

Design and Performance of Ultraprecise 2.5-mc Quartz Crystal Units

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A 2.5-mc crystal unit has been developed for use in a new, extremely stable frequency standard oscillator. A well-balanced design was achieved by using a 30-mm-diameter, plano-convex, polished quartz plate, coated with gold and operated on its fifth overtone. The quartz plate is mounted on its quiescent edge in an evacuated bulb, and achieves a Q of five to six million, representative of the Q of the quartz itself. The temperature coefficient, current coefficient, frequency adjustment tolerance and frequency aging of the crystal unit are all consistent with a frequency stability in the order of one part in 10^{10} . It was necessary to develop polishing methods that would not disturb the crystal structure of the quartz plate and new methods of orienting the crystallographic axes to achieve better temperature coefficient control. New methods of mounting the quartz plate were found that avoid strain and reduce the effects of shock and vibration. The new crystal unit makes possible oscillators characterized by excellent frequency stability, small and uniform aging and straightforward design. For periods up to one month, the frequency stability of such standards compares favorably with that of atomic frequency standards.

I. INTRODUCTION

The quality of a quartz crystal frequency standard is determined by the crystal-controlled oscillator, and particularly by the mechanically vibrating, piezoelectrically excited quartz plate. Special quartz crystal resonators, characterized by high Q, excellent frequency stability under shock and vibration, and small change with time, have been developed for use in a new general-purpose, extremely stable frequency standard.

The development of improved oven and oscillator circuits has contributed substantially to this improved standard, and will be reported in a separate article. Over-all performance of an experimental oscillator has been reported briefly,¹ and similar oscillators are in operation at the Na-

tional Bureau of Standards (see Section 4.5 of this paper), the Naval Research Laboratory and Bell Telephone Laboratories.

In this article particular emphasis will be given to the quartz resonator, considering (a) the design principles, (b) the development of the present design and the related processing techniques and (c) the properties of the quartz resonator as a circuit element, including its thermal, mechanical and temporal characteristics. In order to limit the scope, a cursory knowledge^{2,3} of crystal unit fabrication will be assumed, and only a brief recapitulation of facts already published will be given.

The development of highly stable crystal resonators is a continuing work, because each new achievement in frequency accuracy and stability generates the need for still greater accuracy and stability; to meet these needs, the underlying causes of frequency aging and many other special aspects of the behavior of crystal-controlled oscillators must be more fully understood. A solution of these problems will require further fundamental investigation into the nature of the materials involved.

Such development work for improving quartz oscillators is not likely to be made superfluous in the immediate future by atomic and molecular frequency standards. Atomic standards, whose frequency stability is better than a part per billion for very long periods of time, employ quartz oscillators as part of their circuitry. Thus, their short-time stability is that of the crystal-controlled oscillator. As atomic standards are improved, the need for higher-Q crystal resonators will be increased. Furthermore, as the long-time frequency stability of quartz oscillators is improved, they can be operated for longer periods of time independent of an atomic frequency reference. Use of the oscillator alone would, of course, reduce the size, weight and complexity of the frequency standard.

II. DESIGN PRINCIPLES

In this section the significant parameters in the design of a crystal unit of the highest practical precision are considered, including (a) use of edge-mounted crystal plates operating in high-frequency thickness shear, (b) desirable crystal unit characteristics and their correlation to a well balanced design, (c) the role of quartz plate size and (d) the independence of Q and inductance, and the best choice for the value of the inductance.

There are two basic design concepts in use today for the construction of high-precision quartz crystal units. One makes use of low-frequency, large-size quartz plates supported at nodal points by arrangements of cords and springs or rods, or by soldered wires. Its advantage lies in a high potential Q and a large frequency-determining dimension. Its dis-

advantage lies in the fact that the mounting structure is part of the frequency-determining, mechanically vibrating portion of the crystal unit, making it unstable with respect to shock and vibration and contributing to frequency aging. The other design concept, and the one to be described here, is the use of edge-mounted crystal units in high-frequency thickness shear operation in order to decouple the mechanically vibrating portion of the quartz plate from the mounting. By use of convex shaping, the mechanical vibration can be confined to the center of the crystal plate, leaving the edge quiescent. Such units can be more closely adjusted to frequency and have improved frequency stability characteristics and other operating advantages as shown in Section IV. The construction details are quite different, relying on carefully designed machines rather than on individual craftsmanship.

The crystal unit or resonator for a primary frequency standard must be characterized by high Q , low temperature coefficient of frequency at the operating temperature, low frequency drift with time, low current coefficient, relatively high impedance and small frequency-adjustment tolerance. There is no particular order of importance among these factors, since neglect of any one of them will largely nullify the precision that would be attainable through the use of extreme care with the others.

These requirements, along with performance factors for the oven and circuit, fall naturally into several groupings, with each factor in a group being interrelated with other factors in that group. One combination is the Q of the crystal unit, its frequency accuracy (since frequency adjustment by circuit means is limited by the probable stability of the controlling circuit element) and the phase stability of the oscillator circuit. Other combinations are (a) the crystal unit frequency-temperature characteristics such as temperature coefficient and susceptibility to thermal shock, the oven temperature, and the degree of oven temperature control; (b) the crystal unit frequency-current characteristic, the oscillator current level and the oscillator current control. Care must be taken to see that no combination contributes more than about five parts in 10^{11} frequency change if the over-all design is to be stable to one part in 10^{10} .

In the design of AT-cut high-frequency shear mode crystal units the following two facts must be considered: (a) the Q of the quartz itself, at normal temperatures, increases as the frequency of operation is decreased⁴ and (b) the lowest frequency at which the crystal unit can be operated without significant external losses is severely restricted by the availability of sufficiently large quartz plates. Since circuit phase stability is likely to be better at lower frequencies where the Q of quartz is higher, there is a definite advantage in the use of large quartz plates.

To achieve a Q limited only by the quartz itself, other causes of energy dissipation must be reduced to a negligible point. The following have been found effective:

(a) evacuate the enclosure, thus removing air damping;
 (b) choose the size and shape of the quartz plate so that the edge is quiescent, thus eliminating energy loss through the edge and the mounting structure;

(c) polish the crystal plate major surfaces, thus removing minor imperfections that can dissipate energy in the active portion of the quartz plate (an improvement in Q of about 10 per cent can be achieved).

Once condition (b) has been met, the Q cannot be increased at a given frequency by changing the inductance of the unit, by using other modes of vibration or overtones, or by using electrodes of a different size. Under these conditions, the ratio of L_1 to R_1 , and thus the Q , in the equivalent electrical circuit, Fig. 1, has been found to remain essentially constant, subject only to the three operations enumerated above. This is, of course, reasonable, since there is no change in the source of energy dissipation.

The inductance can be selected, therefore, to operate at an optimum impedance for a better match of crystal unit to circuit. An optimum impedance may be achieved by using an overtone mode of vibration (reversal of phase in the thickness direction). For a given frequency, an overtone mode unit requires a thicker quartz plate (desirable for frequency stability) and has values of L_1 and R_1 of Fig. 1 that are larger by the cube of the overtone employed. The impedance can also be raised by using other modes of vibration that are permitted by reversals in phase along the length or width of the quartz plate, or by parallel field excitation.⁵ These methods, however, are less desirable than the use of the harmonically related overtone mode, since they do not permit the desirable increase in the thickness or frequency determining dimension.

Employing these principles, the crystal unit design proceeded about as follows:

i. The largest practical quartz plate, in view of the quartz supply and probable demand, was selected (30 mm diameter).

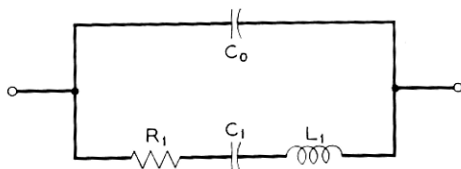


Fig. 1 — Equivalent circuit of crystal unit in vicinity of its operating frequency.

ii. The lowest frequency that could be used without energy loss at the edge of the quartz plate was determined (2.5 mc).

iii. The highest overtone (which is also the greatest thickness and highest $L_1 C_1$ ratio) that would allow a practical adjustment tolerance was chosen (fifth overtone and one part per 10^7 frequency adjustment tolerance).

The resulting crystal plate is believed to have the highest Q, the lowest frequency and the best impedance level that can be obtained from a 30-mm quartz plate in which the edge and mounting structure are not part of the mechanically vibrating (frequency-determining) part of the crystal unit.

III. DEVELOPMENT OF DESIGN AND PROCESSING TECHNIQUES

3.1 *Experimental Determination of Quartz Plate Size and Contour*

In a study⁴ to determine the optimum contour and overtone for AT-cut, plated, 12.5-mm-diameter quartz plates, a series of measurements were made on several quartz blanks of different thicknesses, resonant at approximately 0.7, 1, 3 and 5 mc. Progressive contours from flat to the maximum permitted by the individual blank thickness were used. When these data were correlated, it became evident (a) that the maximum Q obtainable was an inverse function of frequency and (b) that there was a lower limit of frequency below which the Q fell off and became erratic regardless of contour. In other experiments a variation in electrode thickness from 700 to 2100 angstroms at 5 mc failed to show any effect on Q. Likewise, carefully polished quartz surfaces did not show more than a 10 per cent improvement in Q over that of carefully lapped and etched plates. Data taken at 10 mc on crystal units having quartz plates vibrating in the third, fifth and ninth overtone indicated the same maximum Q. This represents a 3-to-1 difference in quartz plate thickness and a 27-to-1 difference in the equivalent electrical inductance and resistance. Data were also taken on larger plates and on higher-frequency plates. The Q data from these tests are summarized on Fig. 2, which shows the most probable room temperature value for the internal friction of quartz, ranging from 15×10^6 at 1 mc to 0.15×10^6 at 100 mc, and the frequency limitation for 15-, 30- and 90-mm diameter plates. Therefore, with 30 mm having been chosen as the largest practical size for the quartz blank, the operating frequency of 2.5 mc is determined.

A chart relating optimum contour to overtone and frequency for AT-cut half-inch plano-convex plates can be found in an earlier paper by the author.⁶ By linear enlargement or reduction of the dimensions, the ap-

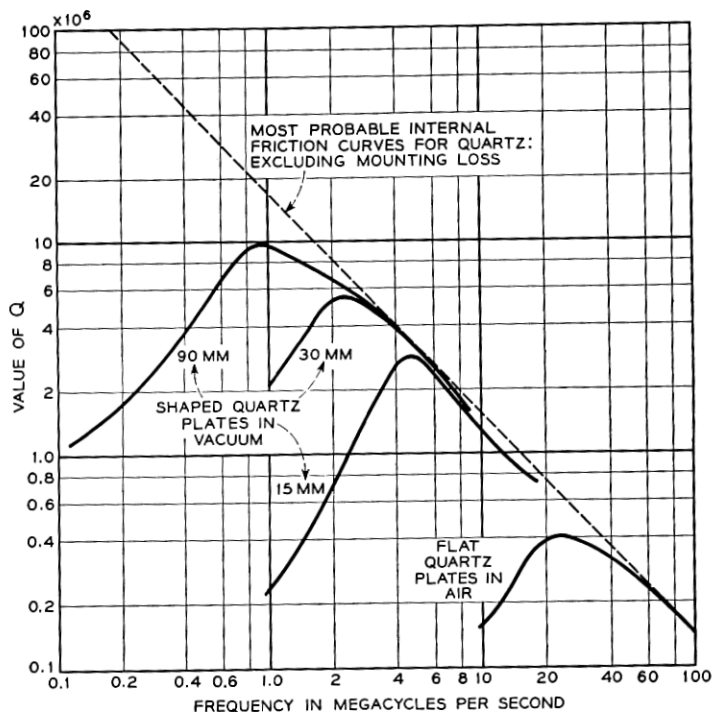


Fig. 2 — Value of Q vs. frequency for properly shaped quartz plates, 15, 30 and 90 mm in diameter. The value of Q is independent of the overtone mode of operation.

proximate contour for larger or smaller blanks can be determined, indicating a plano-convex contour 4 inches in radius for the 30-mm diameter, fifth overtone, 2.5-mc quartz plate.

It is well known² that a nodal plane exists that is centrally located between the faces of a quartz plate vibrating in thickness shear. For this reason, many AT-cut crystal units are designed with a double convex contour, with the mounting points on or near the nodal plane. It has been found, however, that, when the frequency, size and contour are chosen to produce the maximum Q , a plano-convex shape may be used with no loss in Q , and with great benefit in temperature-coefficient control and general handling during fabrication.

The final dimension to be determined, the thickness, was chosen to provide the correct impedance level for minimizing the effects of lead wire capacitance and circuit variations. A thickness of 3.4 mm was chosen, permitting operation on the fifth harmonically related overtone with a series-resonant resistance of 55 ohms and an inductance of 19.5 henries

3.2 *Experimental Development of Quartz Polishing Methods*

The benefits derived from the use of polished quartz plates are improved electrical performance, particularly frequency stability at low current levels, and reduced frequency aging. The surface is not only more easily cleaned, since there are no scratches and fissures to trap contaminants, but the surface area is greatly reduced, requiring less gold for a conducting electrode and reducing the effects of residual contaminants.

The polishing techniques that have been developed differ in many respects from those used in the surface finishing of glass lenses. It is customary in polishing glass lenses to use a carefully prepared pitch lap and rouge, or its equivalent. Since pitch is a brittle material, close control over the curvature can be maintained. Furthermore, small scratches resulting from unavoidable foreign particles are reduced by the use of sufficient pressure to cause local melting and flow of the glass.

Such methods have not been found suitable for contoured quartz plates, nor are they necessary. The curvature is not critical, so there is no need for a brittle lap. Quartz is harder and has a higher melting point than glass and is crystalline in form, and any melting or scratch removal is both undesirable and difficult. A soft material such as an asphalt or cork mixture has proved better for the lap, since it can yield under pressure to give a uniform polish and can absorb foreign particles that would otherwise scratch the surface. Fig. 3 shows a polishing machine using two Trojan automatic bowl-feed sphere polishers. The polishing bowl has been covered with a $\frac{1}{16}$ inch sheet of cork and rubber (Corprene, Armstrong Cork Co.). Barnsite, a form of cerium oxide, is used as the polishing agent.

If polishing time is to be kept within practical limits, care must be given to surface preparation prior to polishing. There are two requirements: first, that surface penetration be small and second, that good thickness control be maintained, since final polish must occur at a thickness determined by the resonant frequency of the quartz blank. Both of these requirements have been met by the use of a resinoid-bonded diamond wheel to generate the convex surface. The apparatus is similar to diamond curve generators used in the lens industry, with the following exceptions: (a) a vacuum chuck is used to precisely hold the quartz blank; (b) a 3-inch-diameter, 180-mesh, resinoid-bonded diamond wheel is used and (c) a positive mechanical feed at 0.012-inch per minute is used. Thickness can be controlled within 0.01 mm, and the time of grinding is less than 3 minutes. The penetration is less than 20 microns, and may be removed by lapping for a few minutes with a cast-iron lap and emery mixture, followed by 5 to 10 minutes of polishing.

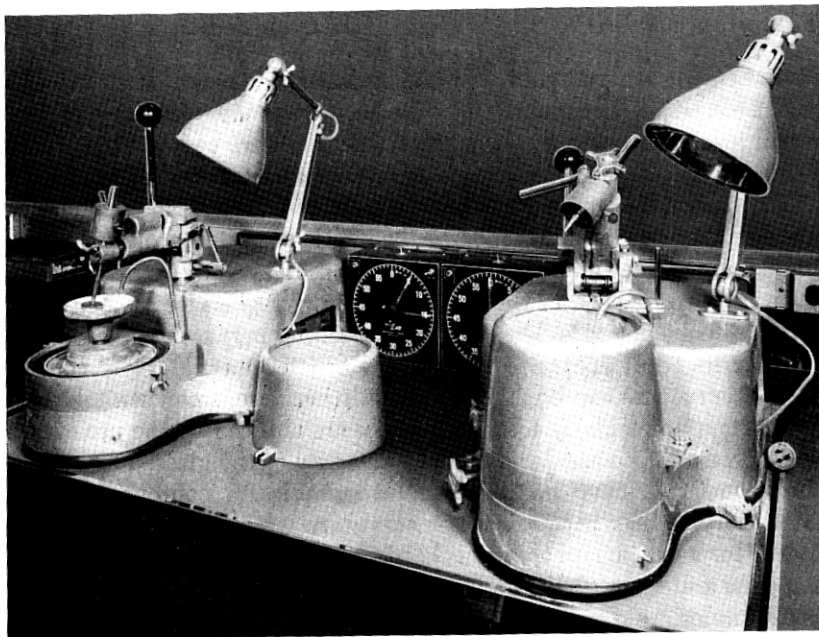


Fig. 3 — Equipment used to polish quartz crystal plates.

Three experimental procedures were developed in connection with the study of polishing techniques and the resultant quartz crystal surfaces:

First, a 200-power microscope was equipped with a dark field condenser, which clearly delineated scratches and cracks in the quartz surface. Fig. 4 is an enlargement of a picture taken through this microscope of what appeared to the unaided eye to be a well-polished blank. Since the blank is curved, all portions are not in focus in the picture. By refining the polishing technique, i.e., choosing best pressure, stroke and time, as well as the best preparation, surfaces that appeared clear by this inspection were consistently produced with 5 to 10 minutes of polishing.

Second, the spread of values for the Bragg angle of the $01\bar{1}$ face was measured, using a double-crystal goniometer.⁷ This apparatus, shown in Fig. 5, is used principally for orientation measurements connected with the temperature coefficient. However, by using the same refined polishing techniques for the reference crystal, extremely sharp curves were obtained when the amplitude of the reflected X-ray beam was plotted against orientation. Fig. 6 shows typical results for quartz plates at various stages of polish. In particular, the use of etching to remove strained, slightly misoriented material is shown to be unnecessary sub-

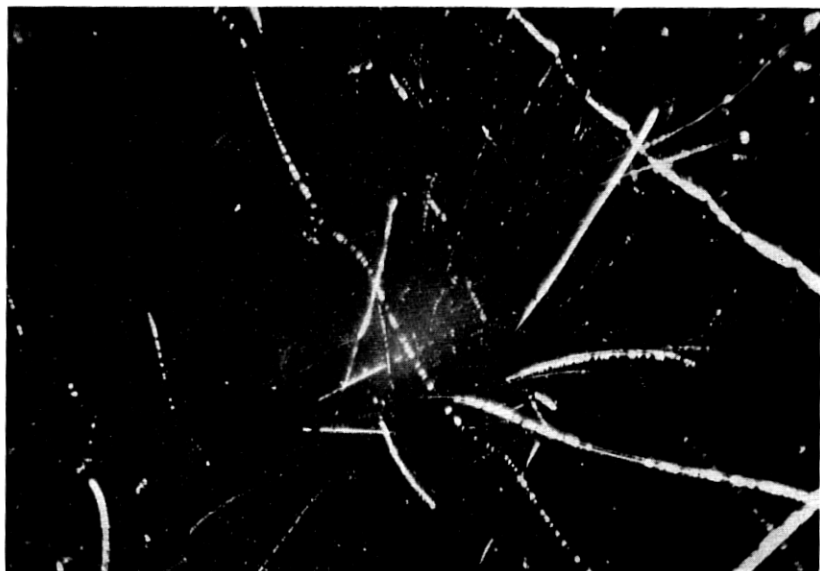


Fig. 4 — Dark-field photomicrograph of polished quartz plate; magnified 1000 \times .

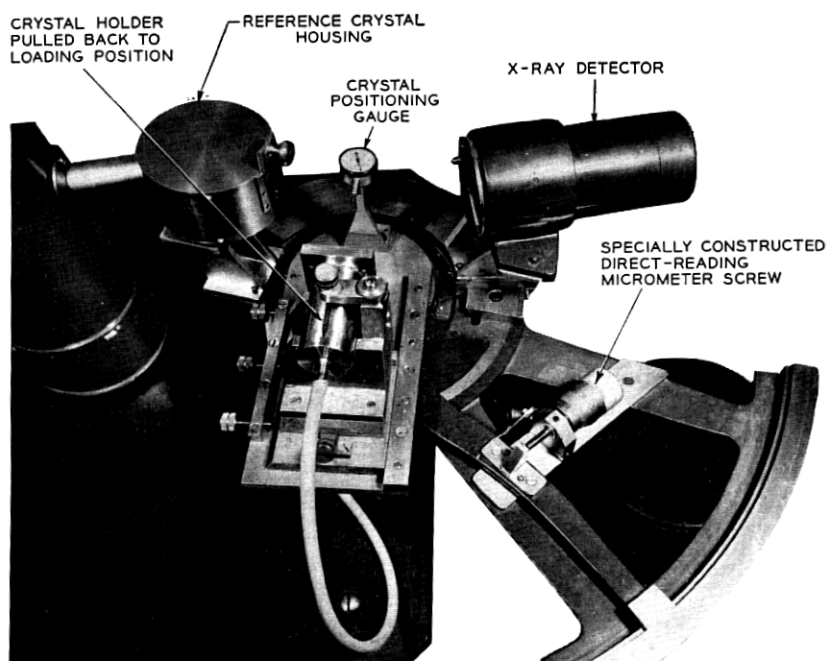


Fig. 5 — Double-crystal goniometer used for orientation measurements.

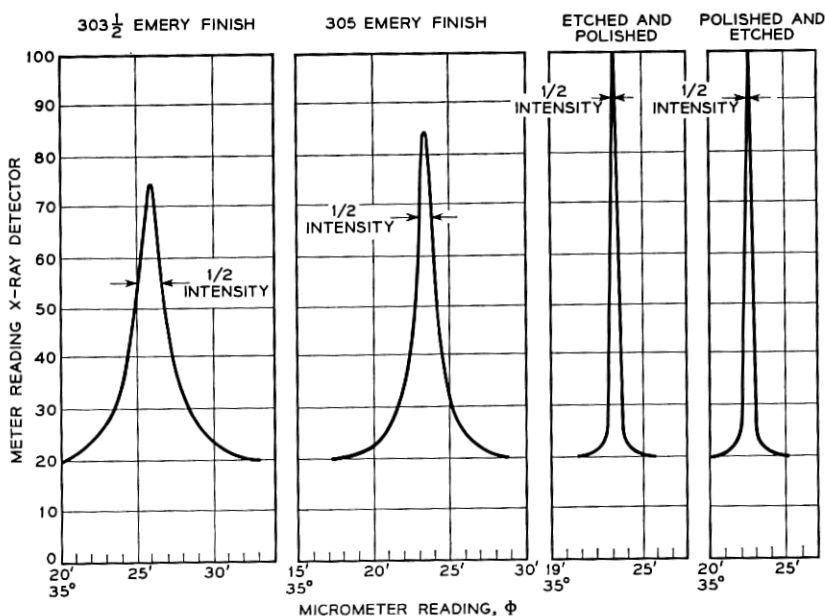


Fig. 6 — Typical response of the double-crystal goniometer for quartz plates at various stages of polish.

sequent to polishing, and therefore this is better performed as the last step before polishing.

Third, samples of polished quartz plates were studied by electron diffraction, following methods outlined by Arnold.⁸ The advantage of this method lies in the fact that a beam of fast electrons (50 kv) will penetrate only a few hundred angstrom units before diffraction takes place, thus involving only the first few surface layers of the quartz plate. Should the formation of a misoriented or amorphous surface layer result from the polishing processes, it would be evident in the resulting diffraction pattern. Fig. 7 shows one such pattern obtained from a quartz plate polished using asphalt and barnsite. The lines observed are known as Kikuchi lines, and it is sufficient for the purpose of this discussion to quote from Arnold:⁸ "Kikuchi line patterns are indicative of the highest type of crystalline perfection, since the slightest distortion of the crystal would cause the Kikuchi lines to spread out and become lost in the general background radiation."

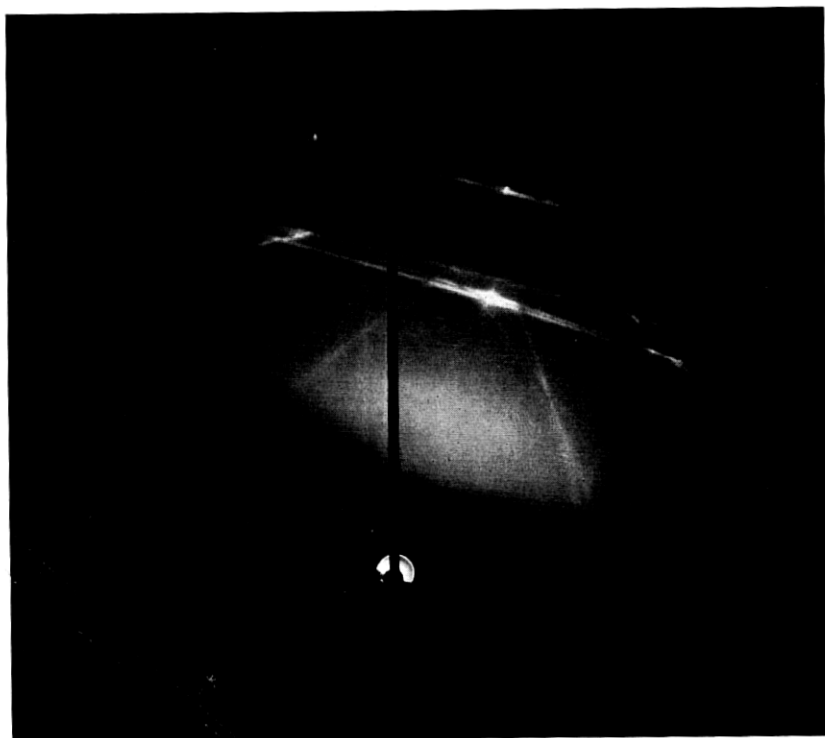


Fig. 7 — Electron diffraction pattern, showing Kikuchi lines.

3.3 *Studies of Correlation Between X-Ray Orientation and Temperature Coefficient*

The relationship between the resonant frequency of the quartz resonator, f , and temperature, t , can be expressed by

$$\frac{f}{f_i} = 1 - (24 \times 10^{-11})(t_0 - t_i)^2(t - t_i) + (8 \times 10^{-11})(t - t_i)^3, \quad (1)$$

where

f_i = frequency at inflection temperature, 27°C,

t_i = temperature of inflection point,

t_0 = temperature at which the temperature coefficient is zero.

The value of $t_0 - t_i$, which establishes the temperature at which the temperature coefficient of frequency is zero, is a function of the orienta-

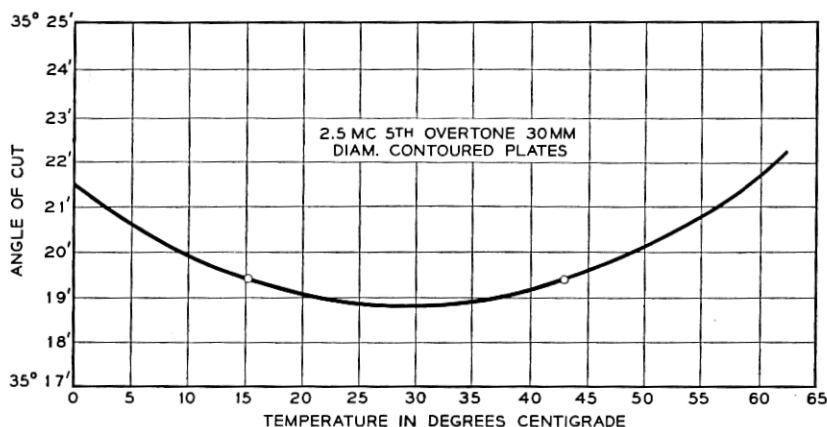


Fig. 8 — Temperature at which the temperature coefficient of frequency is zero vs. the crystal plate orientation about the x axis.

tion of the quartz plate with respect to its crystallographic axes, in particular the rotation about the x axis, Φ . Fig. 8 shows the best determination to date of this relationship. By plotting f versus t for various values of t_0 in (1), a family of curves is produced, as shown in Fig. 9. A close control over the angle of cut not only permits specification of an operating temperature, t_0 , near room temperature, but also provides a much better temperature coefficient in the vicinity of t_0 . This makes it less necessary to be concerned about an exact determination of t_0 or about a small shift in the oven control temperature. Determination of the angle to a few tenths of a minute of arc is very desirable, along with a close correlation between the measured angle and the observed temperature coefficient. The problems are related to the following requirements:

- (a) an X-ray beam capable of resolving $0.1'$ of arc;
- (b) a crystalline surface sufficiently free from misoriented quartz;
- (c) a method of defining the plane that controls the temperature coefficient;
- (d) sufficiently accurate jigs and fixtures.

The double-crystal X-ray goniometer was shown in Fig. 5; it is a modified General Electric XRD1. Requirement (a) above is fulfilled by the use of a polished reference crystal from which a well-defined beam is reflected.⁷ A quartz surface prepared as described above (Section 3.2) is more than adequate to meet requirement (b).

The nodal plane of Section 3.1, which controls the temperature coefficient, is, of course, physically inaccessible. However, an adequate surface [requirement (c)], from which to determine the temperature coefficient

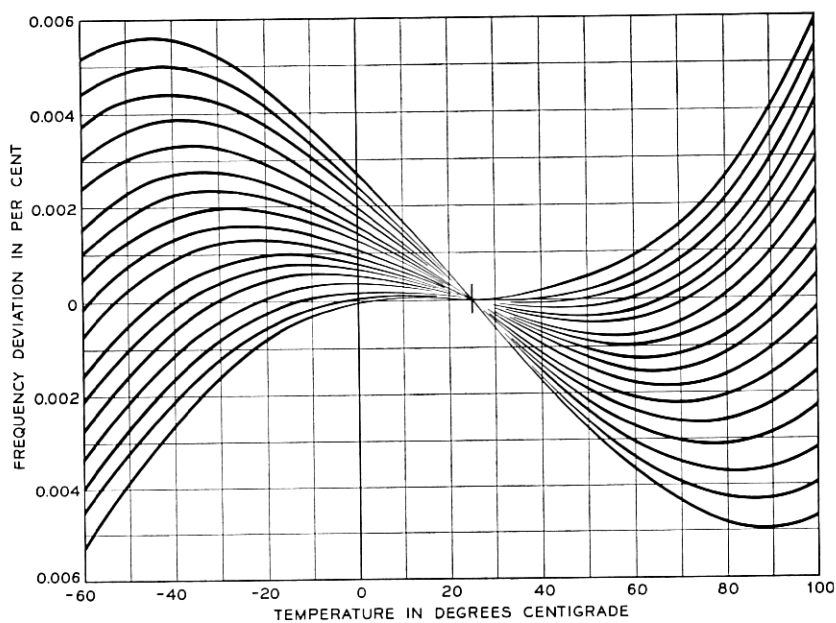


Fig. 9 — Frequency vs. temperature for different values of t_0 , the temperature of zero temperature coefficient.

in contoured quartz plates, may be obtained by plano-convex shaping. The orientation of the convex side has almost no effect on the temperature coefficient, since a slight tilt of this surface with respect to the flat side only shifts the point of greatest thickness a little off center. The 16-mm diameter electrodes more than cover the actively vibrating portion of the crystal unit, and there is no measurable effect on performance.

The principal problem in measuring the effective orientation of the flat side — that of physically defining the surface — resolves itself into a choice between two methods of securing the crystal to the goniometer table: (a) the use of three reference points and (b) the use of a reference plane. If irregularities exist in the quartz surface, there is a possibility that one or more points will not be representative of the controlling surface at the center of the plate. Likewise, when a reference plane is used, the presence of dust or contamination or a slight departure from flatness can shift the orientation. The work described in this article was done using a vacuum chuck with a polished reference surface. Assurance of cleanliness and reasonable flatness was obtained by observing inter-

ference rings between the polished quartz surface and the surface of the vacuum chuck.

Sufficient measuring accuracy in the X-ray fixture itself [requirement (d)] was obtained by the use of a micrometer screw operating on a ball precisely imbedded in the arm of the goniometer (Fig. 5). This use of a linear measuring device to measure arc is permissible because of the limited range involved. In operating the goniometer, use is made of the 01 $\bar{1}$ atomic plane at an angle determined to be $38^{\circ}12.7'$ from the optic axis. The desired orientation for zero temperature coefficient of frequency in the vicinity of $35^{\circ}20'$ is about 3° from this reference plane. Therefore, the value for the radius of the goniometer arm was chosen so that the micrometer would be direct reading (one revolution per degree) and exactly correct at $38^{\circ}12.7'$ and at two points 3° on either side, with the error at intermediate points not exceeding five seconds of arc. A two-pound weight and cable are used to hold the arm against the micrometer to insure against backlash and uneven tension.

3.4 *New Method of Mounting and Measurements to Determine Its Effectiveness*

A new mounting structure, Fig. 10, was devised for the 2.5-mc crystal unit in order to provide a support that was rigid yet free from the effects

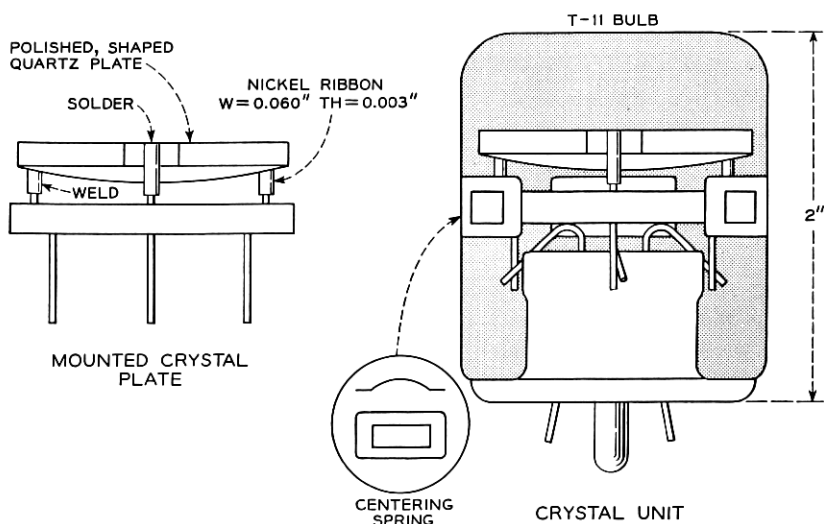


Fig. 10 — New mounting structure combining ruggedness with freedom from strain.

of thermally induced strains. The mounting assembly consists of a pressed-glass disc platform with three fused Kovar terminals. These terminals are welded on one side to the stem press of the glass bulb. The crystal plate is fastened to the terminals on the other side by ribbon-shaped elements of nickel.

The use of the three-ribbon mount permits relatively free radial expansion of the crystal plate, while adequately restraining the plate from translation or rotation during mechanical shock.

Experiments using crystal plates mounted with 0.050-inch rods in place of ribbons have shown that the time for the frequency to recover to within a few parts in 10^8 after a large temperature change (such as an oven shutdown) is reduced from 12 hours for the 0.050-inch rod mount to 2 hours for the ribbon mount. The time for frequency stabilization to about one part per billion per day likewise appears to be affected by residual strains, since it is two weeks for the rod support and two hours for the ribbon support. Experiments using a crystal plate suspended on soft copper wires showed no difference in frequency change with temperature from that of the ribbon-mounted unit, indicating that the ribbon support is essentially strainfree.

3.5 Procedures Used in Forming Electrodes

Electrodes are required in order to couple piezoelectrically to the quartz plate. From the standpoint of stability of the mechanical resonance, such electrodes would be best placed outside of the crystal plate enclosure. However, electrical considerations, such as the value and stability of the static capacitance, require that the electrode be an integral part of the vibrating quartz plate.

Gold is used as the electrode material because of proven characteristics such as ease of deposition, good electrical conductivity, softness, resistance to corrosion and good stability with time. Every effort is made to insure that the gold film, which is formed by evaporation under vacuum, is pure, soft and dense. To be sure, the handling properties of plated crystal units during fabrication are enhanced when certain impurities are present. Zinc and aluminum are effective in making the gold electrode relatively hard, adherent and scratch-resistant. Such electrodes are not, however, best for applications where the highest precision is desired. Experiments have shown that small amounts of impurities (<1 per cent) contribute to frequency-aging, probably through migration of one metal through the other, and that the superior adherence contributes to frequency instability through strains set up at the gold quartz interface.

In order to eliminate surface contamination, the vacuum system employed was specially designed, using oil-free bakable solenoid-operated valves and liquid-nitrogen traps. All vacuum baking to outgas the surface and to provide a hot substrate is done with large-area, relatively low-temperature conducting-glass plates rather than with open filaments. Up to five quartz plates are mounted vertically in the plating chamber, and electrodes are formed simultaneously on both sides by evaporating gold from eight small tungsten heaters, which are placed to assure even distribution. The apparatus is shown on Fig. 11. A gold electrode 16 mm in diameter and about 700 angstroms thick has proved adequate for this application.

3.6 *Frequency-Adjustment Technique*

The exact frequency desired from a crystal-controlled oscillator is obtained partly by controlling the natural resonant frequency of the crystal resonator during fabrication and partly by selecting or adjusting circuit elements in the oscillating loop. The adjustment of the natural resonance during fabrication of the quartz plate is simplified when the

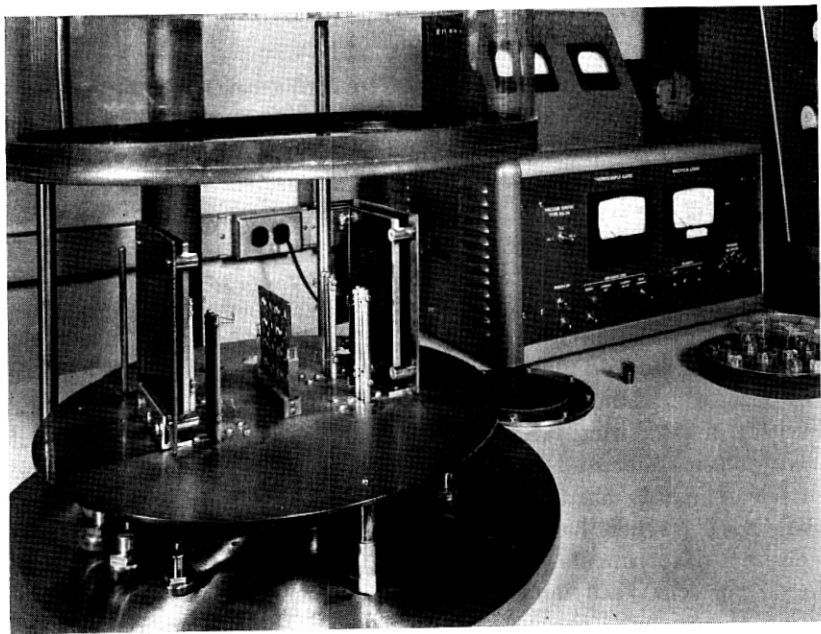


Fig. 11 — Apparatus used to form gold electrodes in vacuum on quartz plates.

control range is large. However, an upper limit to the control range is set by the probable stability of the controlling circuit element, usually a series capacitor. The slope of the crystal unit reactance with frequency is about 0.7 ohms for one part in 10^9 frequency change, as seen in Fig. 13. For example, an assumed instability of a series capacitor of only 0.01 per cent would require a value of $100\mu\text{mf}$ or larger to limit the frequency change to one part per 10^{10} . Under these conditions, practical limitations on size of the capacitor would limit the adjustable range to a few parts in 10^7 .

Adjustment of the resonant frequency of the quartz plate to this degree is accomplished by adding gold to the electrode surface while the crystal plate is in oscillation, making use of the vacuum evaporation apparatus described above. The sequence of operations is as follows: (a) The exact frequency change desired is measured under final use conditions — that is, at operating temperature and proper circuit adjustment. (b) The crystal unit is placed in the vacuum chamber and gold deposition initiated. (c) The frequency *change* is monitored and controlled by continuous frequency measurement during deposition.

This method will usually result in finished crystal units not more than five parts per 10^7 from nominal frequency. The small error in frequency results principally from subsequent glass sealing operations and the cleaning effect of a final vacuum bake. When sufficient numbers of crystal units are processed in series, closer tolerances can be obtained by a method of compensation that uses measurements of finished units to provide information for the frequency adjustment of subsequent units.

3.7 *Hermetic Seal Techniques*

Measurements of frequency aging of crystal units in both metal and glass enclosures⁹ have shown the superiority of glass enclosures, probably because glass can be more effectively outgassed and cleaned at the temperatures involved.

The crystal plate should not be exposed to high temperatures, both to prevent a shift in resonant frequency and to avoid damage to the mounting attachment at the quartz plate. For this reason, a flared stem assembly and a close-tolerance baffle plate (also used as a support) are employed to keep the high temperatures involved in glass sealing away from the quartz plate. For the same reason, the seal is accomplished quickly with a minimum of glass annealing.

Following the stem-to-bulb seal, the unit is evacuated and baked for six hours at 140°C . The optimum length of time has been established experimentally, and is a function of the vacuum system design. With

the new vacuum system described above, using oil-free valves and specially designed liquid nitrogen traps, it has been found that a six-hour bake can be used to good effect.

Following the baking, and with the vacuum at about 10^{-6} mm of mercury, the glass tabulation is sealed by means of a small flame.

IV. PROPERTIES OF THE QUARTZ RESONATOR

4.1 *The Crystal Unit as a Circuit Element*

Table I lists the electrical properties of the new 2.5-mc crystal unit, and the equivalent circuit of the crystal unit in the vicinity of its operating frequency was shown in Fig. 1. The capacity in the upper branch represents the static capacitance of the crystal and its holder. The lower branch represents the electrical equivalence of the mechanical resonance of the crystal, which has an impedance approximately given by

$$Z_1 = R_1 + j2\omega L_1 \frac{\Delta f}{f_r}, \quad (2)$$

where Δf is the difference between the operating frequency and the crystal series resonant frequency, f_r . The total impedance of the crystal, then, is

$$Z_c = \frac{Z_1 Z_0}{Z_1 + Z_0}. \quad (3)$$

This simplifies to

$$Z_c = R_c + jX_c = \frac{R_1}{1 - 2 \frac{C_0 \Delta f}{C_1 f_r}} = \frac{j2\omega L_1 \frac{\Delta f}{f_r}}{1 - 2 \frac{C_0 \Delta f}{C_1 f_r}} \quad (4)$$

when one uses the fact that the magnitude of the impedance Z_1 is much smaller (at the operating frequency) than the magnitude of the impedance Z_0 .

TABLE I

Series resonant resistance, R_1	65 ± 10 ohms
Inductance, L_1	19.5 henries
Dynamic capacitance, C_1	0.00021 μmf
Q	4×10^6
Static capacitance, C_0	4.0 μmf
$r = c_0/c_1$	19,000
Nominal capacitance for operation at standard frequency	50 μmf
Manufacturing tolerance on frequency	± 6 pp 10^7

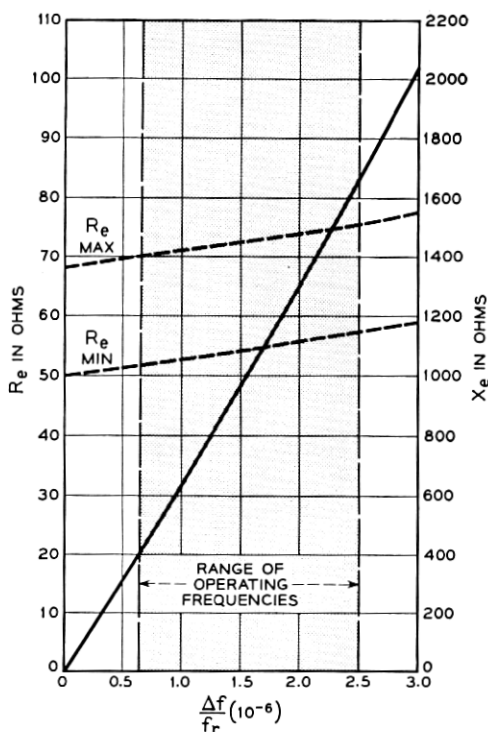


Fig. 12 — Effective resistance and reactance vs. frequency for the 2.5-mc crystal unit.

The first term of (4) is the effective resistance, R_e , and the second term the effective reactance, X_e , of the crystal. These are plotted versus the fractional frequency deviation from crystal resonance, $\Delta f/f_r$, in Fig. 12. The range of operating frequencies shown in the figure is based on the crystal manufacturing tolerances and the expected total aging.

The sensitivity of the oscillating frequency to changes in the reactance of the circuitry associated with the crystal depends on the "stiffness" or reactance slope of the crystal at the operating frequency. This is obtained by differentiating X_e with respect to fractional frequency deviations:

$$\frac{dX_e}{d(\Delta f/f_r)} = \frac{2\omega L_1}{\left(1 - 2 \frac{C_0}{C_1} \frac{\Delta f}{f_r}\right)^2}. \quad (5)$$

Equation (5) is plotted as a function of f/f_r in Fig. 13.

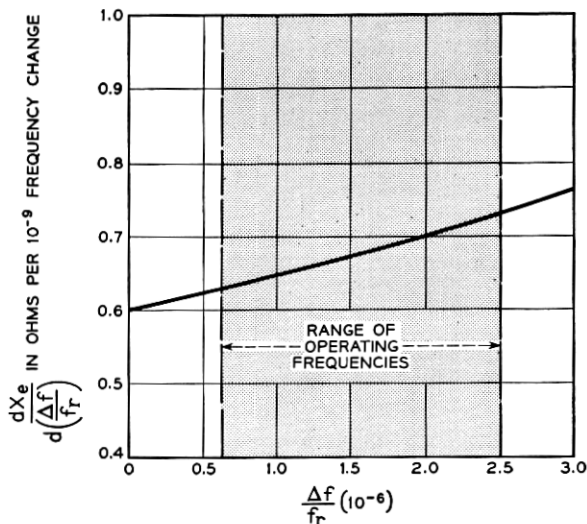


Fig. 13 — Reactance slope vs. frequency for the 2.5-mc crystal unit.

From Figs. 12 and 13 we may obtain the requirements imposed on the oscillating circuit by the crystal. These are:

- i. The range of negative resistance required of the circuit is -51 to -75 ohms.
- ii. The negative reactance of the circuit should be adjustable from 400 to 1700 ohms.
- iii. The total negative reactance of the circuit should be stable to better than 0.1 ohm for a frequency stability of one part in 10^{10} .

Other requirements imposed by the crystal on the circuit are:

- iv. The crystal current should be stabilized at about 70 microamperes to a constancy of 1 db.
- v. The circuit should contain elements to prevent oscillation at unwanted crystal modes of resonance, in particular the third overtone frequency near 1.5 mc.

4.2 Temperature Coefficient of Frequency

The relationship between orientation of the quartz plate with respect to its crystallographic axes and the temperature of the zero temperature coefficient is shown on Fig. 8. By maintaining the angle to $35^{\circ}20' \pm 1'$ the temperature coefficient will go through zero at a temperature, t_0 ,

which lies between 42°C and 57°C. In the vicinity of t_0 , the relative deviation of frequency at temperature t from the frequency at t_0 is given by (1).

In order to prevent possible temperature-control aging of 0.1°C from causing a frequency change of more than one part per 10^{10} , the temperature of the thermostat must agree with t_0 within 0.1°C.

It can be seen that the actual temperature coefficient, which is better than one part per 10^9 per degree, is not a limiting factor in any reasonable oven construction. On the other hand, strains due to temperature changes in the quartz itself are a limiting factor and a temporary shift of one part per 10^{10} will occur if a temperature change of 5 millidegrees per hour is maintained for 10 minutes or more.

4.3 Current Coefficient of Frequency

The frequency of a crystal unit depends to a small extent on the crystal current. If uncoupled to other modes of vibration, the relationship at low currents is approximately $\Delta f/f = Di^2$. Fig. 14 shows a typical curve of frequency versus current for the 2.5-mc crystal unit. In order to keep the current coefficient below one part per 10^9 per db, currents of less than 100 microamperes are necessary.

The current coefficient of frequency in this application is not believed due to dissipation, since the total power is less than 10^{-7} calorie per second, and also because the effect is nearly instantaneous. The most likely explanation is that the elastic constant varies with strain; that is, Hooke's Law is really not obeyed. Further studies indicate that the frequency change is a function of the amplitude of the strains due to oscillation, and that it is independent of Q and frequency.

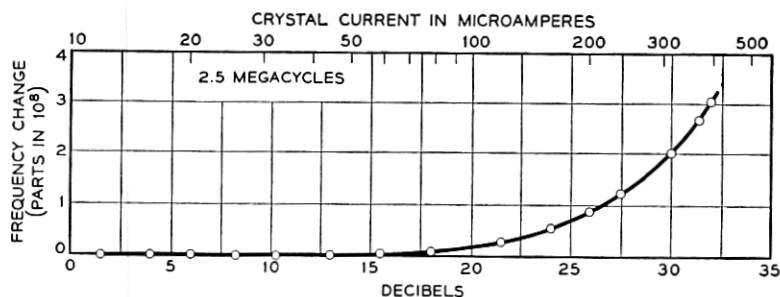


Fig. 14 — Frequency vs. crystal current for the 2.5-mc crystal unit.

4.4 Mechanical Stability

The crystal plate will withstand a static load of 2 lbs (200 g's) in any direction without any apparent movement with respect to its mounting platform. The mounting plate is in turn anchored to the glass bulb by three peripheral springs and the three nickel wires in the glass stem press. Severe shock, such as a four-inch drop, will dislodge the platform, and should be avoided. Normal shipping, however, should have no effect on the crystal unit properties. Similarly mounted 5-mc crystal units have withstood 10g vibration to 2000 cycles with no permanent frequency change greater than one part per 10^9 .

There is an orientation effect on frequency caused by gravity-induced strains, as shown on Fig. 15. The preferred orientation is with the unit installed with the odd mounting ribbon vertical, which will allow a $\pm 20^\circ$ tilt without affecting the frequency more than one part per 10^{10} .

4.5 Frequency Stabilization and Aging

It is customary to differentiate between the rapid frequency drift associated with initial operation of a frequency standard, here called stabilization, and the slower frequency drift known as aging. Whereas the former will have become negligible after a few weeks or months, the latter can extend over several years.

Naturally, the drift should be as small as possible. If it cannot be avoided, it should be a simple function of time, to permit extrapolation.

No uniform result has been obtained in the initial stabilization of the quartz resonators. Evidence suggests⁹ that the frequency change is due principally to a transfer of mass to and from the quartz plate, initiated by a shift in temperature. The rate of transfer and the degree of permanence of the transfer will be a function of the vapor pressure of the

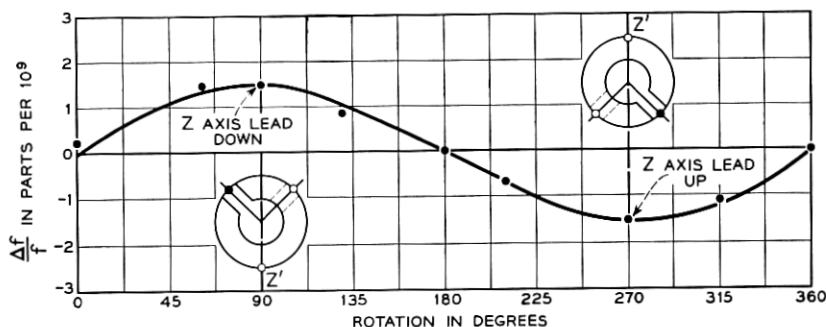


Fig. 15 — Effect of gravity-induced strains on frequency at 2.5 mc.

particular contaminant and the degree of adherence (which may be molecular, chemical or mechanical) between the contaminant and its substrate. Since the equilibrium reached at any given operating condition is not likely to repeat itself, the initial frequency drift cannot be accurately predicted. The magnitude of this drift is not more than a few parts in 10^8 , and may be reduced as improved cleaning techniques in manufacture are developed. Use of a carefully controlled temperature cycle each time the oven is re-started can also reduce this initial uncertainty by as much as a factor of ten. In any case, the drift rate can be expected to decrease to about one part in 10^9 per month by the third month of operation.

The aging of new quartz resonators has not proved uniform, either. Operation at 50°C has, however, consistently shown less aging than operation at 75°C . Of five oscillators at 50° for which records have been kept, the rate varies from one to ten parts in 10^{10} per month. One such oscillator is used in connection with the National Bureau of Standards broadcast from Station WWV, and its frequency versus that of an atomicon at the station has been published.¹⁰ Its aging rate after about 12 months of operation appears to be about two parts per 10^{10} per month. One oscillator operated at Bell Telephone Laboratories, Whippany, New Jersey, which has been monitored by use of a 60-kc broadcast by the National Bureau of Standards from Station KK2XEI in Boulder, Colorado and from MSF in Rugby, England, is shown on Fig. 16. This oscillator was considerably better than one part per 10^9 per month, even in the second month, but the indicated long time rate will be in the order

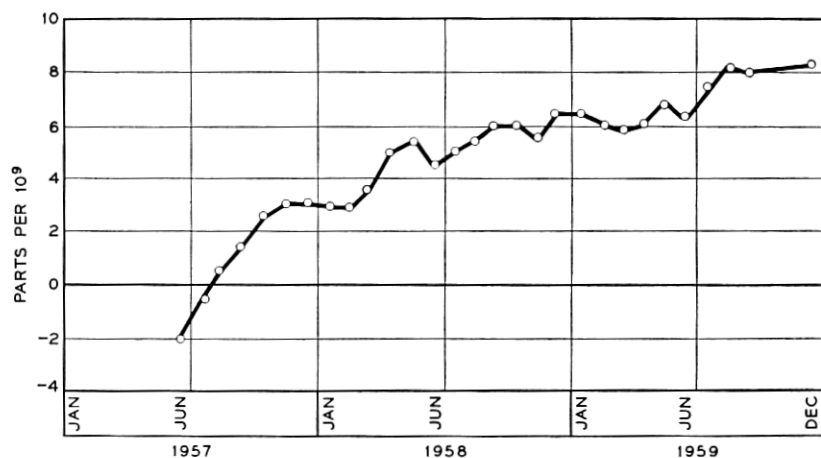


Fig. 16 — Frequency aging data, 2.5-mc crystal unit — KK2XEI received signal vs. Whippany frequency standard.

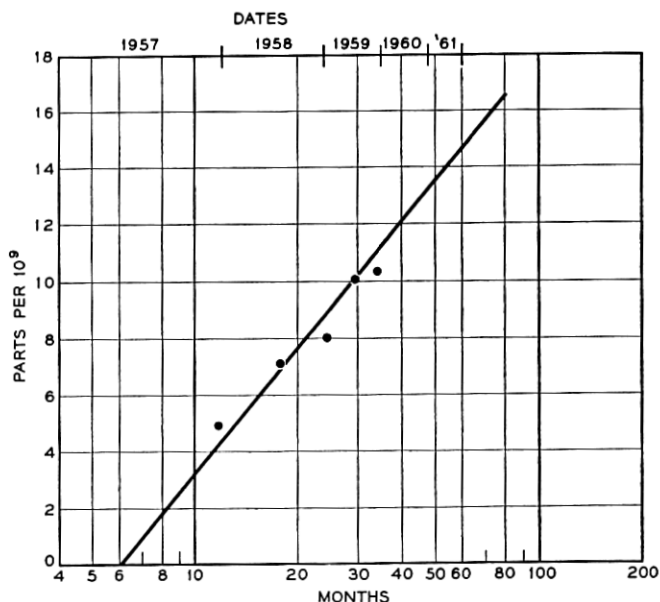


Fig. 17 — Frequency aging data shown to be a simple exponential curve.

of one part per 10^9 per year for some time to come. Fig. 17 shows that the frequency change is a simple exponential curve, and can be easily extrapolated.

4.6 Short-Time Frequency Stability

Short-time frequency stability cannot be determined without a careful analysis of the properties of the frequency measuring system. Even assuming a correct phase relation between oscillator circuit and crystal unit, the stability will be unavoidably lost due to the necessary amplifier and lines, and, ultimately, the measuring equipment itself. These phase distortions cannot be readily distinguished from true frequency variations.

Measurements have been made at various multiplier frequencies up to 1000 mc in an attempt to find the best conditions for measurement, and the following figures represent the results to date:

- 0.1-second averaging: two parts in 10^9 ;
- 1-second averaging: two parts in 10^{10} ;
- 10-second averaging: two parts in 10^{11} .

Since both oscillators contribute to the instability, we may assume that

one oscillator is at least twice as good. That is, the mean relative deviation is one part in 10^{11} or better when the frequency is averaged for 10 seconds or longer.

V. CONCLUSION

The new 2.5-mc crystal units will make possible general-use oscillators characterized by high frequency stability, comparatively little aging, good linearity and uncomplicated design. Such standards compare favorably with atomic standards for periods up to one month or more, and have an advantage over atomic standards in that they may be set to an exact frequency and are more portable and rugged.

The crystal units are uniform in Q and frequency, and need not be specially selected. Although the use of a relatively high frequency and electrodes integral with the quartz plate might be questioned, experiments have demonstrated that the associated difficulties can be as easily dealt with as can those associated with a resonant mounting or isolated electrodes characteristic of low-frequency units. Various advantages accrue from the fact that only the center portion of the quartz plate and its pure gold electrodes determine the resonant frequency. Among these are exceptional stability under conditions of shock and vibration, and uniform and highly predictable electrical characteristics.

The development work leading to the design and fabrication of 2.5-mc crystal units and associated oscillators and ovens has been supported in part by development contracts with the Rome Air Development Center and the U. S. Army Signal Research and Development Laboratory.

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