and make angles of 30° with the electric axes. They are therefore perpendicular to opposite faces of the crystal. Mr. F. R. Lack of the Bell Telephone Laboratories, Inc., has used the name "mechanical

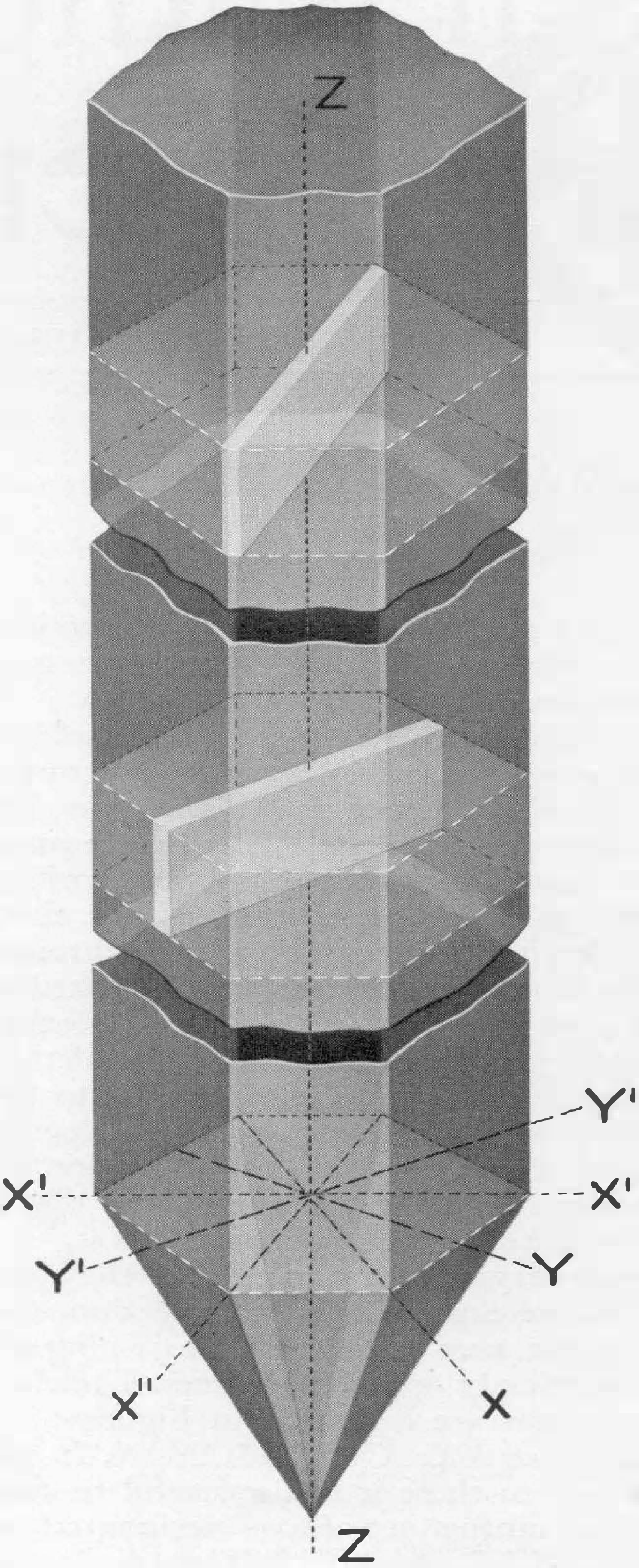

FIGURE 1. This drawing shows how X-cut and Y-cut quartz plates are oriented with respect to the electric (*X*), the mechanical (*Y*), and optic (*Z*) axes of the quartz crystal. The top section represents a Y-cut plate; the center section, an X-cut plate. The *Y''Y''* axis would coincide with the *ZZ* axis and is not shown

axes" to describe them and although they have had no universally accepted name, this one seems to be as good as any.

If mechanical stresses are applied in any direction through the uncut crystal, electric charges are set up on certain faces; and, conversely, if the crystal is placed in an electric field, dimensional changes along certain axes may be observed. This is known as the piezo-electric effect. Since it is a maximum in directions at right angles to the optic axis, quartz plates for commercial use are cut from sections at right angles to this axis. From these sections the plates are cut with either one of two orientations with respect to the electric and mechanical axes. These "cuts" and the sections from which they may be taken are represented in Figure 1, but a better idea of the angular positions involved can be gained from Figure 2.

The center section shows a "zero-angle cut" so called because its normal makes a zero angle with an electric (*X*) axis. It is also called "X-cut" because a *normal* to the face of the plate is parallel with one of the *X*-axes, or "face-perpendicular cut" because the face of the plate is perpendicular to an *X*-axis. This is also called "Curie cut" after the investigators who first used it in studying the piezo-electric effect. The top section shows a "30-degree cut," so called because its normal makes an angle of 30° with an electric axis. It is also called "Y-cut" because a *normal* to the face of the plate is parallel with a *Y*-axis, or a "face-parallel cut" because the face is parallel with an electric axis.

The diagrams of Figure 1 and Figure 2 should not, of course, be interpreted to mean that the plates must be cut to pass through the center of a section. Any portion of the crystal may be used so long as the proper orientation with respect to the electric and mechanical axes is maintained.

TABLE I
COMMON NAMES DESCRIBING THE TWO USUAL CUTS FOR PIEZO-ELECTRIC QUARTZ PLATES

X-Cut Because normal to face of plate is parallel with an electric (*X*) axis	or	Zero-Angle Cut Because normal to face of plate makes angle of 0° with an electric (*X*) axis	or	Face-Perpendicular Cut Because face of plate is perpendicular to an electric (*X*) axis	or	Curie Cut Because the Curies used crystals cut with this orientation when they discovered the piezo-electric effect	Shown Center section of Figure 1 and Figure 2b
Y-Cut Because normal to face of plate is parallel with a *Y* axis	or	30-Degree Cut Because normal to face of plate makes an angle of 30° with an electric (*X*) axis	or	Face-Parallel Cut Because face of plate is parallel to an electric (*X*) axis			Shown Top section of Figure 1 and Figure 2a

Either X-cut or Y-cut plates perform satisfactorily in piezo-electric oscillators, although different characteristics for the two may be expected. For example, a plate suitable for stabilizing a vacuum-tube oscillator at a given frequency will require an X-cut plate about 7% or 8% thicker than a corresponding Y-cut plate. The different temperature-frequency coefficients of the two kinds of plates are referred to in a subsequent paragraph.

When attempting to memorize the location of the *X*- and *Y*-axes and the distinction between X-cut and Y-cut plates, the following may be helpful: (*a*) Remember that one set of axes joins opposite corners; the other set joins opposite sides of the crystal. (*b*) Associate the words *electric* and *X* with the corner-joining positions of the *X*-electric-diagonal axes. (*c*) Remember that the faces of the respective plates appear at first glance to be named incorrectly, i.e. the face of an X-cut plate lies parallel to a *Y*-axis and the face of a Y-cut plate lies parallel to an *X*-axis.

There is a definite relation between the direction of the electric and the mechanical stresses for the piezo-

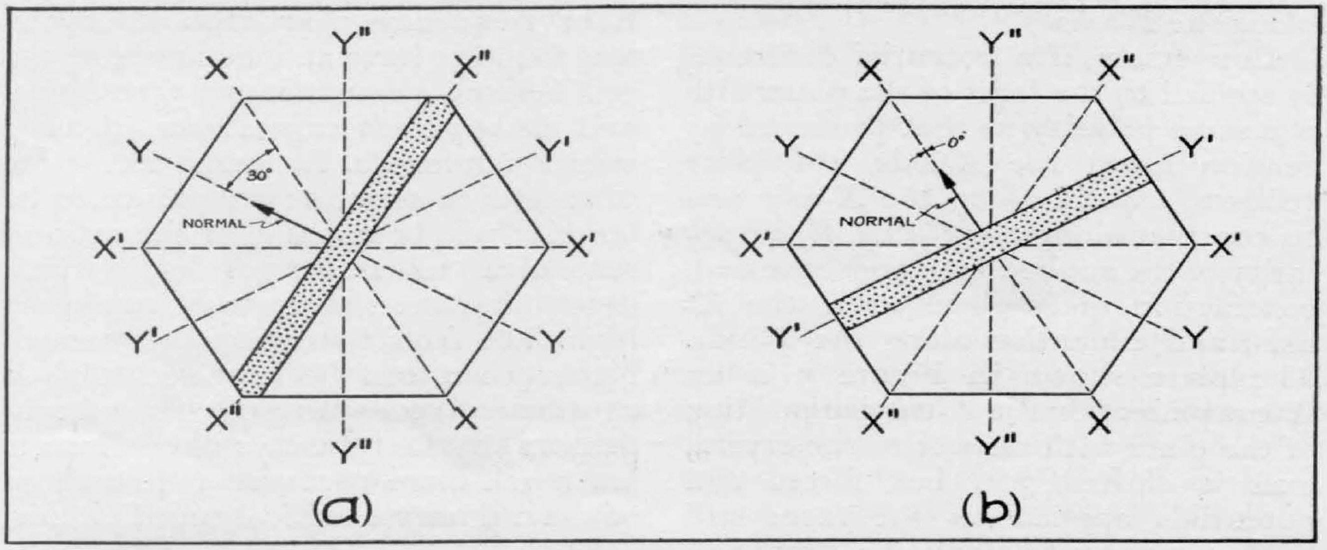

Figure 2. Cross sections of the quartz crystal represented in Figure 1 taken in planes perpendicular to the optic axis: (a) A Y-cut plate, (b) An X-cut plate

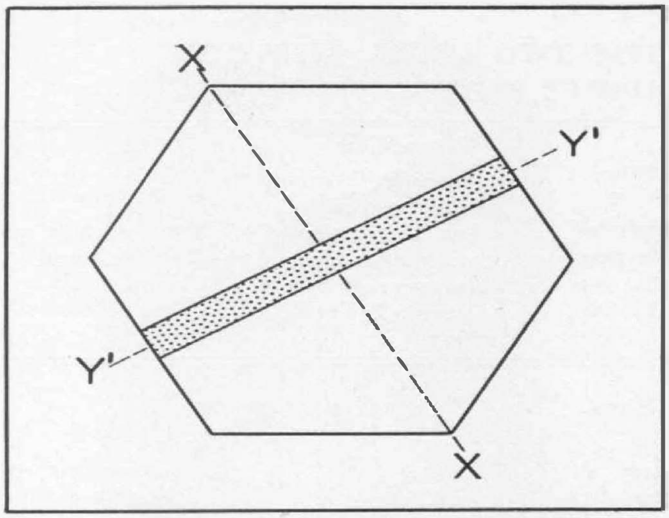

FIGURE 3

electric effect which holds no matter whether the plate is X-cut or Y-cut. If we refer to Figure 3, in which, to avoid confusion, only one pair of axes is shown, the following explanation is made clearer. If compression is applied along the *Y*-axis, opposite charges are developed on the two largest faces of the plate (in Figure 3, those parallel to the *Y*-axis). For tension, the signs of the charges are reversed. If the mechanical stresses are applied along the *X*-axis, tension gives charges on the same two faces of the same polarity as compression along the *Y*-axis, and compression produces the same polarity of charge as tension along the *Y*-axis.

Conversely, if a potential difference is applied to the faces of the plate with the same polarity as that produced by tension along the *X*-axis, the plate tends to expand along the *X*-axis and to contract along the *Y*-axis. If the polarity of the applied voltage is reversed, contraction takes place along the *X*-axis, and expansion along the *Y*-axis. The plate shown in Figure 3 is an *X*-cut plate. For the *Y*-cut the position of the plate with respect to the crystal axes is shifted 30°, but forces and potentials applied on the faces still have components along the axes, and the piezo-electric effect is similar in the two types of cut. Theoretically, there should be no piezo-electric effect along the *Z*-axis, but (due perhaps to imperfections in crystal structure) an electric field applied along this axis can often be made to produce changes in dimensions.

If a quartz plate is placed in an alternating electric field, the change in dimensions takes place at the frequency of the impressed field. The plate has a definite resonant frequency of mechanical vibration, depending on its dimensions, mass, elasticity, etc., and, if the applied voltage is of this frequency, amplitudes of vibration are obtained several times greater than at frequencies far from resonance. Since the phenomenon of resonance is the same in both mechanical or electrical systems, the piezo-electric nature of the quartz crystal furnishes a means of relating the two.

When used as the frequency-determining element in a vacuum-tube oscillator, the quartz plate appears to the rest of the oscillator circuit as a very sharply tuned resonant electrical network having values of resistance, capacity, and inductance which depend on the mechanical coefficients of the plate. As an example of the magnitudes involved, a given crystal* with a resonant frequency near 1100 kilocycles was found to have an inductance of 330 millihenrys, a resistance of 5500 ohms, and an apparent capacitance of 0.065 micromicrofarads. Although this value of resistance seems at first glance to be large, it will be noted that the ratio of reactance to resistance ($\frac{X}{R}$), which determines the sharpness of tuning, is high. The facts that this is very much higher than can be obtained with a tuned circuit consisting of coils and condensers and that the crystal coefficients are much more permanent than those of the ordinary electrical tuned circuit,

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*Van Dyke, "The Piezo-Electric Resonator," *Proceedings of the I. R. E.*, June, 1928.

make the crystal an excellent device for stabilizing the frequency of a vacuum-tube oscillator. When used for this purpose, it takes the place of an electrical tuned circuit in determining the frequency of the oscillator.

It should be noted that the frequency of a vacuum-tube oscillator is not solely determined by the resonant frequency of the *LC* circuit, of the crystal, or of any other so-called frequency-determining element, because the oscillator operates at the frequency for which the total circuit reactance is zero. Since the tube itself has definite input and output impedances, these are a part of the circuit impedance and influence the frequency. In a piezo-electric oscillator, the capacitance due to the exciting electrodes and to the quartz and air dielectrics also modifies the operating frequency.

Figure 3 shows a piezo-electric oscillator circuit* in which the quartz plate is connected between the grid and filament and a parallel circuit of inductance and capacitance is connected in the plate circuit of the tube. The latter operates merely as an inductance for adjusting the plate load to the proper operating value. Since the quartz plate is shunted by the capacitance introduced by its holder and by the apparent input capacitance of the tube, it has an inductive reactance at the frequency assumed by the oscillator in order that the total circuit reactance be zero. The crystal has a resonance curve (reactance against frequency) sharper than an electrical tuned circuit, and a relatively small change in frequency is necessary to make the inductive reactance of the crystal sufficient to cancel the capacitance shunted across it.

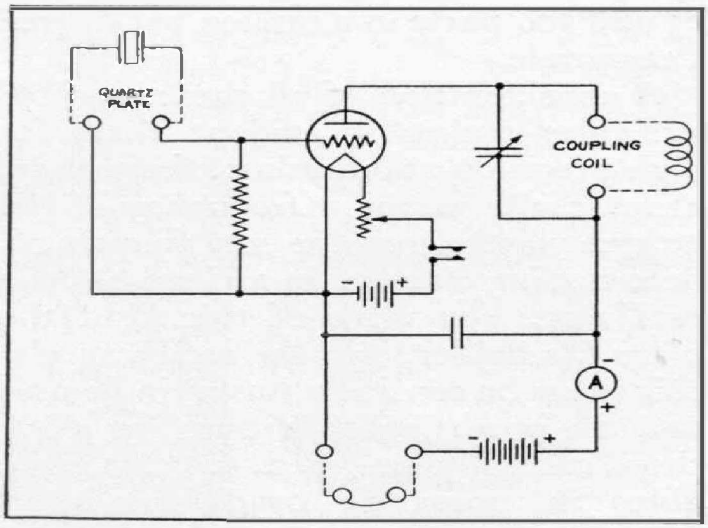

FIGURE 4. Wiring diagram for a typical piezo-electric oscillator

The amount of this shunt capacitance and therefore the frequency of the oscillator are subject to variation: (*a*) Due to the holder capacitance, by changing the electrode spacing; (*b*) Due to the tube input capacitance, by changing the plate voltage or the tuning of the parallel circuit. Some idea of the order of magnitude of these changes may be obtained from the results of measurements made upon an oscillator like that used in Figure 3. Using a low-powered vacuum tube operated at a moderate plate voltage it was found that tuning the plate circuit caused a frequency change of from 50 to 100 parts in a million and that changing the electrode spacing (air gap) caused changes of the order of 1000 parts in a million. Changes caused by varying the plate and filament voltages were negligible.

Another very important factor which influences the operating frequency of a piezo-electric oscillator is the fact that the resonant frequency of the plate changes with temperature by an amount which is somewhat different for the X- and the Y-cut plates. In an X-cut plate, the temperature coefficient is negative (i.e. the frequency decreases for increasing temperature) and amounts to between 10 and 25 parts in a million per degree Centigrade. The temperature coefficient of a Y-cut plate is positive and may be between

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* This is the same circuit that is used in the General Radio TYPES 275 and 375 Piezo-Electric Oscillators.

25 and 100 parts in a million per degree Centigrade.

A consideration of all these possible variables makes it evident that, for high-precision standards of frequency, at least, the resonant frequency of the quartz plate is not the sole frequency-determining element in a piezo-electric oscillator. For work of this kind the plate, its holder, and the oscillator circuit must be considered as a single unit and the operating conditions for all of them carefully specified. Certain variables in operating conditions influence the frequency more than others, and, although it is often possible to ignore some of them, it must be remembered that this can be done only at a sacrifice in the precision with which the desired frequency is maintained. For example, some of the quartz plates manufactured by the General Radio Company are sold in their holders for use in any oscillator that the customer may select. He cannot, however, expect to obtain from them an accuracy in a specified frequency of more than 0.1 per cent.

It is the influence of factors outside the quartz plate itself which makes the problem of frequency control in power oscillators so difficult. Not only is the controlling plate subject to the usual variables that we have mentioned, but in addition its temperature is liable to change due to the internal heating caused by the passage of heavy currents in the crystal circuit. It is evident therefore that the production and calibration of power crystals are parts of the manufacturing of the power oscillator. This is the reason why the General Radio Company does not interest itself in the manufacture of power crystals, but confines its activities to the production of quartz plates for use in low-power frequency standards. It also explains why a power limit is imposed upon all General Radio quartz plates.

An interesting set of difficulties appears when the quartz plate is being given its final adjustment and test before being put into use. Some plates are found which exhibit the phenomenon known as "twinning," that is, a reversal in the piezo-electric effect in certain portions. This effect may be great enough to render the plate useless. Other plates control the vacuum-tube oscillator at more than one frequency. Here the operating frequency shifts or "jumps" as a result of making small changes in circuit constants or in the operating temperature. It is sometimes possible to correct this condition, but, if not, the plate must be discarded and another one prepared.

II

The General Radio Company can supply, for use as frequency standards, quartz plates and bars for any reasonable frequency and degree of precision. All must, of course, be made to order, but by establishing two definite groupings to meet most needs, it has been possible so to standardize the routine of specifications, manufacture of plates and holders, and calibration that the prices are considerably less than if each plate had to be processed as a separate unit. The type numbers 376 and 276-A have been assigned to these two standardized groupings, both of which are described in subsequent paragraphs.

General descriptions of plates and bars not in these two groups cannot be given inasmuch as questions of oscillator design, temperature control, and holder construction are usually involved.

TYPE 276-A Quartz Plates are supplied to have a frequency somewhere in the 160-meter amateur band. They are unmounted and their frequency can be relied upon to within 0.25 per cent. of the specified value. Plates for the 80-meter amateur band have been discontinued.

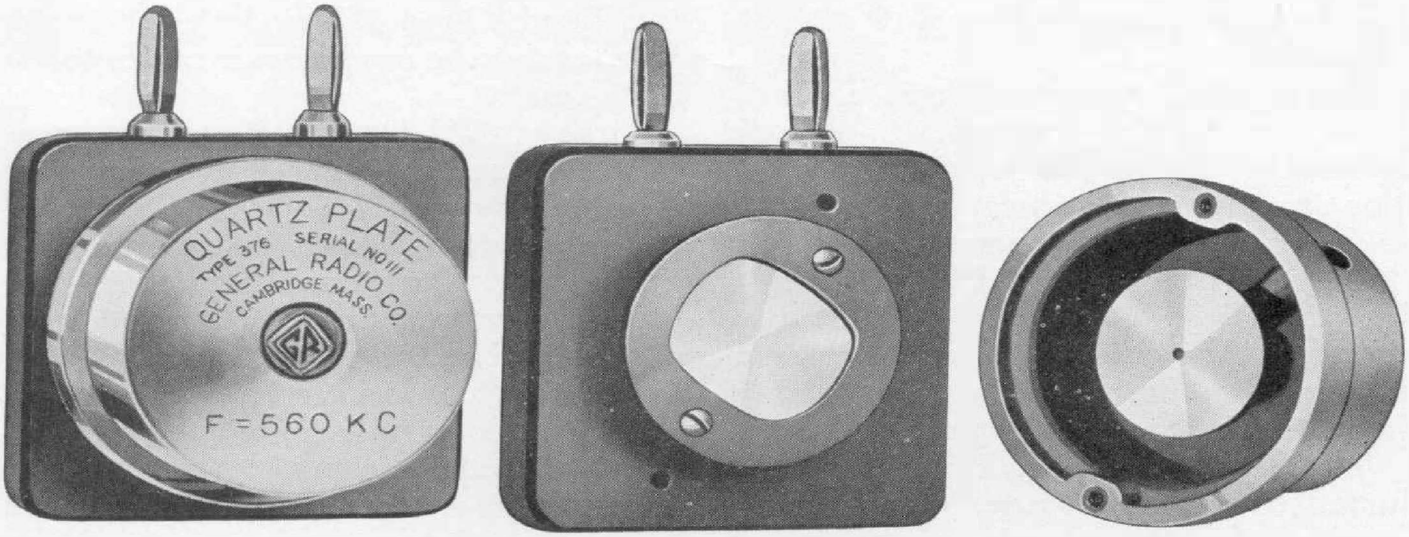

Figure 5. Plate holder for General Radio Type 376 Quartz Plates. The quartz plate rests on the lower electrode and is held in place by the fibre retaining ring

Type 376 Quartz Plates are calibrated and sold in the plug-in holder shown in Figure 5. This consists of a metal base plate mounted on bakelite over which is placed a metal cap carrying the upper electrode. The crystal rests loosely in a fibre ring and the frequency is adjustable over narrow limits by changing the air gap with the screw carrying the upper electrode. After the crystal has been adjusted to the correct frequency, the air gap adjustment is sealed. The frequency is again measured with the greatest possible accuracy in terms of the General Radio Company's highly precise standard-frequency assembly. The result of this measurement, expressed with the proper number of significant figures, becomes the certified frequency.

A certificate of accuracy is furnished which states the frequency of the plate, the conditions under which the calibration was made, and the range of operating conditions over which the guarantee of accuracy is valid. The certified frequency and the percentage accuracy is marked upon the plate holder.

A reclassification of General Radio crystals has recently been made and the classification and prices set forth in Catalog E, Second Edition, are discontinued.

FREQUENCY RANGES

The following frequency ranges will be recognized:

100–200 Kilocycles: Plates in this range vibrate along the longest dimension and are Y-cut.

200–400 Kilocycles: Plates that will operate satisfactorily in this range cannot be mounted in the Type 376 Plate Holder because of their size and inasmuch as frequencies in this range can be obtained as harmonics from plates in the 100- to 200-kilocycle range, Type 376 Quartz Plates will not be supplied in this range. If necessary, plates for this range can be supplied in special mountings.

400–1800 Kilocycles: These plates vibrate along the thickness dimension and are Y-cut.

ACCURACY CLASSIFICATION

Type 376-B Quartz Plates are adjusted to within 25 per cent. of any specified frequency within the above ranges, and their frequency can be relied upon to within 0.1 per cent. This accuracy is guaranteed if the plate is operated at low powers and within the temperature range between 18 and 32 degrees C.

TYPE 376-C Quartz Plates are adjusted to within 5 per cent. of any specified frequency in the above ranges. The statement of accuracy is the same as for TYPE 376-B Quartz Plates.

TYPE 376-D Quartz Plates are adjusted to within 0.1 per cent. of any specified frequency within the above ranges. The statement of accuracy is the same as for TYPE 376-B Quartz Plates.

TYPE 376-F Quartz Plates are adjusted to within 0.03 per cent. of any specified frequency and are calibrated only in a General Radio piezo-electric oscillator or with an oscillator which meets with our approval. The frequency of the oscillator and plate will be within 0.03 per cent. of the nominal frequency of the plate when the temperature is kept between 20 and 24 degrees C. (68 to 75 degrees F.). This class corresponds rather closely to the old Class E which was maintained to meet the requirements of American broadcasting stations. The Class F limit is equivalent to an allowable deviation of 500 cycles at the upper limit of the band (1500 kilocycles); at lower frequencies the deviation is correspondingly less.

TYPE 376-H Quartz Plates are supplied and calibrated to within 0.01 per cent. of any specified frequency in the above ranges. These plates must be calibrated in approved oscillators and the temperature must not deviate from a given value (near 50 degrees C.) by more than 0.25 degree C. Ordinarily it will be necessary for the customer to supply for calibration the temperature-control box he proposes to use, but before shipping an oscillator it would be well to get definite instructions on this point. When the temperature-control box is one built by the General Radio Company, it will not need to be returned.

PRICES AND CODE WORDS

Type	*Code*	*Price*
276-A	LABOR	$15.00
376-B	LAGER	40.00
376-C	LAPEL	45.00
376-D	LARVA	60.00
376-F	LEPER	70.00
376-H	LEVEL	85.00

MISCELLANY

By THE EDITOR

A NEW booklet giving complete operating instructions for the TYPE 443 Mutual-Conductance Meter is now available and will be sent without charge to owners of the instrument who request it. Address the Service Department of the General Radio Company, being sure to mention the serial number of the instrument with which it is to be used.

CONTRIBUTORS

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The General Radio *Experimenter* is published monthly to furnish useful information about the radio and electrical laboratory apparatus manufactured by the General Radio Company. It is sent without charge to interested persons. Requests should be addressed to the

GENERAL RADIO COMPANY
CAMBRIDGE A, MASSACHUSETTS

RUMFORD PRESS
CONCORD, N.H.