ADVANCES IN THE STABILITY OF HIGH PRECISION CRYSTAL RESONATORS

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ABSTRACT

This paper describes recent advances in technology directed toward minimizing the temporal changes in frequency of crystal resonators, as well as reducing their susceptibility to temperature, acceleration, and other environmental effects.

INTRODUCTION

Exceedingly stringent frequency control requirements follow from the performance specifications of the latest generations of communications, navigation and identification systems. Unfortunately, the present generation of crystal resonators, which are the stabilizing elements in the reference oscillators required in such systems, are frequency sensitive to acceleration fields produced by the dynamic environments surrounding land- and air- mobile use. These resonators are also susceptible to frequency shifts due to transient temperature variations and static stresses transmitted by their electrode and mounting systems. The acceleration effects lead to degradation of the short-term frequency stability, while the stress component contributes primarily to long-term aging and to distortions of the frequency-temperature behavior of oscillators.

This paper describes recent advances in quartz resonators that permit simultaneous compensation against both dynamic and static conditions, and that are compensated, moreover, against rapid temperature transients encountered in fast-warmup oscillators for manpack use.

Acceleration sensitivity is greatly reduced by utilizing novel monolithic compound vibrators having racemic* structures to nullify frequency shifts. Static compensation is achieved by means of unique lateral mounting contours, located so that nonlinear elastic constants cancel. Compensation of thermal transients comes about by use of a special, doubly rotated orientation of cut. We show that all three features may be realized at one time to yield a highly stable quartz resonator immune to accelerations in any direction, and to boundary stresses and thermal transients. No additional electronics are

* left- and right-handed combinations.

required, nor are increases in size, weight, and power requirements.

The aging is minimized through the use of: (1) the SC-cut, (2) ultra-clean, ultrahigh vacuum fabrication techniques, and (3) packaging techniques which are capable of preserving the ultraclean surfaces. Additional concepts for high precision short-, medium-, and long-term frequency control are presented.

A crystal resonator is comprised of a piece of quartz, or other piezo-electric substance, together with a system of electrodes, mountings, and encapsulation. For the high precision units dealt with here, the form of the crystal vibrator is that of a thin disc with flat or lenticular major surfaces. The electrodes are most often deposited directly upon the major surfaces to form a capacitor-like structure; the connection to its external environment is made from the electrodes via the mounting supports, through the enclosure, to form a one-port device which is connected to the remainder of the oscillator circuitry.

Insofar as the external world is concerned, the mechanically vibrating element may be represented by means of the equivalent electrical circuit shown in Figure 1. The static capacitance Co is the actual capacitance of the crystal dielectric between the electrodes, plus additional stray capacitance due to the mount, etc. The C_1, L_1, R_1, combination arises from the mechanical vibration of the crystal as reflected at the output terminals by the piezoelectric effect. A knowledge of these four elements suffices in many instances to characterize the resonator in oscillator and filter design. The motional values C_1, L_1, R_1, pertain to a single resonance of the system; if operation is not confined to the narrow vicinity of a resonance, then the equivalent circuit must be augmented by RLC series arms placed in parallel with that shown, one for each mode of vibration. We assume that a single motional arm suffices to character-ize the resonators under discussion. Relationships between the critical frequencies associated with Figure 1, and definitions of other parameters, are given in [1].

Typical values for a high precision quartz resonator operating in the fundamental mode of thickness shear are

- f_R = 5 MHz
- Q = 750,000
- R_1 = 4Ω
- r = 475 = Co/C_1
- C_1 ≈ 10.6 fF

- $C_0 \approx 5.04$ pF

- $L_1 \approx 95.4$ mH

These values will be used in subsequent examples. In the above,

$$(2\pi f_R)^2 L_1 C_1 = 1, \quad \text{and}$$

$$(QR_1)^2 = L_1/C_1 .$$

In some oscillator applications, the resonance frequency f_R is adjusted to the "load" frequency f_L by means of a series capacitor C_L; a typical value of which is

- $C_L = 100$ pF .

This adjustment is necessary to bring the oscillator to a precise frequency, and to provide a means of correcting for subsequent frequency offsets. It is instructive to calculate the effect of changes in C_L itself on the frequency of a high precision oscillator. The load frequency is [2]:

$$f_L \cong f_R \sqrt{1 + \alpha/r}, \quad \text{where}$$

$$\alpha = C_0/(C_0 + C_L).$$

Therefore the sensitivity coefficient S is

$$S = C_L \; (\partial(\Delta f/f)/\partial C_L) = (-\alpha^2 C_L/2rC_0\sqrt{1+\alpha/r}).$$

This is to be multiplied by the fractional change in C_L to obtain the fractional frequency shift $\Delta f/f$. Evaluating S for our resonator gives

- $S \cong -48 \times 10^{-6}$.

Temperature is one reason that C_L might change, and if C_L had a temperature coefficient of

- $TC_L \cong 2 \times 10^{-6}$/K,

then the resulting frequency shift would be

- $|\, S\, T_{CL} \,| \cong 10^{-10}$/K.

Thus changes in the temperature of only 10 millikelvins will change the frequency by parts in 10^{12}. In reality, the temperature coefficient of C_L is apt to be larger than 2 ppm/K, with correspondingly higher frequency excursions.

Reverting now to the physical quartz crystal plate, it has been known for many years that by cutting the plate at an angle to the crystallographic axes, the frequency-temperature (f-T) behavior could be greatly improved; in particular, that two orientations exist (the AT and BT cuts) where the temperature coefficient of frequency is zero. These cuts contain the crystallographic X axis and are referred to as singly rotated cuts. Figure 2 shows an example of such a cut as well as the more general doubly rotated cut, plus the locus of zero temperature coefficient (ZTC) as function of the two orientation angles θ and ϕ [3], [4].

For the orientations shown in Figure 2 by the solid line, the ZTC is obtained for the slow shear wave propagating along the plate thickness; the locus shown dashed is for the fast shear waves. These are distinguished by the terms "b-mode" (fast shear), and "c-mode" (slow shear); the thickness extensional mode is the "a-mode", but does not possess a ZTC for any orientation in quartz.

A ZTC means a flat f-T curve at some particular temperature. Over a wider temperature range, the curve is cubic in shape for those cuts on the upper portion of the locus (AT, FC, etc. branch), and parabolic for cuts on the two lower branches (BT and RT branches). The precise shape of the curve is dictated primarily by the elastic constants' behavior, and by the behavior of the piezoelectric, dielectric and thermoelastic constants. These are functions of ϕ and θ. Of smaller, but non-negligible influence on the f-T curve, are the load capacitance, the electrode mass-loading and the harmonic of operation.

In subsequent sections we will discuss parameters leading to resonator instabilities and point out how emerging technologies will minimize the various sources of frequency instability.

MAJOR PARAMETERS INFLUENCING FREQUENCY

Some of the major parameters that enter every discussion of high precision crystal resonators are given in Table 1. These will be addressed in turn.

1. Temperature

a. Static behavior

The overwhelming majority of conventional high precision resonators are fashioned of AT-cut quartz plates. The classical treatment of their properties was given by Bechmann [5]. These resonators have f-T curves similar in form to the cubic sketched in Figure 3. The curve is characterized by the three values a_o, b_o, c_o:

$$\frac{\Delta f}{f} = a_o \, \Delta T + b_o \, \Delta T^2 + c_o \, \Delta T^3;$$

$\Delta f/f$ is the fractional frequency change from the frequency at the reference temperature, and ΔT the corresponding temperature difference measured from the reference. The quantities a_o, b_o, c_o are the first, second, and third order temperature coefficients of frequency, respectively; they are functions primarily of ϕ and θ, and are also weaker functions of resonator geometry, electroding and mounting.

Representative values for the AT and SC cut are:

	AT	SC	UNIT
a_o	0	0	$10^{-6}/K$
b_o	-0.45	-12.3	$10^{-9}/K^2$
c_o	108.6	58.2	$10^{-12}/K^3$
$\partial a_o/\partial\theta$	-5.08	-3.78	$10^{-6}/K$, deg θ
$\partial a_o/\partial\phi$	0	-0.18	$10^{-6}/K$, deg ϕ

These figures are for a reference temperature of 25^oC. The inflection temperatures for the AT and SC cuts are 26.4 and 95.4^oC, respectively. By changing θ slightly, the curves can be optimized for a given application. For wide temperature variations, as encountered in temperature compensated crystal oscillators (TCXOs), an AT cut can be made so that the total variation over a 0^oC to 50^oC range is less than 2.5×10^{-6}; then the TCXO circuitry can compensate this variation further to less than 5×10^{-7}. When the resonator is used in an OCXO (oven controlled crystal oscillator), the temperature excursions are much smaller, and the θ angle is adjusted so that the f-T curve maximum or minimum is located at the desired oven temperature. If the oven temperature should coincide with, or be near to, the inflection temperature, then θ variations in the order of seconds of arc become very important as the slope changes rapidly in this region compared to its variation at the extrema when these are well separated. For OCXOs using AT cuts, the operating point usually is made the f-T minimum; for the SC cut the f-T maximum is used because of the high inflection point.

For cuts located on the upper locus of the graph in Figure 2 the inflection temperature monotonically increases as function of ϕ. Having the angle ϕ available, in addition to θ, allows the static f-T curve to be optimized for a given application. In high precision applications, however, the static, cubic, curve is found not to be invariant unless the temperature changes are made very slowly (quasi-isothermal = static). This problem did not become important until the past few years when requirements became increasingly stringent; this situation will be discussed further below; it has led to the necessity of using the doubly rotated SC cut.

b. Dynamic behavior

It has been known for many years that abrupt temperature changes produce in cyrstal resonators frequency changes that are unpredicted by the static f-T characteristic [6]. For the AT cut, an increase in temperature produces a negative-going frequency spike that slowly approaches the expected new frequency value; for BT cuts, the effect is reversed in sign. An example is shown in Figure 4, which shows the warmup characteristics for AT and SC cuts. Note the logarithmic ordinate. The oven warmup time is that required to approach within 10 mK of the final setting point, or operating temperature. Even with the oven at temperature, the AT crystal frequency is not constant for quite a while longer. Making the oven warmup shorter is of little help, because then the overshoot is larger. A typical figure with an AT cut is 20 minutes to get within 5×10^{-9}. The desirability of fast warmup oscillators has been stressed at PTTI meetings by systems users; a resonator unaffected by thermal transients is an urgent need. It is to be found in the SC cut. With its use the problem is determined by the oven alone, as seen in Figure 4, where the frequency is better than 10^{-9} in the oven warmup time.

The dynamic thermal effect has been given a phenomenological explanation by a modification of the cubic f-T curve to include a time-dependent term [7]-[8]. Evaluation of the added term using the results from thermal transient data enables one to simulate the effect of sinusoidal temperature variations about a fixed reference point. An example is shown in Figure 5. The nearly flat horizontal line is the static f-T curve for an AT cut, expanded about the frequency minimum. Superimposed are the ellipses that result from the dynamic effect having its basis in nonlinear elasticity, and characterized by the parameter $\tilde{a}$ in the modified expression

$$\Delta f(t)/f = (a_0+\tilde{a}\dot{T}(t))\cdot\Delta T(t)+b_0[\Delta T(t)]^2 + C_0[\Delta T(t)]^3,$$

$$\text{where } \dot{T}(t) = dT(t)/dt.$$

From Figure 5 it is seen that sinusoidal variations of temperature with magnitude $\pm \frac{1}{2}$ mK produce large frequency variations when the orbital period is hours long. With a period of 8 hours, the frequency change is about 3×10^{-12}; when the period is lengthened to 1 week, the change is still about 1×10^{-13}, whereas the static f-T curve would predict a change of only a few parts in 10^{-14}, irrespective of cycling rate.

Recent results point to the necessity of including a second term $\hat{a}$ in the equation:

$$\Delta f(t)/f = a_0\Delta T(t) + b_0[\Delta T(t)]^2 + c_0[\Delta T(t)]^3 + (\tilde{a}\,\Delta T(t)+\hat{a})\cdot\dot{T}(t).$$

Since thermal transients, temperature cyclings, and fluctuations cannot be entirely avoided, the dynamic temperature effect is a very important consideration in high precision resonators. Means of reducing the effect are discussed in a subsequent section.

2. Time

The variation of resonator frequency with time is shown for a typical case in Figure 6 [9]. The curve has the over-all form of

$$\Delta f(t)/f = A \ \ell og\ (1+t/\tau),$$

with A an amplitude factor, and τ the time constant of the dominant rate-process leading to the frequency variation.

Superimposed on the long-range shape are perturbations having a distribution of time constants. The curve is somewhat arbitrarily broken up into three regimes: short term ($\tau \lesssim 10$ sec), intermediate term (~ 10 sec $< \tau < \sim$ several hrs.), long term ($\tau > \sim$ several hrs.).

a. Short term

This regime is characterized by noise effects whose origins are not fully understood [10]-[11]. Typical values of $\Delta f/f$, for 1-second sampling times, obtained with room temperature crystal oscillators (RTXOs), TCXOs, and OCXOs are

RTXO	2×10^{-9}
TCXO	1×10^{-9}
OCXO	1×10^{-11}

Contributing factors to short-term instability are

- fluctuations in temperature
- shock and vibration
- fluctuations in the active device; Johnson noise
- electromagnetic interference (EMI)
- circuit microphonics
- quartz plate to mount electrical noise
- fluctuations in surface contamination

Concerning this last point, consider the example of the 5 MHz, fundamental resonator. A monolayer of contamination will, by mass loading, reduce the frequency by approximately 1×10^{-6}. Since the relative fluctuation of the number of particles is proportional to the reciprocal square root of the number [12], for a disc 10 mm in diameter there will be about 3×10^{14} molecules / monolayer, and the relative fluctuation will be about 6×10^{-8}. Thus the frequency instability due to this cause is estimated at about 6×10^{-14}, which, coincidentally, equals the best short term stability reported to date [13]. The discussion in the introduction concerning changes in C_L is germane here as well, as fluctuations in C_L and other circuit components contribute to the short-term frequency instability. A phase shift ϕ in the oscillator loop will give rise to a frequency change of

$$\Delta f/f = \phi/(2Q);$$

therefore, for the crystal parameters quoted in the Introduction, phase shifts of only 86 microdegrees (1.5 microradians) will produce $\Delta f/f$ shifts at the 10^{-12} level.

There is preliminary evidence that points to the quartz-electrode interface as a contributor to short-term instability. In a number of measurements, Healey [14] has found a $1/f^2$ phase noise dependence, close-in, in Cr-Ag-Ni plated units, and a $1/f^3$ dependence in $A\ell$-$A\ell_2O_3$-Au plated units.

Another contribution to short-term phase noise is bulk elastic nonlinearities. For example, when the b-mode of an SC-cut is driven simultaneously with the c-mode, an increase in the phase noise of the latter is found; although both modes would be independent if the crystal were linear, they are coupled by nonlinearities in the crystal.

b. Intermediate term

In this regime the greatest contributor to instability is probably the temperature control used. Ovens are normally of two general types: a switching controller type, and a proportional controller type. In the former, a snap action thermostat is used, where low cost and moderate performance are important. This type begets wear and sticking of the contacts, and contact arcing produces electrical noise. The proportional type uses a bridge circuit that provides constant adjustment because the heat supplied is proportional to the difference between the crystal temperature and the oven setting point. Some high precision oscillators use a double proportional oven so that inside the first oven the temperature never varies more than 1K, and this is reduced to less than 0.01K within the second proportional oven.

Other contributors to intermediate term variations are changes in crystal attitude, and low frequency vibrations. These will be considered under acceleration effects.

Additional causes are stress relief in mounts and electrodes, and changes in circuit reactance and drive level.

c. Long term [15]

Long-term frequency drift is called aging. It is usually found to be a logarithmic function of time. When the oven and/or oscillator are turned off and then on, the oscillator typically experiences an offset in frequency and the onset of a new curve of the same form.

Typical values of aging are

RTXO	$3x10^{-7}$/month
TCXO	$1x10^{-7}$/month
OCXO	$1.5x10^{-8}$/month

A major contributor to long term aging is mass transfer due to contamination. Since, for a 5 MHz plate, one monolayer of contamination lowers the frequency by about $1x10^{-6}$, to achieve high stability long-term performance, the mass transfer allowed must be a very small fraction of a monolayer. But, assuming that all molecules stick to the surface, the number of molecules adsorbed by a surface at a pressure of 10^{-6} torr would form a monolayer in approximately 1 second. It is obvious, therefore, that high precision resonators must be processed in a high vacuum to avoid contamination. This includes cleaning, handling and packaging.

Adsorption and desorption phenomena such as outgassing of surface contaminants from the electrodes and quartz are not the only causes of long-term drift. In back-filled units, changes in pressure due to atmospheric pressure variations produces oilcanning of the enclosure which will change the frequency by 10^{-7} per atmosphere; the oilcanning also produces time dependent stresses in the mounting structure. Permeability of the enclosure to gases is another contributor to aging.

Intrinsic stress relief with time changes the resonator's frequency as well. The stress relaxation takes place in the mounting structure, the bond between mount and crystal, and in the electrodes. As an example, a 5 MHz crystal of 14 mm diameter, mounted along the X-axis, would increase in frequency by $8x10^{-8}$ for a force produced by a mass of 1 gram applied to the mount [16]; microgram force changes are therefore perceptible in high precision applications. The observed aging is the sum of the aging produced by the various mechanisms, and can be positive or negative.

d. Thermal hysteresis

Thermal hysteresis, or thermal retrace is shown in Figure 7 [17]. This phenomenon is largely unpredictable, although Hammond, et al. [17] did find a variation with orientation angle θ about the AT-cut angle. It is a function of bonding, mounting and previous history, and as such is not a candidate for modeling in systems applications, and ways to reduce it are discussed subsequently.

3. Acceleration

a. Attitude

Changes in the resonator's orientation with respect to the gravitational field produce frequency shifts because of the stresses set up in the resonator. For 180^{o} changes one usually has a shift of about 2×10^{-9}. This is referred to as the "2-g tipover" value. This effect is equivalent to the acceleration effect next described.

b. Vibration

Valdois [18] established experimentally the behavior of resonators subjected to acceleration fields. His results are shown in Figure 8. It is seen that the frequency shift reverses sign with reversal of the direction of acceleration, and that the magnitude of the effect is dependent on which axis the acceleration is directed along. For a given system of mounting and direction of acceleration, the frequency shift will be given by

$$\Delta f/f = \bar{a}_o \, \gamma,$$

where $\bar{a}_o$ is the acceleration (usually expressed in "g" units) and γ is the acceleration sensitivity coefficient of the crystal for that configuration. Values for γ normally run a few parts in 10^9 per g (AT-cut).

When the acceleration takes the form of vibration, the same considerations apply. If the vibration is sinusoidal, sidebands are produced at the carrier frequency $\pm$ the modulation frequency. An example is shown in Figure 9 [19]. The ratio of single sideband to carrier powers follows from FM theory as

$$\mathcal{L}(fm) \approx (\Delta f/2fm)^2,$$

where Δf is the frequency shift under acceleration, and fm is the modulation frequency. Measurement of $\mathcal{L}(fm)$ yields γ from

$$\gamma = (2fm/\bar{a}_o f) \cdot 10^{(\mathcal{L}(fm)/20)}$$

For high performance oscillators it is imperative that γ be significantly reduced; methods of attaining this end are discussed in the sequel.

c. Shock

Shock is distinguished from vibration and tipover only by its magnitude. If the shock level exceeds the elastic limit for the quartz or mounting structure, permanently offset frequency will result.

In certain sensor applications the crystals may be subjected to as many as 20,000 g's and be required to survive with minor frequency shifts; methods for shock-hardening will be described in a later section.

4. Radiation

a. Transient

Pulsed ionizing radiation produces frequency changes in quartz resonators by a mechanism similar to the dynamic thermal effect mentioned previously. Thermal gradients are set up in the quartz, leading to frequency changes brought about by the nonlinear elastic constants. The effect depends on the crystal cut, being negative for the AT cut, but is almost insensitive to the type (natural or cultured) of quartz used, and to the quality, although Q degradation and even cessation of the oscillation has been observed when impure quartz is used.

b. Permanent

Steady state or continuous radiation produces permanent frequency shifts in quartz resonators [20], [21]. The effect is due primarily to changes in the defect structure of the material, which changes, in turn, the effective elastic constants. Because the effect is very structure sensitive, the type and quality of the quartz material used is extremely important. Typical values for ionizing radiation are

$$\text{natural quartz: } \sim -10^{-11}/\text{rad}$$

$$\text{swept cultured quartz: } \sim < 10^{-12}/\text{rad.}$$

For neutrons displacement damage occurs at the level

$$\text{neutrons: } \sim 10^{-21}/\text{n/cm}^2.$$

Improvement of radiation insensitivity will be described in the next section.

TECHNOLOGIES AND TECHNIQUES IMPACTING STABILITY

In the last section some of the predominant parameters affecting frequency of resonators were described. In this section, technologies and techniques that are being brought to bear on the problem of resonator frequency changes will be reviewed in the light of latest developments. Some of these have been touched upon before at previous PTTI meetings [22], [23]. The "cures" to be described for the various effects already enumerated are surprisingly few in number; the most prominent of which is the substitution of the doubly rotated SC cut for the perennial AT cut. This is because many of the effects have their basis in nonlinear elasticity [24], [4]. The more important emerging/

improving technologies being brought to bear on the problem of improving high stability resonators are shown in Table 2. These will be briefly discussed in the same framework as the prior section. Cutting across the Temperature/Time/Acceleration/Radiation categories is the SC cut. Table 3 gives a preview of the sequel.

1. Temperature

The f-T behavior of SC cuts is shown in Figure 10, with adjacent curves separated by 1 minute of arc. The inflection temperature is about 95.4°C, as opposed to nearly room temperature for the AT, and the cubic parabola term is only about one half that of the AT. In many applications these are advantages over the AT cut, but relatively minor ones. The real advantage of the SC vis à vis the AT, as far as temperature effects are concerned, is that the curves in Figure 10 are nearly the dynamic as well as the static curves, because the SC-cut is compensated for thermal transients occurring in the thickness direction; lateral compensation of gradients does not in general occur, but very little experimental or theoretical work has been done on the lateral effect [10], [8]. Because of the compensation for temperature changes, setting an SC oscillator to its temperature operating point is rapid; anyone who has performed this feat with a high precision AT resonator will appreciate this practical advantage. More importantly, fast warmup oscillators are a reality with the SC cut, with warmup dictated solely by the oven, as shown in Figure 4; also highly important is the absence of the orbits of Figure 5 and the corresponding meanderings of frequency due to temperature fluctuations.

The consequences of eliminating dynamic thermal coupling are brought out dramatically in Table 4. The tabular entries pertain to an SC cut operated with its reference temperature at one of the two turning points. Refer to Figure 3 for the definitions of oven offset and oven cycle range with respect to oven setting point. For state-of-the-art ovens with cycling ranges in the millikelvin regime, resonator stabilities in the 10^{-14} range ought to be attainable. In fact, a stability of 6×10^{-14} for a sampling interval of 128 seconds has been reported for an SC cut [25].

Stabilities approaching those of Table 4 assume that the additional causes of instability can be sufficiently reduced or eliminated. As ambitious as such a program might appear at first to be, the path to doing just this is reasonably straight-forward and possible of accomplishment in the future for production quantities of high stability resonators.

The major drawback of the SC with respect to the AT is the increased criticality of the orientation angles ϕ and θ for oven operation near the inflection temperature; where a few minutes of arc suffice for the AT cut, the tolerance becomes seconds of arc for the SC cut. Fortunately, an automated x-ray goniometer with microprocessor control is being developed under ERADCOM contract, and this should provide the necessary accuracy and precision.

2. Time

Under this category we will discuss just two areas of recent, significant progress: mounting and electrode stresses, and contamination control. Other areas discussed in this category in the last section will be addressed later on, in this section, or the next.

Figure 11 shows traditional metal enclosures, and the recently developed ceramic flat-pack enclosures [26]-[28]. The ceramic units have the advantages of cleanliness: they are cleaned more easily, can be baked at higher temperatures to remove contaminants, and the alumina enclosure is impervious to gaseous diffusion unlike metals and glasses. The flat-pack design also provides a geometric factor not possessed by the metal holders, and is microcircuit and hybrid circuit compatible. Within the ceramic enclosure, the resonators are attached to the mount with polyimide [29]. This material can be vacuum baked at above 350°C and thus has minimal outgassing. This means of attachment can be used from cryogenic temperatures to 350°C. The lid is sealed to the rest of the ceramic enclosure by metal-to-metal, clean surface adhesion.

The resonator blank sealed within the ceramic flatpack has gold electrodes deposited upon its surfaces. This provides a minimum of stresses and interface reactions. The interface between the gold and quartz must also be clean. Near-atomic cleanliness can be obtained by, among other things, UV/ozone cleaning [29]-[31].

Adherent electrodes are still subject to thermal stress cycles, and to stress relaxation, regardless of how ductile the electrode material may be. Means of obviating this problem are: 1. the use of the SC-cut, which is insensitive to electrode stress relief, and 2. the use of air gap designs [32], [33]. An embodiment of the air gap type of mounting/electroding design is the BVA of Besson [23]. The absence of electrodes directly on the vibrator surface rules out surface stresses and possible electrode asymmetry that would lead to couplings with even harmonics and with flexure. The BVA design also utilizes a ring structure with monolithic quartz bridges that isolate the vibrating portion from the quartz supporting ring.

The other area, contamination control, is best summed up by saying that all processing, from initial input of quartz blanks and ceramic enclosures, to finished resonator units, must be done under ultraclean conditions. The final, most critical fabrication steps must be performed in ultrahigh vacuum. An apparatus that accomplishes this is shown in Figure 12. This is the Quartz Crystal Fabrication Facility (QXFF) [34]. It consists of five separate chambers: 1. entrance,

2. UV cleaning-bakeout, 3. gold plating, 4. sealing, 5. unloading. Chambers 2,3, and 4 are under 10^{-8} to 10^{-9} torr continuously, and never see air after the initial pump-down. All chambers are separated by ultrahigh vacuum gate valves, and each chamber is separately cryo-pumped. The QXFF is being developed under ERADCOM contract; the pilot run for 22 MHz fundamental mode high shock crystals is scheduled to take place during 1980. The pilot production run for high precision 5 MHz and 10 MHz crystals in scheduled for 1981-82.

3. Acceleration

For accelerations out of the crystal plate plane, desensitization of the acceleration-induced frequency shift may be partially accomplished by use of ring-mounted resonators as shown in Figure 13 [35]. The improvement comes about by the alteration of the boundary conditions at the plate periphery as described at the bottom of Figure 13. When the acceleration is in the plane of the plate, one cannot make any a priori statements concerning the magnitude of the effect, except that it will be azimuth dependent. The ring-supported resonator may be fabricated of any cut.

It is an experimentally observed fact that SC cuts are considerably less sensitive to the effects of acceleration (attitude, shock and vibration) than AT cuts; the improvement may be as much as a factor of ten. Beyond this, one may use dual resonators with two crystal axes antiparallel [23], to obtain compensation along these axes, or one may use enantimorphs in a three-axis antiparallel configuration to produce a dual resonator compensated against the effects of an acceleration field in any arbitrary direction [36].

The enantiomorphous composites may be fashioned as paired:

- conventional resonators
- ring-supported resonators
- BVA resonators
- stacked resonators
- ring-supported resonators with the ring structures stacked

Additionally, the electrical connections may be series or parallel, and the crystal cut may be singly (AT) or doubly (SC) rotated [36]. Examples of stacked crystal composites are given in Figure 14.

In order to render quartz vibrators capable of withstanding shock levels approaching the theoretical breaking strength of the material, it has been found that microscratches and imperfections left by the conventional mechanical polishing operation had to be completely removed. Otherwise, the stress magnification that took place as the stress wave passed over the scratch resulted in plate fracture. The method newly introduced into quartz resonator fabrication for this purpose is chemical polishing [37]-[39]. Chemical polishing consists of etching the crystal to produce pure crystalline surfaces that reveal defects and makes the plate much stronger. The proper etchant and procedure is dependent on the orientation angles ϕ and θ. For $\phi \neq 0°$, even though each surface may be chemically polished, the result is different on each side; this can be used as a polarity test of axes when using paired plates as enantiomorphous composites.

4. Radiation

Temperature gradient effects on resonator frequency, arising from pulsed ionizing radiation can be largely compensated by utilizing SC cut resonators. Steady state radiation effects depend strongly on defects in the material. Just as annealing has been used to increase the Q of quartz, and to attempt to reduce aging [40], a combination of high temperatures (below the α-β transition point) and strong electric fields (referred to as "sweeping") has been found to produce material with superior purity and thus superior radiation hardness [41]-[43], [21]. In addition, the sweeping process (done in a vacuum) has been shown [37] to produce material having many fewer etch channels than non-swept cultured quartz. Etch channels degrade the strength (shock resistance) and serve as repositories of etchant that can produce instabilities.

The use of tuned IR and UV to excite lattice vibrations, and impurities, respectively, to aid in the sweeping process has been proposed [44].

Further improvements in radiation hardness, Q, and long-term aging of the material itself due to diffusive phenomena will require further developments in crystal growth. Among these are use of defect free natural quartz seeds, special seed preparation, use of select high purity nutrient material, special cleaning of autoclaves, and use of precious-metal-lined autoclaves.

ADDITIONAL CAUSES AND CURES

1. Quasistatic forces

These include thermoelastic forces, and intrinsic stress relief mentioned under long-term aging. For in-plane forces applied to a circular plate as shown in Figure 15, it is found that there are azimuth angles such that applied force-pairs produce no frequency change [16]; this is true even for doubly rotated plates on the upper ZTC locus [45]-[48]. When this criterion is used to locate four mounting points [49], then thermoelastic forces will have no influence on the resonator frequency, as long as no asymmetry exists, i.e. so that bending moments are not generated. The structure is thus only conditionally stable, that is, only as long as the forces are colinear in pairs. Another difficulty is that the force coefficient has an appreciable gradient with angle about the zero points. Two means of overcoming this difficulty are: 1. use of ring-supported resonators, and 2. use of special polygonal shapes instead of circular outlines. Ring-supported structures, which can be produced by chemical etching [49], absorb most of the forces and/or torques applied and are less sensitive than conventional resonators. Plates of special lateral contour have been developed [50] for singly and doubly rotated cuts that have the property of being frequency insensitive to in-plane forces applied normal to two pairs of edges. The edges are used for mounting, and the stress levels are greatly reduced over point-mounts. Moreover, the polygons are self-orienting in their holders. Examples of the plates are shown in Figure 16 (AT cut), and in Figure 17 (SC cut).

2. Line voltage changes

This is an oscillator, rather than a resonator, characteristic. Defining a voltage coefficient of frequency as

$$\overline{V}_f = \frac{Vo}{fo} \cdot \frac{df}{dV} ,$$

one has the following typical figures for $\overline{V}_f$:

RTXO	10^{-6}
TCXO	$5x10^{-7}$
OCXO	10^{-9}

The RTXO figure of 10^{-6} means $\Delta f/f$ changes 10^{-7} for a 10% change in line voltage. Improvement of these figures depends mainly upon circuitry design and improvement.

3. Resonator drive level

The amplitude-frequency-drive level surface for a typical AT cut is given in Figure 18 in schematic fashion. For high power levels the surface becomes pleated, indicating a multiple-valued amplitude-frequency curve. A rule-of-thumb figure for the frequency change in an AT at low drive is parts in $10^9/\mu W$, but this depends on geometry. The BT cut bends in the opposite direction [4], [51], [52]. In the vicinity of the SC-cut the curve does not skew until much higher levels of drive.

Besides the amplitude-frequency effect, another nonlinear effect may occur, viz., the presence of a very high starting resistance at very low power levels [53], [54]. It is strongly suspected that surface preparation is responsible; chemical polishing and processing under ultraclean conditions should eliminate this feature.

4. Static charge - dc field sensitivity [55]

The electric field coefficient of frequency is defined as

$$E_f = \frac{1}{f_o}\frac{df}{dE}.$$

In terms of this coefficient, measured values for three quartz cuts are [55]:

AT cut	0.04 pm/V
SC cut	2.3
LC cut	16.7

For rotated-Y-cuts, the effect should vanish for electric fields in the plate thickness direction; but any x component of field will produce a contribution for any cut. In a clean, dry environment, static charges on insulating surfaces can produce many kV with respect to ground. From the figures above it is seen that the SC cut is more susceptible to this effect than the AT cut. It is gotten rid of in a simple manner, by placing a high resistance in parallel with the vibrator.

5. Other nonlinear effects

- effect of bonding on f-T curve [56]
- piezoelectric hysteresis [57]
- nonlinear permittivity [58], [59]
- parametric excitation [60]-[62]

It remains to be seen if these effects are reduced in size for certain doubly rotated orientations. It has been established that the SC cut is remarkably free of another nonlinear effect-activity dips.

CONCLUSION

In many of the papers presented at the 1979 PTTI meeting that detailed system requirements, it was heard again and again that it was highly desirable or imperative that frequency sources be developed that possess fast-warmup capabilities, and that are insensitive to accelerations and other environmental effects.

This paper reports developments that make these requirements realistic for the future. The path is open for the realization; no "breakthroughs" are required to reach the goal. This is not to say that the goal has been reached already! Ahead lies an exciting period consisting of putting together coherently the developments reported in this paper. It will require time and support on the part of the interested systems users.

Table 5 shows a comparison relating to high stability oscillators. The first column gives figures derived from manufacturers' specifications as to what can be bought today off-the-shelf, in small quantities. The second column provides a "guesstimate" of the state-of-the-art in precision oscillators as of 1989 if the developments reported here are carried out. Prices are in 1979 dollars. The 50,000 quantity includes the sum of JTIDS, GPS, NIS, SINCGARS, SEEK TALK, etc.

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Note: Many of the references were presented at the Annual Frequency Control Symposium, U.S. Army Electronics R&D Command, Fort Monmouth, NJ 07703. They are cited here as AFCS for brevity.

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Table 1
Some Parameters Influencing Crystal Frequency

1. TEMPERATURE
   A. STATIC
   B. DYNAMIC
2. TIME
   A. SHORT TERM (NOISE)
   B. INTERMEDIATE TERM (OVEN FLUCTUATIONS)
   C. LONG TERM (AGING)
   D. THERMAL HYSTERESIS
3. ACCELERATION
   A. ATTITUDE
   B. VIBRATION
   C. SHOCK
4. RADIATION

Table 2
Emerging/Improving Technologies

1. SC-CUT
2. BVA DESIGN
3. NEW FABRICATION TECHNIQUES
   A. SURFACE CLEANING
   B. CHEMICAL POLISHING
   C. ULTRAHIGH VACUUM FABRICATION
   D. CERAMIC FLATPACKS
   E. POLYGONAL PLATES
   F. DUAL RESONATORS
   G. AUTOMATED X-RAY ORIENTATION/ANGLE CORRECTION
4. QUARTZ GROWING AND SWEEPING
5. BETTER THEORETICAL UNDERSTANDING
6. LOW TEMPERATURE STUDIES

Table 3
SC–Cut vs. AT–Cut

ADVANTAGES

1. PLANAR STRESS COMPENSATED (LOWER AGING, LESS HYSTERESIS)
2. THERMAL TRANSIENT COMPENSATED (FASTER WARMUP)
3. LOWER ACCELERATION SENSITIVITY
4. LOWER DRIVE LEVEL SENSITIVITY
5. HIGHER CAPACITANCE RATIO (LESS ΔF FOR OSCILLATOR REACTANCE CHANGES, HIGHER Q FOR FUNDAMENTAL MODE RESONATORS OF SAME GEOMETRY)
6. LOWER ΔF DUE TO EDGE FORCES AND BENDING
7. IMPROVED STATIC F VS. T, WITH FEWER ACTIVITY DIPS
8. LOWER SENSITIVITY TO RADIATION

DISADVANTAGES

1. MORE DIFFICULT TO MANUFACTURE
2. FAST SHEAR (B-MODE) EXCITED
3. MORE SENSITIVE TO ELECTRIC BIASING FIELDS

Table 4
SC–Cut Frequency Change vs. Oven Parameters

$\Delta\theta$ & $\Delta\phi$ = 5''		OVEN CYCLE RANGE (K)		
		0.1	0.01	0.001
OVEN OFFSET (K)	0.1	2.1×10^{-11}	2.1×10^{-12}	2.1×10^{-13}
	0.01	3.8×10^{-12}	2.1×10^{-13}	9.8×10^{-14}
	0.001	2.7×10^{-12}	3.6×10^{-14}	2.3×10^{-15}
	0	2.6×10^{-12}	2.6×10^{-14}	2.6×10^{-16}

Table 5
High Stability Oscillators

		1979	1989 GUESSTIMATE
STABILITY:	1 SEC	1 PP 10^{12}	PP 10^{14}
	24 HOURS	2 PP 10^{11}	PP 10^{13}
	5 YEARS	5 PP 10^{8}	PP 10^{10}
	RETRACE	PP 10^{9}	PP 10^{11}
	ACCELERATION	1 PP 10^{9}/G	PP 10^{12}/G
	RADIATION	2 PP 10^{12}/RAD	PP 10^{15}/RAD
	-40 TO +75°C	5 PP 10^{10} (TO 60°C)	PP 10^{12}
WARMUP		2 PP 10^{8} IN 1 HOUR	PP 10^{10} IN 1 MIN
POWER AFTER WARMUP, AT -40°C		≈ 3 W	<250 mW
SIZE		>400 CM^3	10 CM^3
PRICE IN QUANTITY		>$1,000	<$300
OSCILLATOR CIRCUIT AND OVEN DESIGN		CRITICAL	LESS CRITICAL
QUANTITIES REQUIRED		FEW	≈50,000

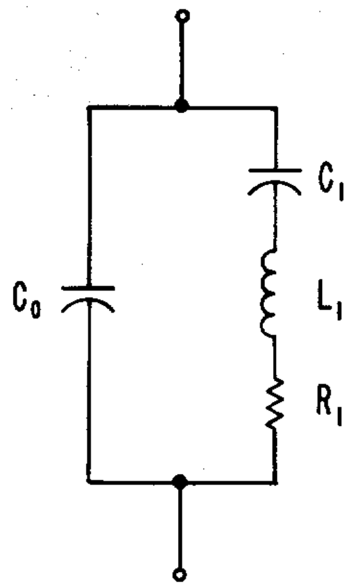

Figure 1. Crystal Resonator Equivalent Circuit

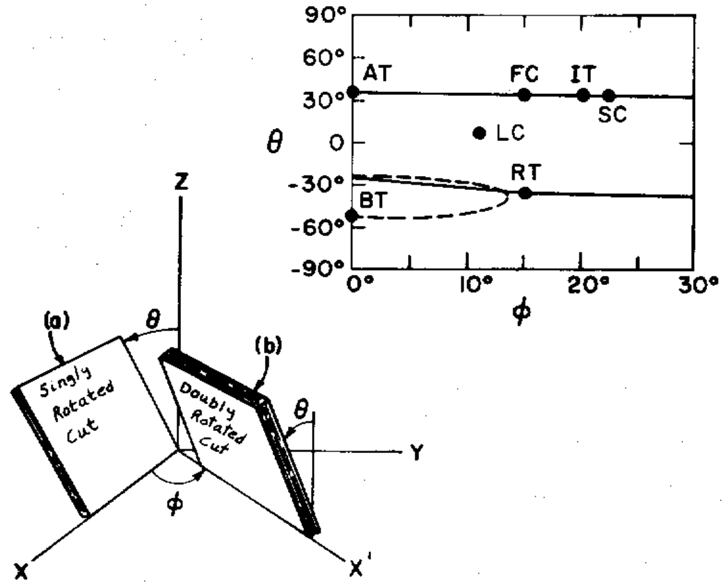

Figure 2. Doubly Rotated Quartz Cuts

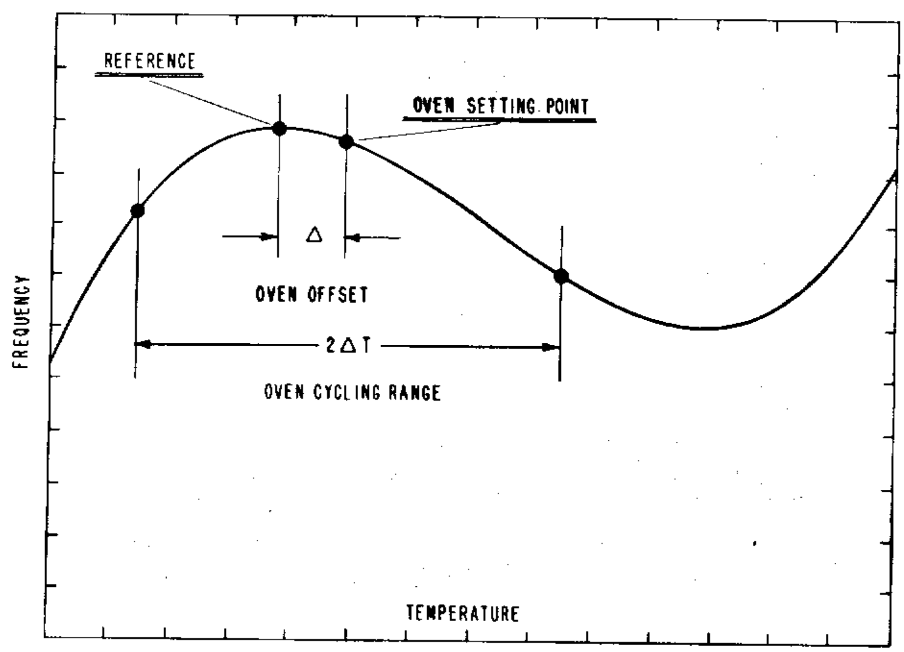

Figure 3. Static Frequency–Temperature Behavior

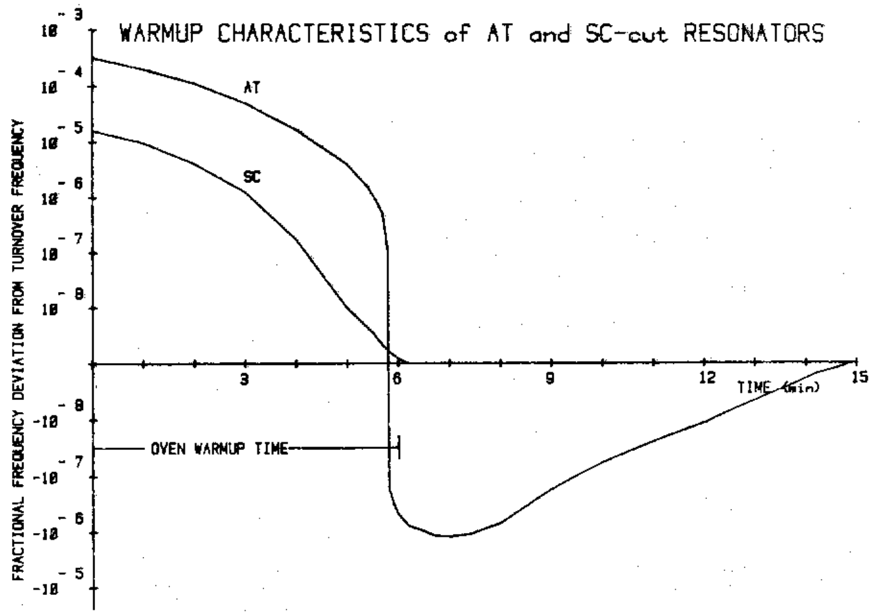

Figure 4. Warmup Characteristics of AT & SC Resonators

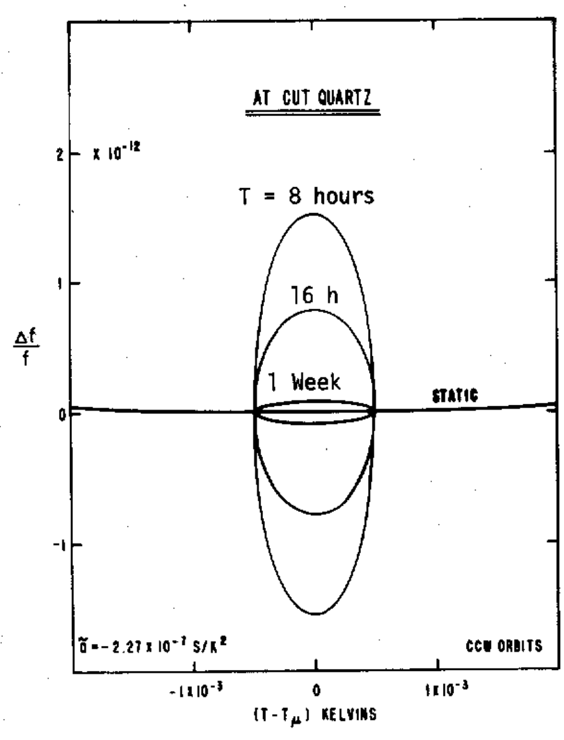

Figure 5. Dynamic Frequency–Temperature Behavior

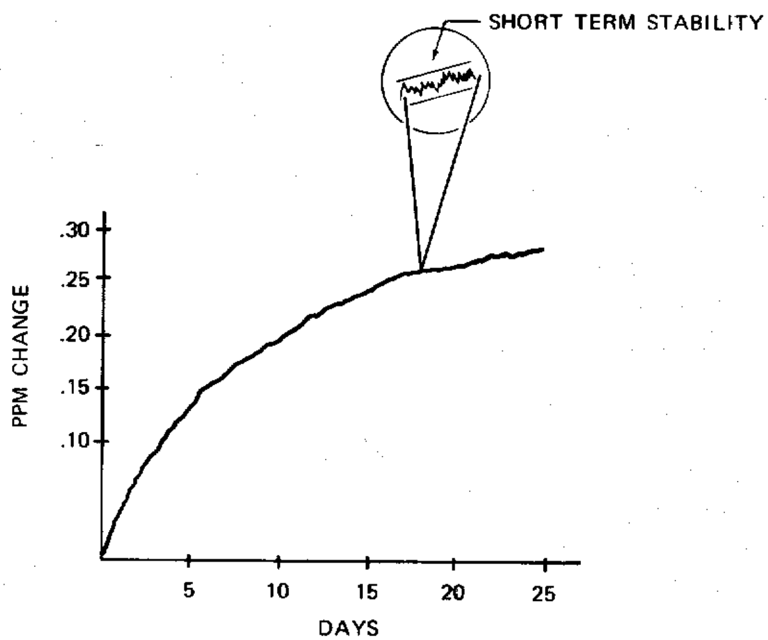

Figure 6. Resonator Frequency Versus Time

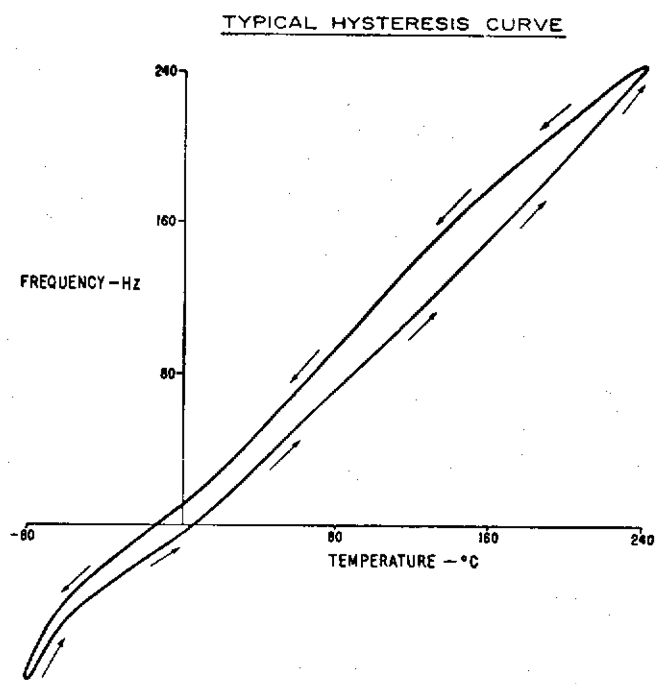

Figure 7. Thermal Hysteresis

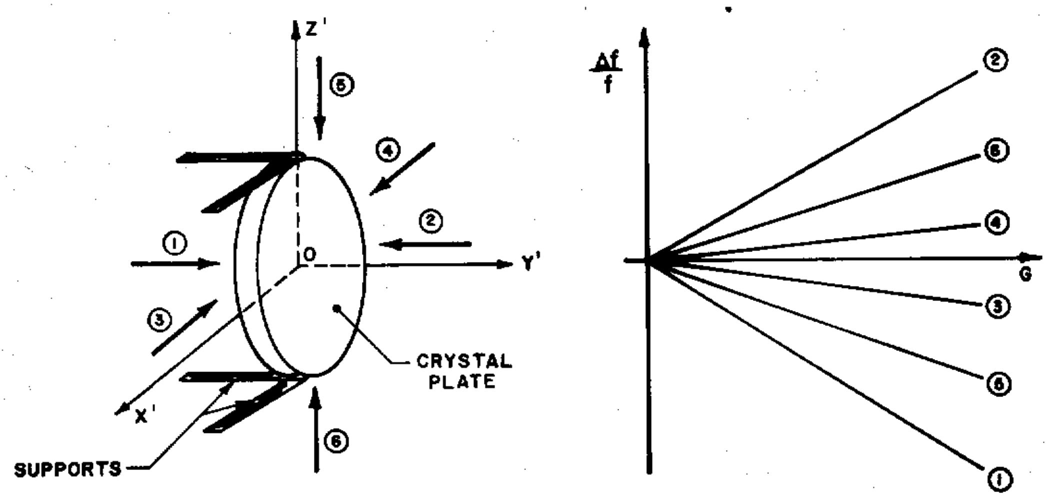

Figure 8. Acceleration–Frequency Behavior

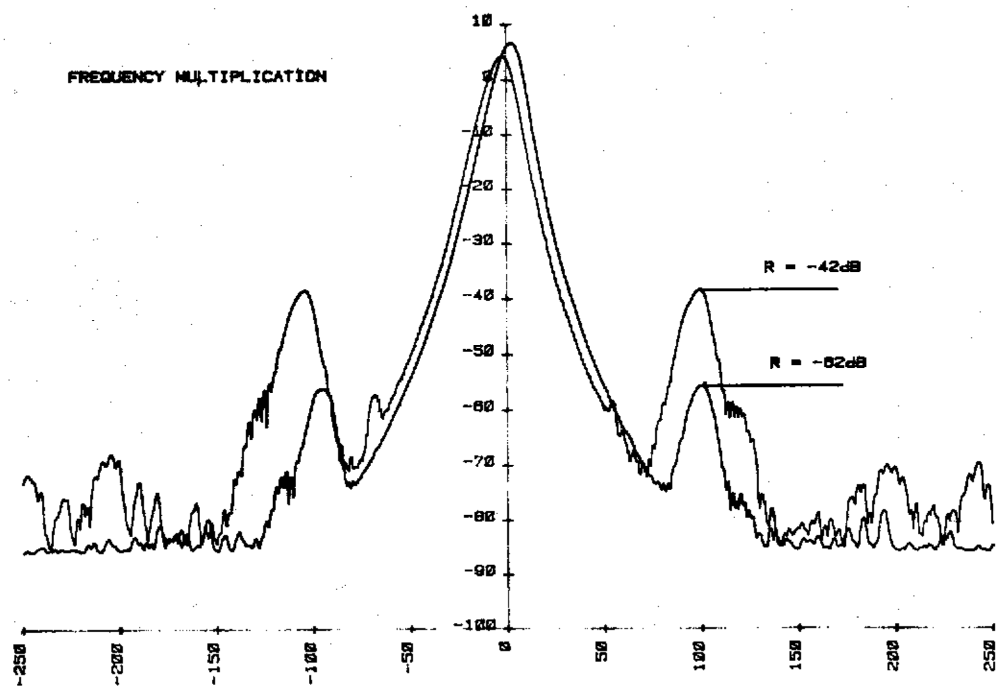

Figure 9. Resonance Spectrum Under Vibration, Showing 20 dB Sideband Increase Upon x 10 Frequency Multiplication

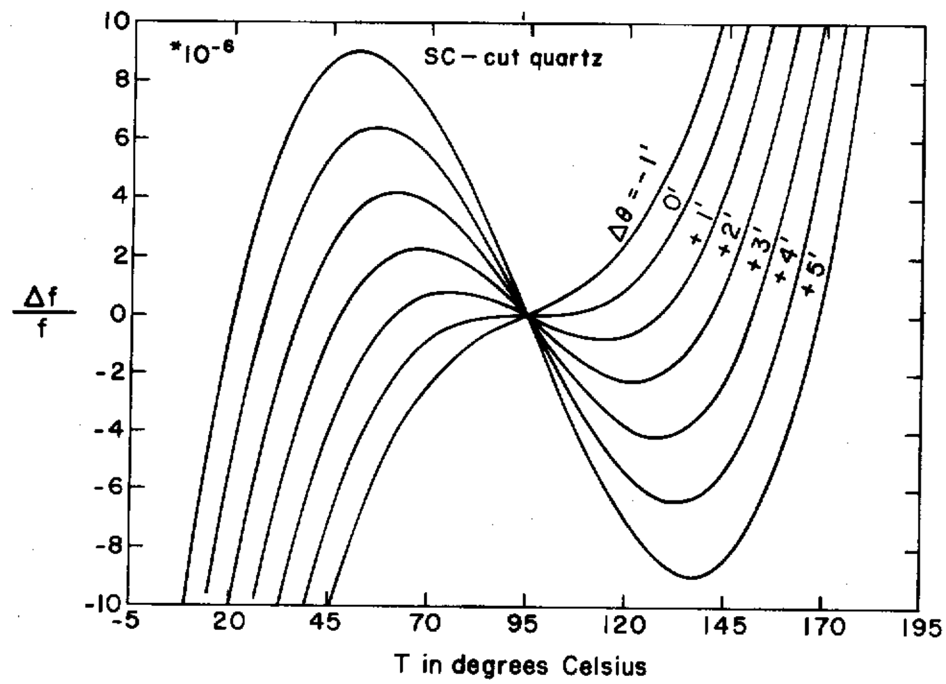

Figure 10. Frequency–Temperature–Angle Plots, SC Cut

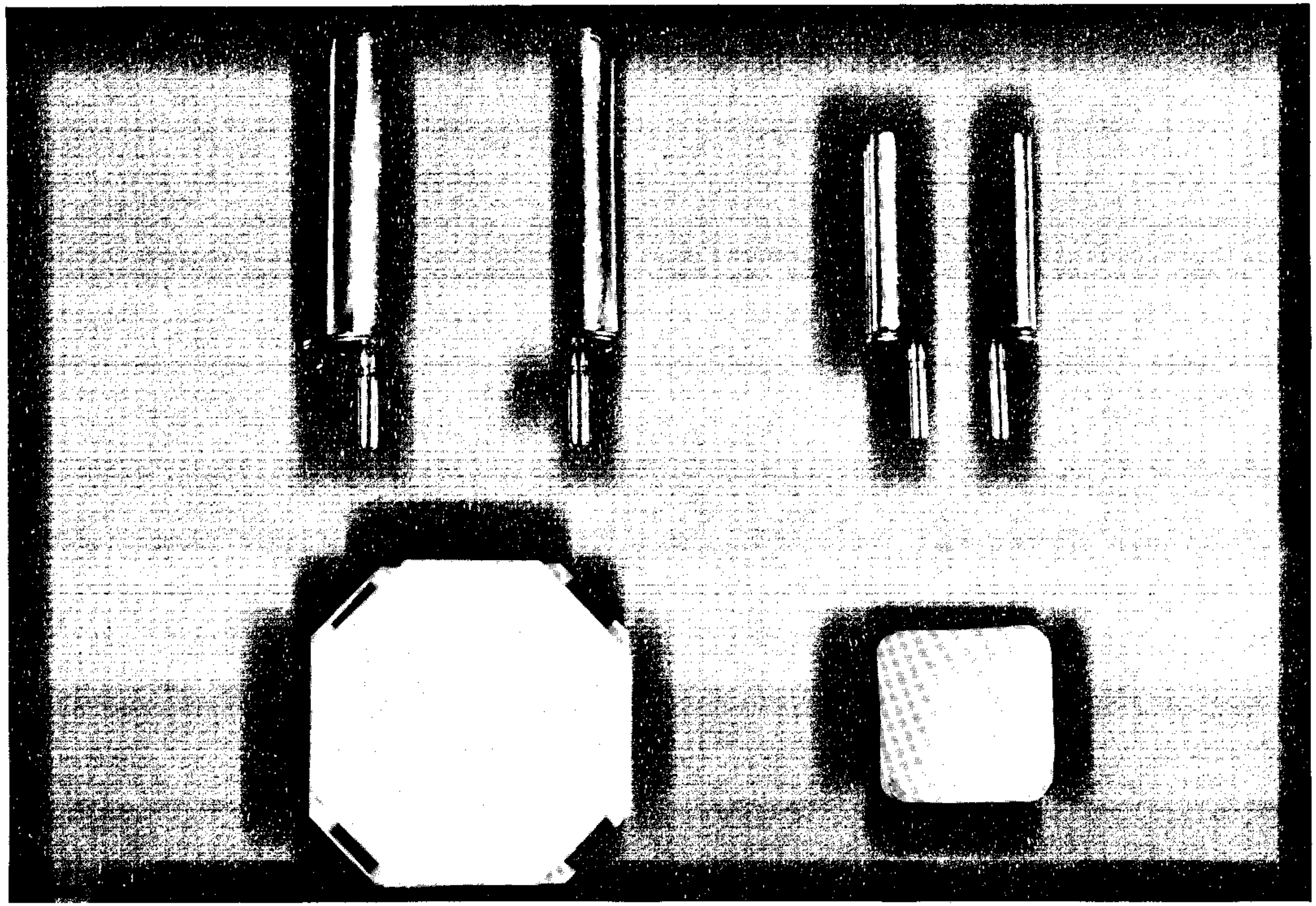

Figure 11. Metal and Ceramic Crystal Enclosures

Figure 12. Quartz Crystal Fabrication Facility (QXFF)

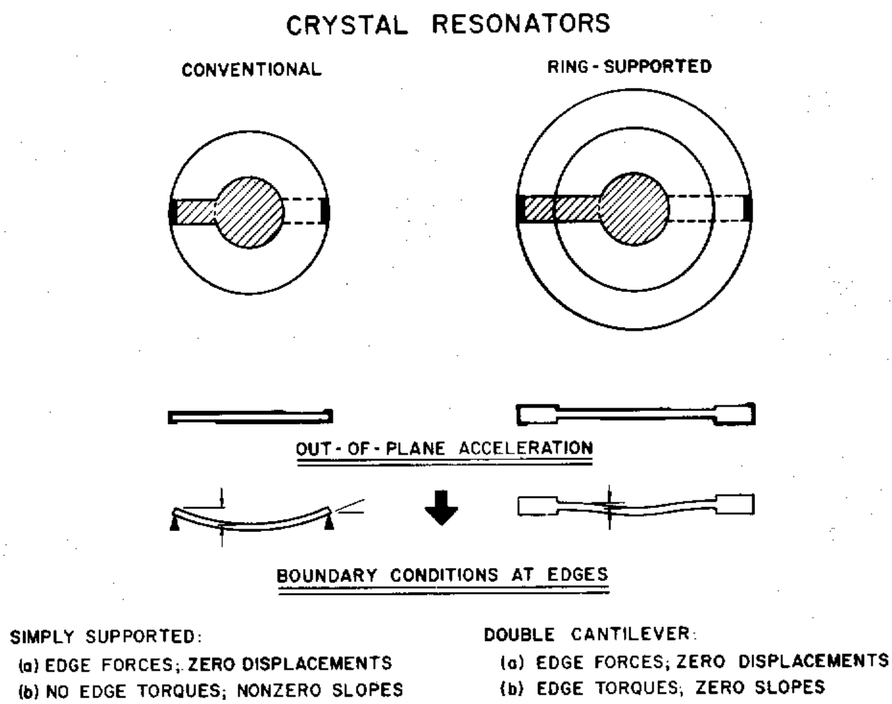

Figure 13. Conventional and Ring-Supported Resonators

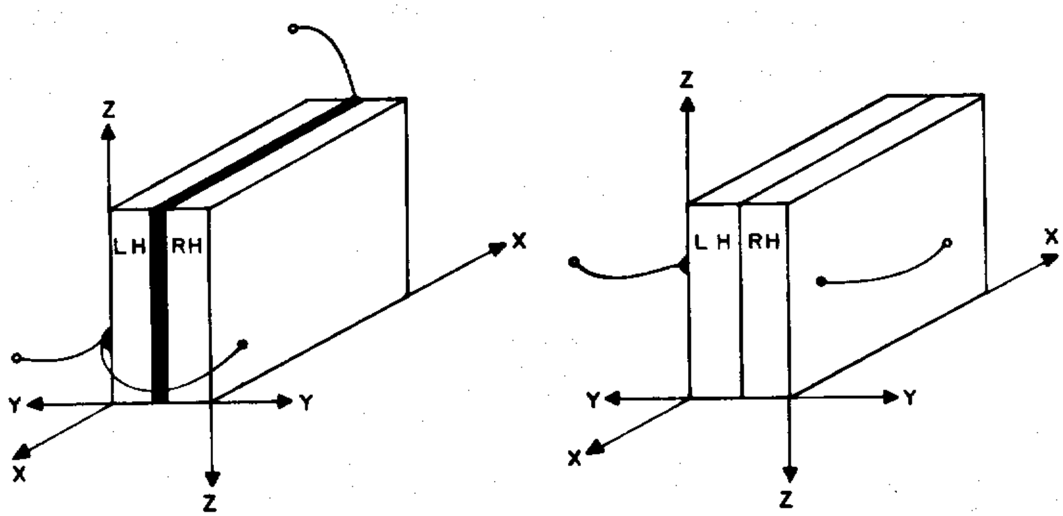

Figure 14. Stacked Crystal Enantiomorphs

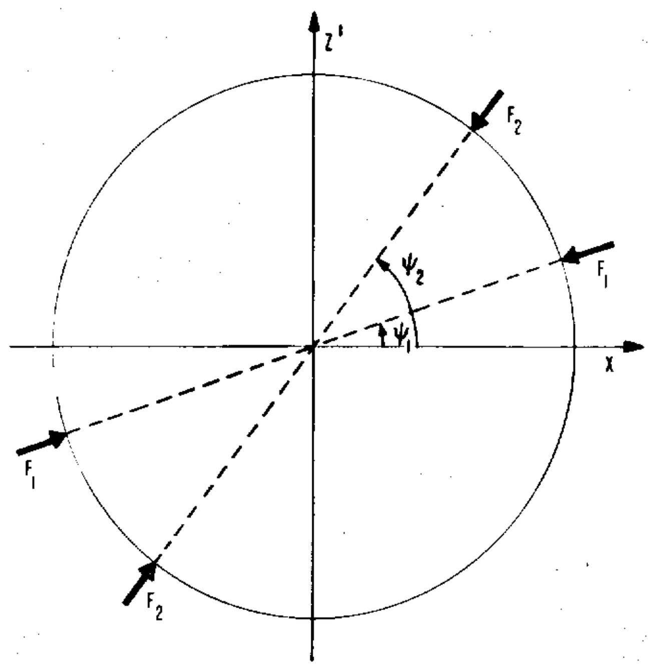

Figure 15. Crystal Disc with Edge Forces

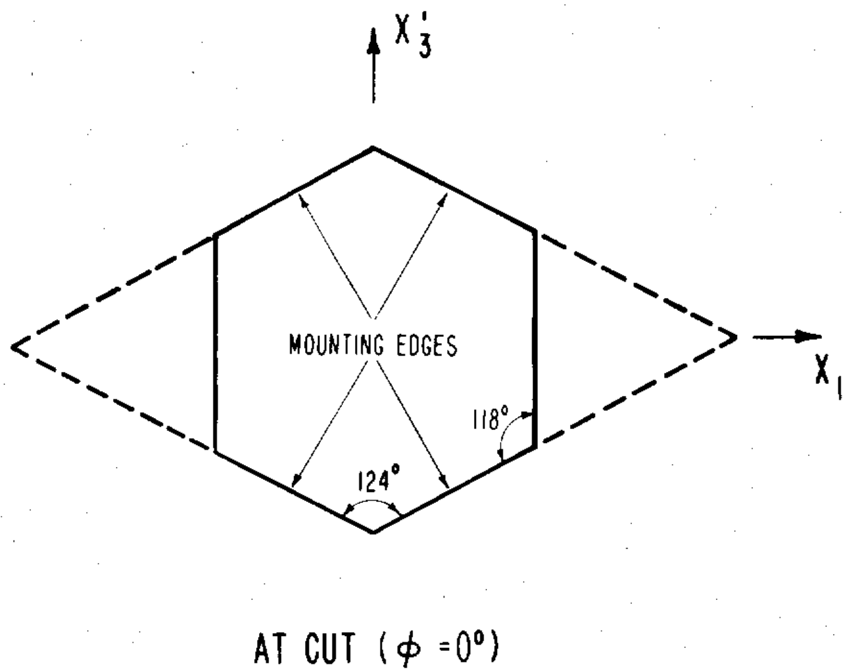

Figure 16. AT-Cut Polygon

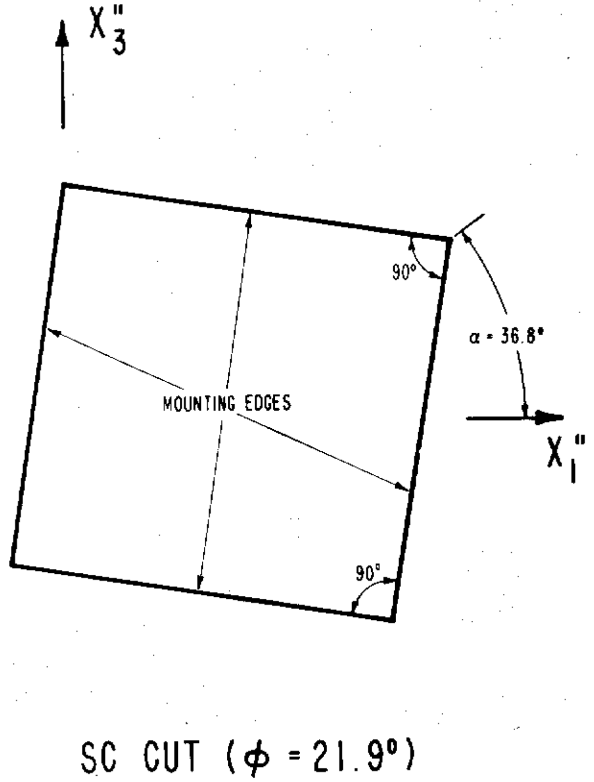

Figure 17. SC–Cut Polygon

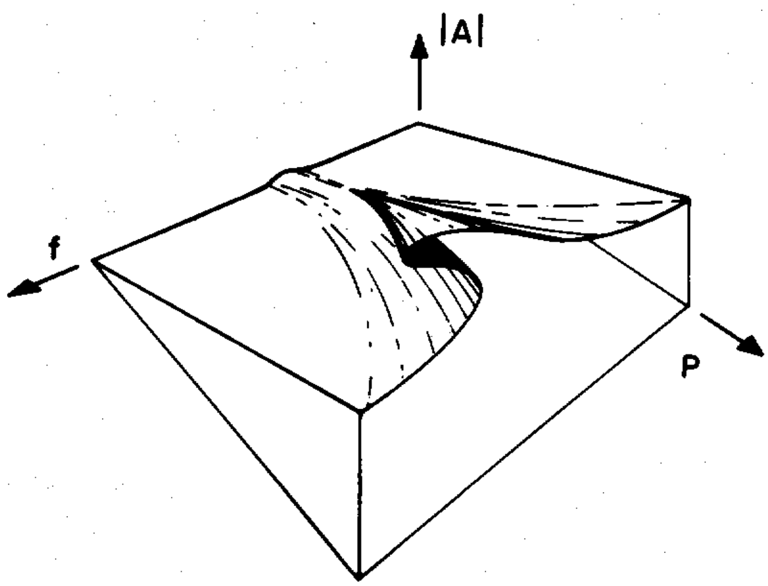

Figure 18. Frequency–Power–Amplitude Pleated Surface

QUESTIONS AND ANSWERS

QUESTION:

Is there any availability today commercially for SC cut crystals?

DR. BALLATO:

For SC cut crystals? Yes. They are-- Well, it depends upon the quantity. John, would you like to say a few words about that?

DR. VIG:

Yes. I would like to comment on the fact that, no, you cannot buy quantities of SC cut crystals and the ideas that are presented are, at this time, many of them are ideas, and they need to be reduced to practice and they need to be worked out, and there is a lot of work that needs to be done before we get to the point where we can mass produce SC cut crystals at a reasonable cost.

There are a couple of manufacturers who can provide very small quantities of SC cut crystals, whose angle controls is very poor. In other words, the turnover temperature is all over the place. There is no way you can buy an SC cut crystal with a turnover of 95 degrees, for example, if that is what you want. In order to get one of those, you might have to make a few hundred and select the one that meets your specification. So, there is a lot of work that needs to be done on manufacturing technology before we get to the point where we can afford to buy quantities of SC cut crystals.

QUESTION:

What about all the cases where they are needed, the majority. Not everybody needs 10, 11, 12, 13 crystals. If you need one today, what do you do?

DR. VIG:

If you reset your turnover temperature control, it doesn't make any difference. Okay? The SC cut plate is difficult itself to make today. You don't have the methods of angle control. As Art pointed out, you need to control both the Theta and the Phi angles to within a couple of seconds of arc. That is extremely difficult.

Okay? In theory the SC cut is going to be a beautiful cut. In practice, before you can buy it off the shelf, a lot of work needs to be done.

DR. WALLS:

Something of a comment I guess. From the work at the Bureau and work that we have done with Raymond Buisson and Jean-Jacques Ganupoint, I would guess that stress probably plays a greater role in frequency instability than what temperature contamination does and that the range between one second and a thousand seconds is dominated by temperature fluctuations in the AT as you have demonstrated in the last couple of talks and what we have seen. But beyond that, I would think that stress relaxation, stress in the mounting, stress in the plating is more important than contamination. Even at 10 to the minus 9 torr, you are still going to get monolayer exchanges of contamination within your enclosure at 1,000 seconds, so really it is an equilibrium between absorbed stuff on the inside of the enclosure and on the crystal blank. So I would guess that beyond 1,000 seconds it is really stress, and as we get better resonators, the aging and the long-term stability will be dominated by circuit parameters isolation in the output stage because of feedback and other things and it is my guess the architecture of our crystal oscillators must drastically change if we are going to achieve the stabilities of 10 to the minus 13 for long periods of time.

DR. BALLATO:

You are right, Fred. But stress is very very important, especially in the long-term. Also, some other rather subtle phenomena, that is to say diffusion of electrodes, if you have electrodes. Of course you don't need electrodes, or diffusion of impurities in the lattice. You need a lot of work on getting better quartz. Those will contribute significantly to long-term aging.

QUESTION:

How does the electromagnetic pulse change the frequency and stress?

DR. BALLATO:

How does that change the frequency? By heat effect.

QUESTON:

Heat?

DR. BALLATO:

Yes.