

# FOCUS

on  
Piezoelectric  
crystals  
and  
devices

Piezoelectric oscillator crystals and filter elements have simple basic shapes, such as bars, plates, or discs. When leads are attached to the element and it is mounted in any of the variety of MIL-standard or commercial crystal packages, it is a simple device that appears deceptively easy to specify.

But the reverse is true. Specifications for these devices are extensive and detailed. Frequently they are confusing and difficult to understand.

There are several reasons for the current confusion in crystal specs, some historical. But a main factor is that the quartz vibrating element is not simple electrically. It is a complex electromechanical system with several modes of resonance. Its operation is derived from the piezoelectric phenomena in which the mechanical strain or distortion of certain crystals that occur in nature, like quartz, produces an electric charge on their surfaces. Synthetic materials, including the barium-titanate and lead-zirconate-titanate crystalline ceramics, also exhibit this piezoelectric behavior.

The inverse effect—distortion of the crystal when a voltage is applied—is inherent in these piezoelectric devices. Use of this mechanical response to applied voltages is made in piezoelectric elements that perform as active, frequency-control devices in oscillators and provide passive, frequency-selective elements in bandpass or band-reject filters.

Device specifications have been developed by many independent authorities and agencies over the last 30 or 40 years. As a result, there is confusion today in terminology, in crystal manufacturers' specifications and in industry specifications like the MIL standards and the EIA and IEEE specifications. Nonstandardization of

names and symbols is a problem. Frequently the same quantity is represented by different symbols.

No manufacturers' literature provides an exact, detailed analysis of the equivalent circuit of the quartz crystal operating in the resonant and anti-resonant modes. Instead approximations are given, and frequently they differ from manufacturer to manufacturer.

Specifications like aging rates are often given in terms that will make the device look better. Important specifications, like "pullability" are omitted by most manufacturers.

Other less obvious specs—like spurious response, which is particularly important in crystals used for filters—are generally omitted.

## Specs don't agree

Some specs are not in agreement with themselves. For example, it's not unusual to find the L, R and Q of a crystal specified for a filter application, with a Q value that differs considerably from the  $X_L/R$  ratio. And in some cases L, C and the operating frequency may not be compatible for the same device.

Dependence on MIL standards for specifying commercial devices—a common practice—can be misleading and costly. Crystal users frequently refer to the MIL specs and select a unit from that listing, giving the manufacturer a CR number. But the CR number is associated with a comprehensive specification that includes a requirement for withstanding salt-spray corrosion. Also, CR types tend to have close tolerances over a temperature range of  $-55$  to  $105$  C. For a commercial application in a controlled environment, the designer is paying a high cost for salt-

spray resistance and operation over a temperature range that he doesn't need.

Temperature-stability specifications vary widely from manufacturer to manufacturer for the same type crystal and the same type cut.

A comparison of manufacturers' specifications, and in particular the curves that illustrate crystal characteristics and performance—like the plots of frequency drift vs temperature change—show wide variations in performance. Which data can you believe?

John Holmbeck, president of Northern Engineering Laboratories, points out that the industry suffers from excessive use of ideal curves that have been picked up years ago and passed on without revision from catalog to catalog. In evaluating a group of different vendors' specs, he suggests that the tightest tolerances are probably theoretical, while the loosest, or apparently the poorest performance, are substan-

tially closer to what can be realistically expected.

This brings up the question of just how much can you believe in the specifications? Can you expect to buy crystals and get the specified characteristics and performance?

According to Don Montgomery, vice president of engineering for Monitor Products Co., when you buy crystals, there's a good chance you won't even come close to getting the specified performance if you test the crystals in your own circuit.

Why? Let Montgomery explain.

Today, he says, most crystal manufacturers are using test sets that the Government requires for contractors supplying MIL-spec crystals. They continue to use the basic numbers that MIL specs have established over the years, such as drive level and equivalent resistance. But these test sets, which are a minimum of 20 years old, are vacuum-tube crystal impedance meters that are series oscillators, in which the crystal is



Photo by John Mutrux for ERC

Quartz crystal wafers, sawed from synthetically grown quartz boules, are polished and mounted in a variety of packages, including glass. Electrodes are plated or de-

posited on the quartz blank and connections are made to them through the mounting structure. These crystals, by Electronic Research Co., show wide variety available.



Seventy masked quartz crystals are being inserted, at Bulova Watch Co., into a fixture for vacuum deposition of electrodes. These crystals are fabricated for a TCXO.

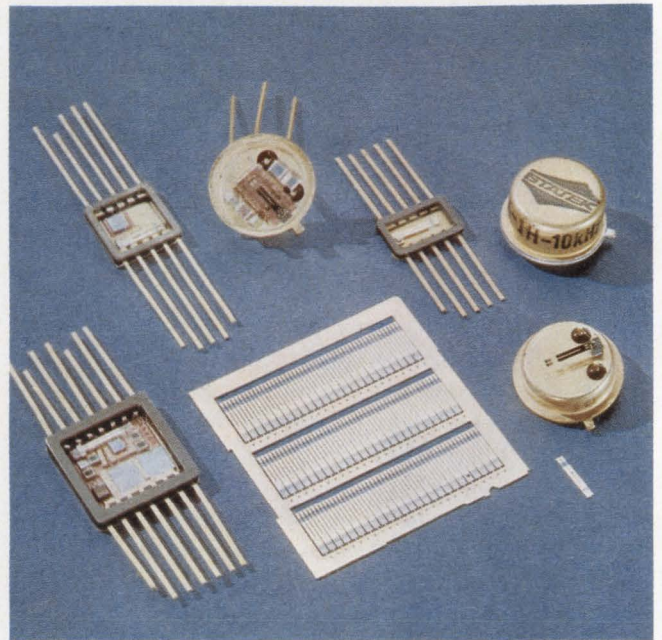
actually operating as the oscillator frequency-control element.

This has created a major problem in the industry, Montgomery insists. For a direct comparison of performance, crystals must be compared on the basis of exactly the same kind of measurements. For example, he says, the industry specifies and ships crystals on the basis of its tests with the Government equipment that has high drive levels. But customers today use the designs with transistorized or IC circuits, where the drive levels are very low. This alone is sufficient to cause a frequency difference of as much as 1 to 5 ppm.

"Now the customer, upon receiving the crystal, may turn around and measure it with a Hewlett-Packard vector-impedance meter," Montgomery says. "This is an extremely good and accurate method. But it's measuring the characteristics different than we are, and the results will not agree."

Whereas in the test oscillator the crystal is actually a part of the oscillating circuit, in the vector-impedance meter the crystal is being driven by a signal generator. As a result, there will be a phase-angle difference and an equivalent resistance difference.

Montgomery cites a 2-MHz crystal. Assuming you measure it with a 10-mW drive on the Government test equipment, the crystal may measure 180  $\Omega$ . In the vector impedance meter this may drop to 100  $\Omega$ . And the frequency will also change slightly.



A wafer of 75 tuning-fork crystals, by Statek, is flanked by typical packages and hybrid circuits in which they are mounted. The TO-5 header shows mounting.

If the customer wants a crystal within a 0.005% tolerance, his vector-impedance measurements will indicate the crystal is out, although the manufacturer calibrated it to that tolerance on his own equipment.

What's the answer to this problem? Montgomery recommends that where the required calibration tolerance is closer than 0.002%, the crystal circuit designer provide the manufacturer with a test oscillator configuration exactly like that in which the crystal is to be used.

As the first step in specifying a crystal properly, the equivalent circuit of that device must be analyzed, according to John Gliever, crystal circuit designer at Hewlett-Packard's Santa Clara Div. in California. For the best insight, he suggests taking the equivalent circuit (Fig. 1) and analyzing it mathematically.

In the electromechanical system represented by the equivalent circuit of Fig. 1, the crystal blank itself has a vibrating mass that appears to the circuit to be a motional inductance ( $L_1$ ).

The mechanical losses of the vibrating element—which include the molecular friction and acoustic loading of the blank by the ambient air or inert gas in the case in which it is sealed—appear as an equivalent resistance,  $R_1$ .

The elasticity of the quartz crystal appears to the circuit to be a small motional capacitance,  $C_1$ .

Capacitance  $C_0$  is the static capacitance between the electrodes plated on the quartz blank together with the stray lead and holder capacitances. A crystal can operate in the series-reso-

nant mode or in the parallel anti-resonant mode, or at some frequency between these points.

At frequency  $f_s$ , at which the reactance of  $L_1$  and capacitance  $C_1$  are equal ( $f_s = \frac{1}{2\pi\sqrt{L_1 C_1}}$ ), the net reactance is zero and the series-resonant circuit becomes an equivalent of  $R_1$  connected in parallel with  $C_0$ . The  $R_1$  is very small compared with the reactance of  $C_0$ , and series resonance will occur at minimum impedance and at zero degrees phase shift.

As the frequency is slightly increased above  $f_s$ , the inductive reactance increases and the capacitive reactance decreases. This produces a rapid increase in the net inductive reactance. Capacity  $C_0$  is now a portion of the frequency-determining network. When  $X_{L_1} - X_{C_1} = X_{C_0}$ , parallel anti-resonance occurs. In this case the impedance is a maximum and parallel anti-resonance occurs at the frequency  $f_p$ .

The frequency separation between the series and parallel resonance points of the crystal is a function of the ratio

$$C_1/C_0, \text{ or } f_p - f_s = 1/2 f_s (C_1/C_0).$$

At anti-resonance,  $f_p$ , the crystal has a very high impedance and is also highly inductive. Because a voltage applied across it would also be inductive, this fact should be considered when measurements are made of the drive level at which the crystal is operating.

In the anti-resonance mode any capacity added to the crystal, such as a load capacitor  $C_L$ , becomes a portion of the frequency-determining network. The effective operating frequency of the crystal changes. As shown in Fig. 1, the frequency is slightly reduced by the added capacitance.

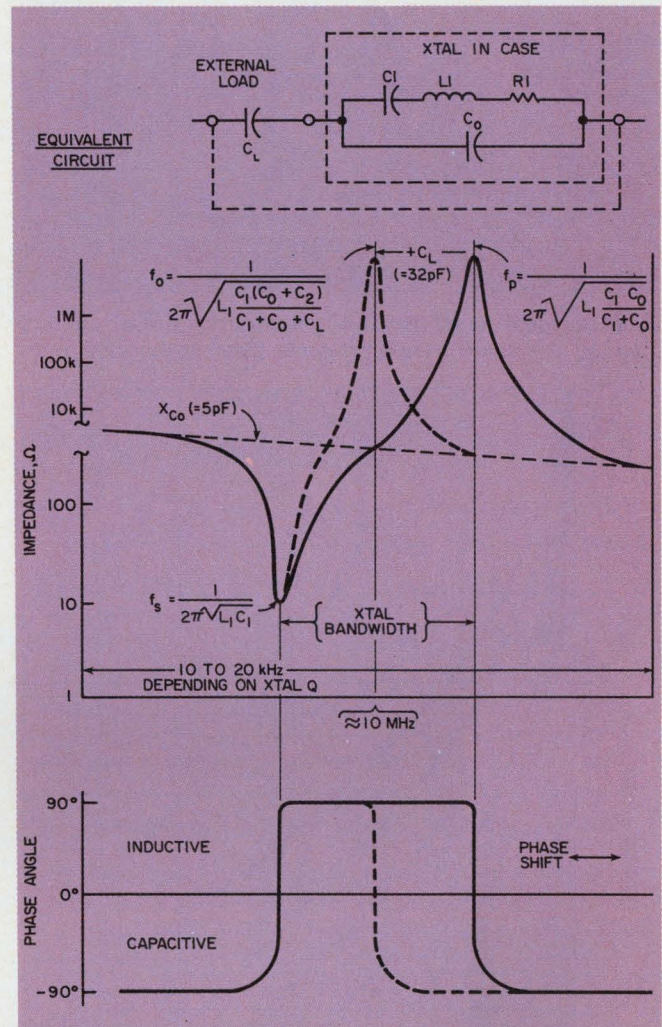
### Check for crystal capacitive load

The only difference between a crystal that is designed for series-resonant operation and one for parallel anti-resonant operation is the capacitive load for which the crystal is calibrated. Where closer adjustment of the crystal frequency is required than that which can be provided by manufacturing tolerance, operation in the anti-resonant mode is usually used.

The preferred value for  $C_L$  below 1-MHz operation is 20 pF, Holmbeck points out, while 30 pF is preferred above 1 MHz. While 32 pF has been specified in the U.S. for over 23 years, 30 pF is the international standard.

Holmbeck cautions that extremely small values of  $C_L$  are generally avoided. He points out, however, that a tradeoff may be made here that normally would be unacceptable. As an example, he points to the fact that to obtain the low-power drain of CMOS circuits such capacitances must be kept very low.

A disadvantage of very large values of  $C_L$  is



1. Characteristics of the equivalent circuit of a quartz crystal are such that when operating at series resonance  $f_s$  the reactive components of  $C_1$  and  $L_1$  are equal and the load is resistive. At the antiresonant frequency  $f_p$  the crystal presents a high inductive reactance.

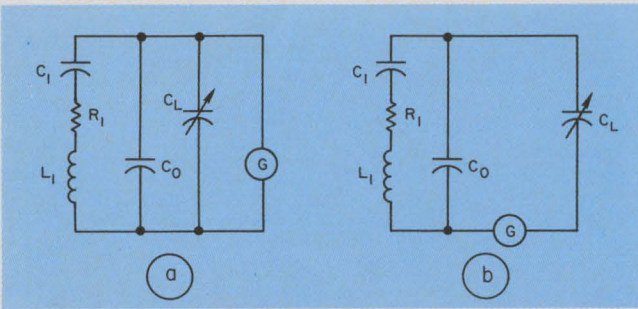
### Typical crystal parameter values

Parameter	200 kHz	2 MHz	30 MHz
$R_1$ ( $\Omega$ )	2k	100	20
$L_1$ (mH)	27 k	520	11
$C_1$ (pF)	0.024	0.012	0.0026
$C_0$ (pF)	9	4	6
Q	18 k	54 k	100 k

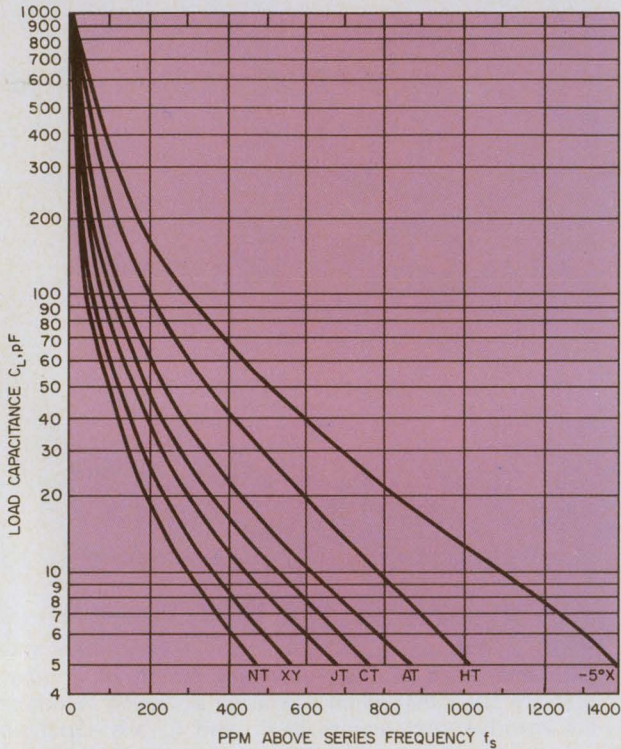
inconvenience in getting a large enough capacitance to obtain a desired frequency variation.

The pullability—or ability to shift the operating frequency of a crystal over a given range by means of a change in the capacitive load,  $C_L$ —is important for such applications as voltage-controlled crystal oscillators, temperature-controlled crystal oscillators and the design of crystal filters.

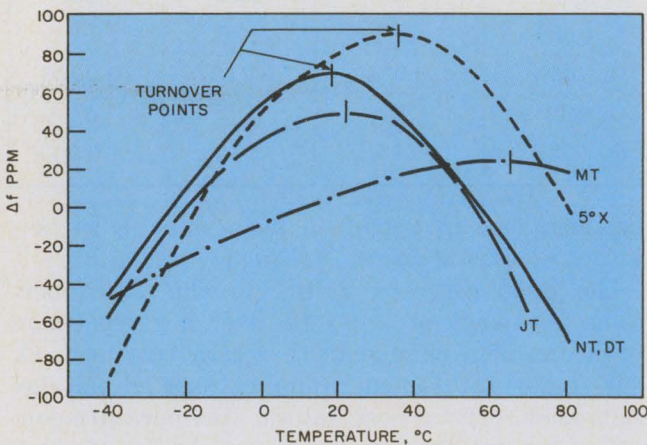
The bandwidth over which the frequency may be pulled is limited at the low end by series-resonant operation and at the high end by



2. With ideal crystals and generators, these circuits produce the same frequency for a given value of  $C_L$ .



3. The degree to which a crystal can be varied in frequency depends upon the ratio of the motional capacitance  $C_1$  and stray capacitance  $C_0$  as well as the  $Q$  of the device. Variations of bandwidth are shown.



4. Frequency variations vs temperature change for several kinds of low-frequency crystal cuts have same general shape. These curves can be shifted along the temperature axis to a limited degree by crystal fabricating methods.

parallel anti-resonant operation (Fig. 1). This bandwidth is a prime function of the ratio of motional and static crystal capacitances ( $C_1/C_0$ ) and also of the  $Q$  of the crystal.

This  $C_1/C_0$  ratio varies from about 1/900 for an NT cut to about 1/130 for the 5-degree X cut. (This ratio is conventionally stated in inverse form— $C_0/C_1$ ). Consequently, the NT cut has a narrow bandpass characteristic and the 5° X cut is a wide bandpass crystal. This bandwidth can be varied in manufacturing by control of the equivalent  $R_1$ ,  $L_1$  and  $C_1$  parameters. For a given crystal, the operating frequency can be changed by a change of load capacitance (Fig. 3). The shift in frequency can be determined by the approximate formula

$$\Delta f = 1/2 f_s \left( \frac{C_1}{C_0 + C_L} \right)$$

By special attention to control of crystal parameters and by the addition of capacity or inductance external to the crystal and within the total resonant circuit, it is possible to double normal pullability and bandwidths in voltage-controlled crystal oscillator applications.

The atomic structure of a quartz crystal has a unique orientation about three principal axes: the Z, or optical axis, which is nonpiezoelectric; the X, or electrical axis, which shows greatest piezoactivity, and the Y, or mechanical axis. A Y-cut plate—one with a major face normal to the Y axis—is also piezoelectric, and it has a positive temperature coefficient of about 100 ppm/°C. The X plate has a negative tempco of -10 to -25 ppm/°C.

By slicing, from a quartz crystal, a plate that is rotated with respect to one or two of the axes, the manufacturer can combine the positive tempco of the Y plate and the negative tempco of the X plate, so that at one or more temperatures the coefficients tend to cancel each other. This can create a point at which there is no frequency shift with small temperature changes. This is called a turning point.

For the low-frequency types of crystal cuts shown in Fig. 4, which range in frequency from about 1 kHz to 700 kHz, the frequency-temperature curves are parabolas that can, by crystal design, be varied over a wide range.

For example, the curve shown for the NT, DT crystals may be shifted left or right, with the turning point falling between -50 C and over 100 C.

The range within which the turnover temperature may be shifted back and forth along the temperature axis is found in most detailed specifications of low-frequency crystals. If the range is missing, the manufacturer can provide it.

The AT-cut crystal, which covers more than 75% of today's requirements, is unique in that it has a cubic tempco of frequency that makes

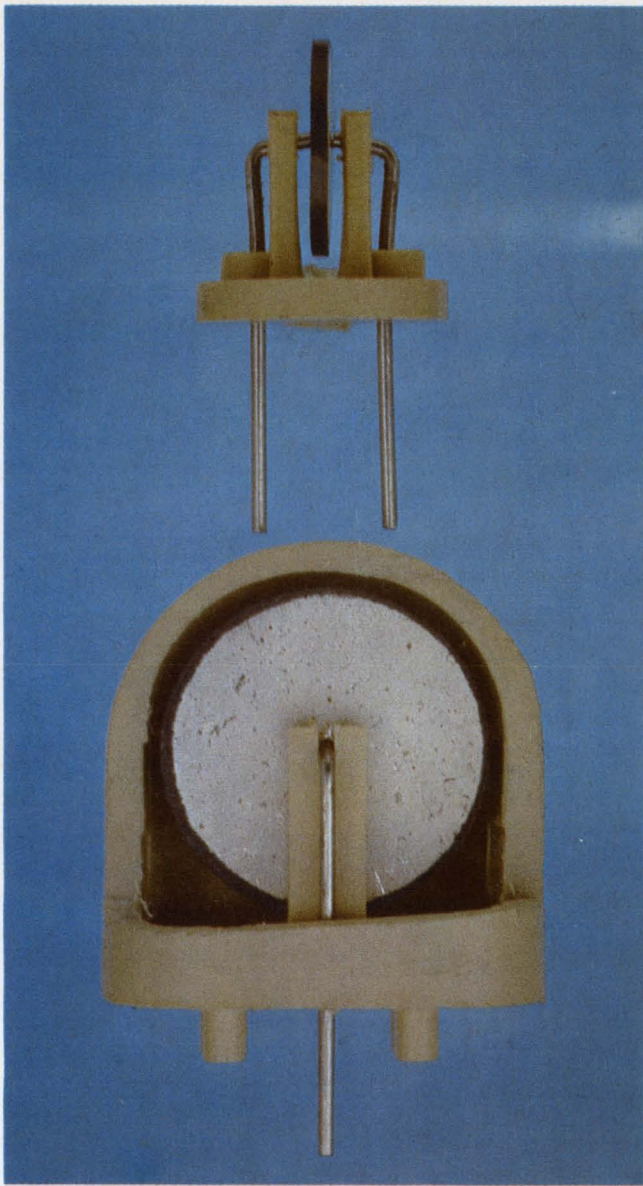


Piezoelectric ceramic elements, like these from Vernitron, can be fabricated in a wide range of sizes and shapes impossible to produce in single-crystal materials.

These elements are electrically poled during fabrication to produce their piezoelectric activity. This poling is applied to give a preferred electrical output or motion.

## Piezoelectric transducer material characteristics

Material	Designation	Mode	k	$\epsilon/\epsilon_0$	d ( $10^{-12}$ m/V)	$c$ (C/m <sup>2</sup> )	$\frac{v^2 \rho}{10^{10} \text{ N}} \left( \frac{\text{m}^2}{\text{m}^2} \right)$	Curie Point (°C)	$\rho$ (g/cm <sup>3</sup> )
Lead Zirconate Titanate	Navy I Vernitron PZT-4 Channel 5400 Edo West EC-64 Gulton HDT-31	TE	0.51	635	—	15.1	15.9	328	7.5
		TS	0.71	730	—	12.7	5.2		
		LE <sub>D</sub>	0.70	1300	289	—	12.7		
		LE <sub>t</sub>	-0.33	1300	-123	—	8.1		
		PE <sub>t</sub>	-0.58	1300	-246	—	9.1		
	Navy II Vernitron PZT-5A Channel 5500 Edo West EC-65 Gulton G-1500	LE <sub>D</sub>	0.705	1700	374	—	10.6	365	7.75
		LE <sub>t</sub>	-0.34	1700	-171	—	6.1		
		PE <sub>t</sub>	-0.60	1700	-342	—	6.9		
	Vernitron PZT-5H Channel 5550 Edo West EC-70 Gulton G-1278	LE <sub>D</sub>	0.75	3400	593	—	11.1	193	7.5
		LE <sub>t</sub>	-0.39	3400	-274	—	6.05		
		PE <sub>t</sub>	-0.65	3400	-548	—	6.9		
	Navy III Vernitron PZT-8 Channel 5800 Edo West EC-69 Gulton G-1408	LE <sub>D</sub>	0.64	1000	218	—	12.5	300	7.6
LE <sub>t</sub>		-0.30	1000	-93	—	8.7			
PE <sub>t</sub>		-0.51	1000	-186	—	9.9			
Lead Metaniobate	Keamos, Inc. — Linden Labs —	TE	0.37	190	—	—	—	570	6.0
		LE <sub>D</sub>	0.38	225	85	—	3.7		
Barium Titanate	(Widely available under chemical name)	PE <sub>t</sub>	-0.36	1700	—	—	11.7	115	5.7



**Piezoelectric resonators**, like this one from Radio Materials Co., can be used as active frequency-determining elements in oscillators or as filters.

it possible to maintain the tightest frequency tolerance over the widest range of any readily producible resonator. Fundamental operating frequencies range from about 0.5 to 30 MHz, while operation on third and fifth overtones produce frequencies from 10 to 150 MHz.

#### **AT crystal has families of curves**

Curves showing deviations of frequency with temperature for the AT crystal are invariably displayed in families of three or more (Fig. 5). These curves are produced by slightly different orientations of the crystal plate with reference to the crystallographic axis.

The curves in Fig. 5, from Northern Engineering Laboratories, are bounded at the  $-50$  and  $50$  ppm scales by a  $0.005\%$  tolerance. The minimum coefficient over a wide temperature range

falls well within a  $0.0025\%$  frequency tolerance between  $-55$  and  $105$  C, while the minimum room temperature coefficient is within  $0.0025\%$  at  $-35$  and  $85$  C. These values are typical.

Where precise temperature stabilities are required for AT crystals, ovens are recommended. For a frequency stability on the order of 10 ppm, the crystal temperature must be maintained within  $\pm 5$  C. For 1-ppm stability, the temperature must be controlled to within  $\pm 1$  C.

Excessive crystal drive levels can cause catastrophic failure of the quartz for the low-frequency cuts and destruction of the thin, deposited electrodes for the high-frequency cuts, at worst. At best, high drive levels force the frequency upward for AT cuts at high frequencies and down at low frequencies.

Permanent frequency shift can occur at drive levels that are substantially below catastrophic. High drive can also degrade aging characteristics and increase the crystal resistance.

Generally speaking, maximum drive levels for AT crystals range from 1 to 10 mW, depending upon the frequency, with the higher levels for the lower-frequency AT crystals. Low-frequency crystals—like the CT, DT, E-plate ( $+5^\circ$  X)—have a maximum drive of 2 mW, while others—like the HT, NT and XY—are held to but 0.1 mW. When used in ovens, the 2-mW low-frequency AT crystals should be reduced to a drive of only 0.1 mW.

#### **Aging is a complex phenomena**

Aging of a quartz crystal is caused by many factors, such as leakage of the seals, contamination, wire and solder-mounting fatigue, outgassing of materials within the sealed holder, and overdriving.

Aging exhibits an asymptotic type of behavior, with most of the aging occurring during the first several weeks of dynamic operation. The aging rate then decreases to what is an essentially constant value for the life of the unit. A reasonable level for aging of room-temperature AT-cut crystals is about 5 ppm per year and double that for the low-frequency crystals, according to Holmbeck of Northern Engineering Laboratories.

Many suppliers specify the room-temperature crystals with a daily aging rate. This, according to Marvin Willrodt, applications engineer at Hewlett-Packard, Palo Alto, Calif., may make the crystals look better in some cases. But in any event, he points out, it is a meaningless specification because it simply can't be measured in a room environment. Daily temperature perturbations caused by drafts, air-conditioning or heating, completely obscure the aging rate.

"I prefer to use a monthly aging rate," Will-

rodt says, "because the same temperature variations in a plant environment tend to occur about the same time every day. And a different, but consistent, temperature variation occurs on the weekends. After a month's observation of these temperature cycles, the trend becomes obvious, and an averaging line drawn through the perturbations provides the true aging rate."

If aging rates of a crystal must be low, the crystal can be pre-aged by operation in a circuit for an extended period, by temperature-cycling or by giving it a high-temperature bake.

"In our high-reliability programs," Frank Wolf, manager of the high-reliability testing group at McCoy Electronics, says: "We find a high-temperature bake is sufficient. We age the crystals from two or three weeks to 1000 hours or more at elevated temperatures."

### Best seal gives lowest aging rate

Crystal aging is strongly dependent on the seal of the crystal housing, Wolf points out. The glass-enclosed unit is the most permanent seal and provides the lowest aging rate, with the cold-weld seal next best. Solder seals give higher aging rates than either of the two.

The spurious response characteristics of crystals are like unwanted children. They're there, but nobody ever talks about them.

"You need to know spurious response," says HP's Gliever, "because such a response at an unwanted resonance close to an oscillator operating frequency can cause some circuits to lock onto a false frequency at start-up."

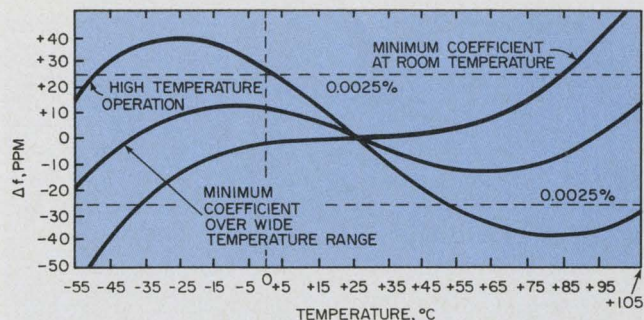
All crystals have spurious modes of operation, Gliever points out, and some manufacturer's products have worse parasitics than others.

Since spurious response is notable for its absence in manufacturers' specs, Gliever checks his crystals with an RX meter and a sweeping oscillator, used in combination. The relative separation and heights of the responses can be seen on the scope.

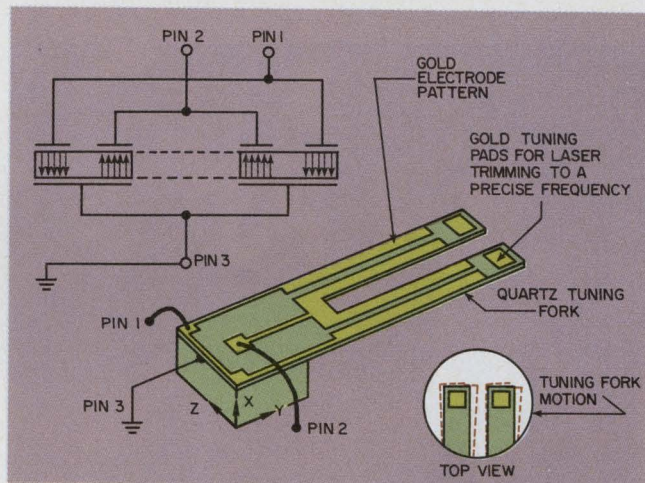
Gliever notes that when he makes spurious response a part of his purchasing spec, suppliers insist on an additional charge.

Today the AT-cut crystal, because of its superior temperature and frequency-stability characteristics, as well as range from about 1 to 200 MHz, is used in over three-quarters of all applications. The various cuts of low-frequency crystals—developed for World War II military applications in radar, sonar and low-frequency navigation and communication systems—make up the remainder of the market.

However, within the last two years a new mass market for low-frequency crystals has emerged: electronic watches and clocks. Initially a tiny 32.768-kHz XY bar was the industry's



5. The temperature curves of the AT-cut crystal have unique shapes that can, by proper fabrication, be rotated about the turning point. For the example shown the crystal was designed for room-temperature operation.

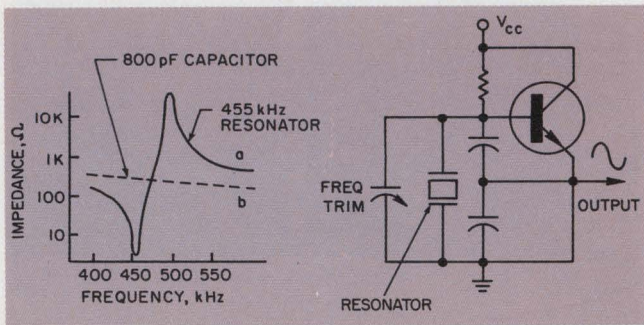


6. The tuning-fork crystal has gold-plated electrodes on both top and bottom. The varying electric field bends the tines towards and away from each other. The frequency of this configuration is about four times lower than that of a standard crystal of the same dimensions.

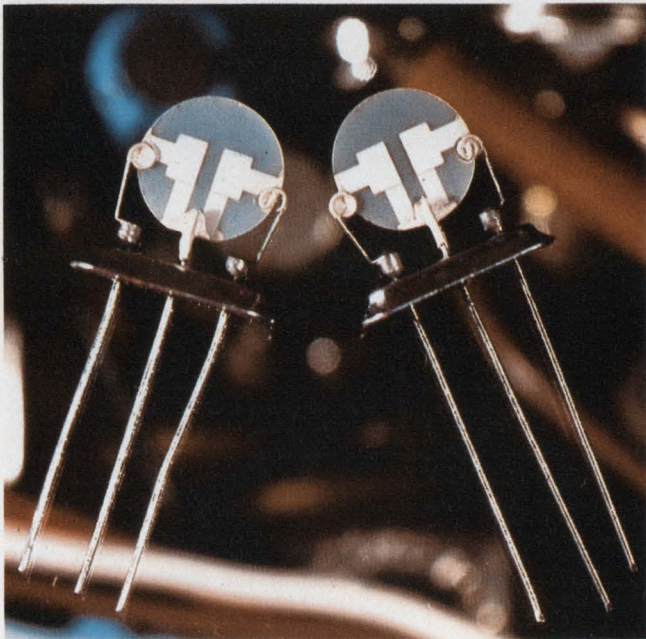
first watch standard and even today these crystals are being produced in the U.S. by Bulova, Motorola, CTS Knights, Reeves Hoffman and other firms. But in a drive to reduce further the size of these crystals, newer miniature elements, using conventional low-frequency crystal cuts, have emerged. They have frequencies of higher binary multiples like 131.071, 262.144, 245.760, 327.68 and 409.60 kHz. Miniature AT-cut crystals in the 1 and 4-MHz ranges are also under development.

For low-frequency applications in watches and also for frequency-selective applications, such as in beep-tone pocket pagers and telephone data-transmission systems, a new type of low-frequency quartz crystal has emerged—the first major development in quartz-crystal production technology in many years. This is the tuning-fork crystal, produced by Statek Corp. (Fig. 6).

Tuning-fork crystals, which operate in the fundamental mode from 10 to 100 kHz and in the sixth overtone mode from 100 to 600 kHz, are tiny quartz tuning forks 160 to 250 mils long,



7. The curves of a ceramic resonator are similar to those of a quartz crystal. Here, the impedance of a 455 kHz resonator, by Radio Materials, is compared to the reactance of an 800 pF capacitor. The device is used in the oscillator circuit to produce a sine-wave output.



These two-pole, 21.4-MHz monolithic filters by Piezo Technology are ultraminiature. Four, six and eight-pole filters are made using multiple two-pole units.

25 to 40 mils wide and 1 mil thick. Fork-tine lengths range from 40 to 150 mils, and tine widths are 10 to 15 mils.

These forks are formed in multiples of 75 on a 1-inch-square polished quartz blank that is 1-mil thick. On this is deposited a thin film of gold. With standard photolithic techniques of IC technology, the gold electrode patterns for 75 resonators are etched on the blank. Unwanted quartz areas are then chemically milled out of the wafer, leaving 75 tiny tuning forks.

The crystal forks are then probed for activity. For the good ones, the gold pads on the ends of the tines are laser-trimmed to frequency. The standard tuning tolerance is within 0.01% at room temperature, although 0.002% can be obtained at additional cost. Statek watch crystals are currently being specified at 0.001%.

While quartz has been the sole piezoelectric

crystalline material for years in frequency control and communications, a new synthetic material—lithium tantalate—has appeared. Developed by Bell Laboratories, it promises to be substantially cheaper and to provide filters with bandwidths that are 10 times larger than for quartz. Bell is using the lithium tantalate as a 1.5-MHz resonator, replacing quartz in telephone systems.

Other new synthetic crystals have been produced in recent years, such as lithium niobate. It is well-suited for surface-wave applications because of its high coupling coefficient and low acoustic velocity of  $3.47 \times 10^5$  cm/s. Bob Carlson, marketing manager of Crystal Technology, Inc., pioneer producers of this material, says that until recently it was used in surface-wave delay lines only in military applications. But recent cost reductions have made it of possible use as a surface-wave broadband i-f filter in color TV receivers.

### Piezoceramics are like quartz

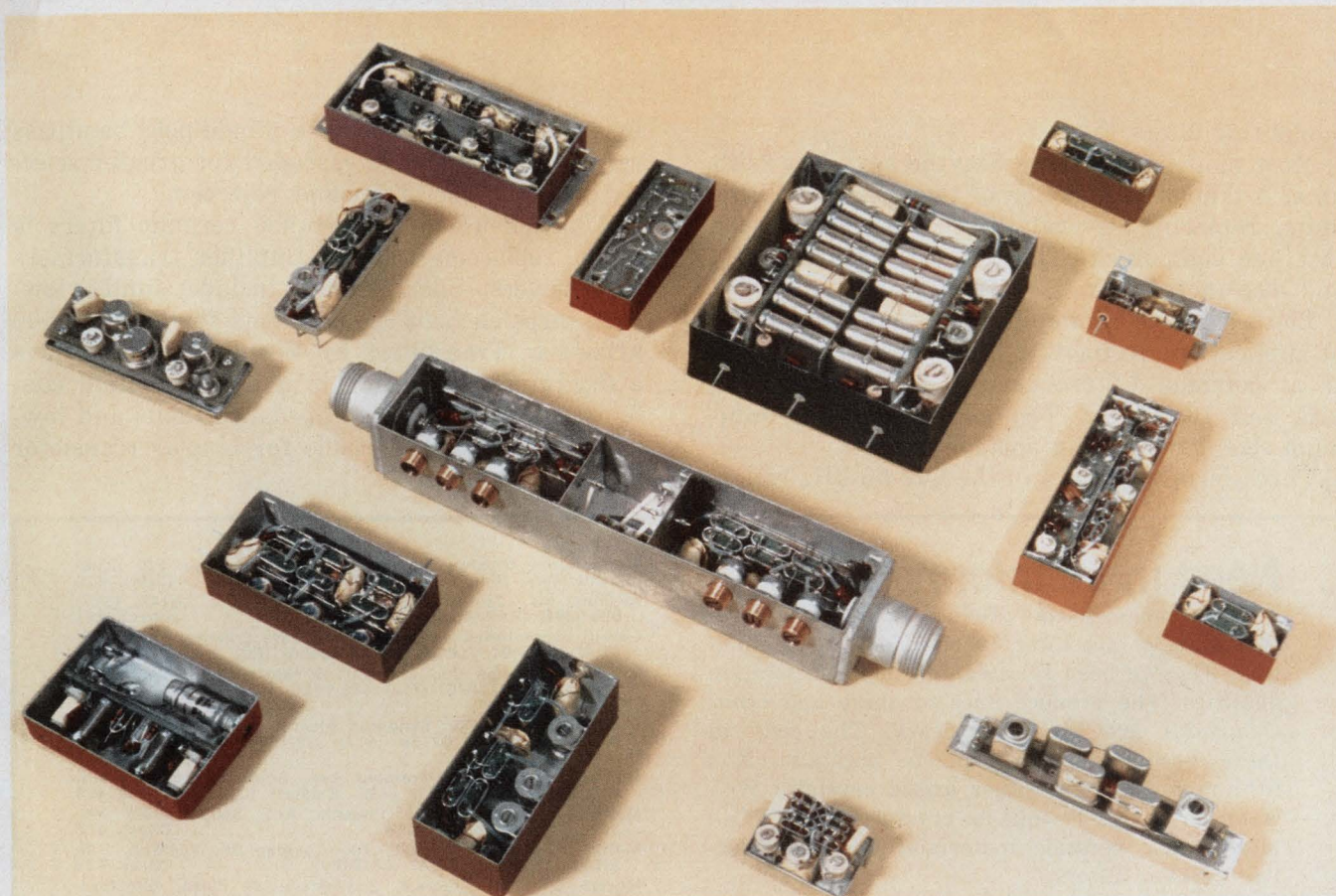
Piezoelectric ceramic materials are available that have the same basic piezoactivity as quartz and other crystalline materials. These ceramics—the lead zirconate titanates, the barium titanates and lead metaniobate—are nonpiezoelectric until a high voltage “poling” field is applied during high-temperature fabrication of the various shapes in which they are made.

Many of the larger forms are used as transducers in sonar, depth finders, fish finders, ultrasonic cleaners and other applications involving considerable power output. Smaller forms are used in earphones and microphones, phonograph pickups, vibration pickups and accelerometers, and frequency-sensing elements for low-precision oscillators. And smaller elements are also i-f filters for communications receivers, transceivers, and AM and FM radios.

Piezoelectric ceramic devices using ceramic resonators are produced by Radio Materials Co. for frequency-determining elements in low-frequency oscillators suitable for clock generators, sine and square-wave oscillators (Fig. 7) and carrier-current communications systems. One of these elements has a small disc resonator mounted in a proprietary way that minimizes spurious responses. The prime advantage of the ceramic devices is improved stability over IC circuits used for the same purpose. Frequency drift is less than 0.2% deviation from a 25-C value between -20 to 65 C.

Nominal frequency tolerance is 1 kHz for resonators operating with a series-resonant frequency from 180 to 550 kHz, depending upon disc diameter. The range can be increased to 1700 kHz with the use of overtone response.

The equivalent circuit of this resonator is



**Crystal filters** are used in applications where very sharp bandpass or band-reject characteristics are needed. Operating frequencies of these filters, by McCoy Elec-

tronics, range from about 20 to 200 MHz. The largest assembly, upper right center, is a 24-crystal, switchable bandpass filter that is used in the S3A aircraft.

identical to that of a quartz crystal. The motional inductance is on the order of a few millihenries, as contrasted with between 300 and 400 HF for a CT-cut crystal operating in the same range. The resonator material—a lead-zirconate-titanate system—has a large dielectric constant and is a relatively large ceramic capacitor. For the PC-18 material used in the device, the ratio of  $C_0$  to  $C_1$  is on the order of 8:1, giving an  $f_r$ -to- $f_p$  bandwidth ratio of 1.06, as contrasted with 0.125% for the crystal.

Crystal filters are used where narrowband filtering of signals in the 10-kHz-to-100-MHz range is needed, such as in sonar receivers, AM, FM, ssb, dsb, cw and fsk radio receivers, and in radar and navigation systems. Both crystal filter designers and experienced filter application engineers indicate that the design and specification of these filters is orders of magnitude more difficult than selecting a single crystal.

Because of the complex interaction of ranges of parameters—including center frequency, bandwidth, shape factor, group delay, transient response, phase linearity, insertion loss, temperature characteristics and so on—an engineer who is not a crystal filter specialist cannot be expected to generate the optimum crystal filter

spec for his application. This is one area, at least at the present state of the art, where close liaison between the equipment designer and the vendor's engineering group is essential.

Crystal filters today use both standard crystals and monolithic crystal elements. Below about 2.5 MHz standard crystals are used.

"Below about 2.5 MHz," says Vin Bates, director of operations for Damon Electronics Div., "we go to the regular filter because the physical realization of a monolithic device gets too big. And the amount of quartz that goes into the blank makes it expensive. With the regular filter, you have small quartz blanks."

Another area where conventional crystal filters would be chosen is in applications requiring ultimate rejection levels of  $-90$  or  $-100$  dB, Bates points out. In a monolithic filter this is still difficult, he notes.

The use of monolithic filters is still fairly new but is expanding rapidly. R. C. Smythe, president of Piezo Technology, Inc., specialists in the monolithic field, notes that in existing designs lower-cost monolithics are replacing conventional crystal filters. And new applications—like hand-held, two-way radios and pocket-paging receivers—have been made practical by the use of

monolithic filters.

Most monolithic filters, Smythe says, are built up as a tandem connection of two-pole monolithic units, replacing several discrete elements with just one component. This reduces size and cost and also increases reliability.

Piezoelectric ceramic filters cover a wide range of applications in the 6-to-550-kHz region as well as at common i-f frequencies of 455 kHz, 500 kHz and 10.7 MHz. The advantages are minimum size, fixed tuning and lower costs.

Three-terminal filters in the 6-to-55-kHz range,

by Analex Corp., provide a single-pole bandpass response. They can be cascaded for greater selectivity and higher stopband rejection.

A prime use of fixed-tuned ceramic filters is in the replacement of i-f amplifier transformers in receivers. Such devices include simple low-cost, three element replacements for 455 and 500 kHz—like Transfilters by Vernitron, which have a fixed-tuned resonator in a three-terminal configuration with a high-impedance input and low-impedance output, suitable for bipolar transistor matching. ■■

## Need more information?

The companies and products cited in this report have, of necessity, received only brief mention. They've been selected for their illustrative qualities. The product lines of these and other companies are identified below. The code to these products is: Q—quartz crystals; X—lithium niobate and other exotic crystals; W—watch crystals; F—quartz crystal filters; PC—piezoelectric ceramic materials; PF—piezoelectric ceramic filters.

Accutronics, Inc., Div. Gibbs Manufacturing Research Corp., 628 North St., Geneva, Ill. 60134. (312) 232-2600. (F) **Check 396**

American Electronics Labs, Inc., Box 552, Lansdale, Pa. 19446. (215) 822-2929. (A. Rosset) (C) **Check 397**

American Trans-Coil Corp., 124-06 101 St. Ave., Richmond Hill, N.Y. 11419. (212) 441-5207. (W. Clancy) (F) **Check 398**

Analex Corp., 7076 Big Creek Pkwy., Middleburg Heights, Ohio 44130. (216) 845-1953. (Anthony Lungo) (PF) **Check 399**

Blackhawk Networks Corp., 14 N. Parker Dr., Janesville, Wis. 53545. (608) 752-8701. (R. W. Brandt) (F) **Check 400**

Bliley Electric, 2545 W. Grandview Blvd., Erie, Pa. 16512. (814) 838-3571 (Dave Bliley) (Q), (F) **Check 401**

Bulova Watch Co., 6120 Woodside Ave., Woodside, N.Y. 11377. (212) 335-6000. (R. Ansell) (Q), (F), (W) **Check 402**

Channel Industries, 839 Ward Dr., Santa Barbara, Calif. 93105. (805) 967-0171. (R. M. Callahan) (PC) **Check 403**

Collins Radio Co., Dallas, Tex. 75207. (214) 235-9511. (C.I. Rice) (F) **Check 404**

Crown, Ltd., Div. W. Kidde & Co., 500 Beech St., Whitby, Ont., Canada. (416) 668-3324. (R. E. Dix) (Q) **Check 405**

Crystal Technology, 2510 Old Middlefield Way, Mountain View, Calif. 94040. (415) 961-9311. (Bob Carlson) (X) **Check 406**

Crystek Div., Whitehall Electronics, 1000 Crystal Dr., Fort Myers, Fla. 33901. (813) 936-2109. (Q) **Check 407**

CTS Knights Co., Sandwich, Ill. 60584. (815) 786-8411. (Q), (F) **Check 408**

Damon Corp., Electronics Div., 115 4th Ave., Needham Heights, Mass. 02194. (617) 449-0800. (N. Roy) (F) **Check 409**

Dietz Design, Inc., 100 Electronics Pkwy., Belton, Mo. 64012. (816) 331-4911. (W. Priest) (F) **Check 410**

Dittmore Freimuth Corp., 2517 E. Norwich St., Milwaukee, Wis. 53207. (414) 483-5100. (F.W. Dzurabala) (F) **Check 411**

E.B.L. Co., 78 Tolland St., East Hartford, Conn. 06108. (203) 289-5428. (Q), (X) **Check 412**

Edo Western Corp., 2645 S. 2nd W., Salt Lake City, Utah 84115. (801) 486-7481. (T.J. Hilton) (PC) **Check 413**

Electronic Research Co., Div. Textron, Inc., Box 913, Shawnee Mission, Kan. 66202. (913) 631-6700. (G. J. Dehnert) (Q), (F) **Check 414**

Erie Frequency Control, Div. Erie Technological Prods., 453 Lincoln St., Carlisle, Pa. 17013. (717) 249-2232. (K. Dance) (Q) **Check 415**

Filtech Corp., 10103 W. Pacific, Franklin Park, Ill. 60131. (312) 678-8900. (E. Argoudelis) (F) **Check 416**

Frequency Electronics, 3 Delaware Dr., New Hyde Park, N.Y. 11040. (516) 328-0100. (A. Lazar) (F) **Check 417**

Gulton Industries, Inc., 300 S. State College Blvd., Fullerton, Calif. 92631. (714) 871-2150. (Chuck Edmiston) (PC) **Check 418**

Hughes Aircraft Co., Communication Prods. Dept., 500 Superior Ave., Dept. E-2, Newport Beach, Calif. 92663. (714) 548-0671. (F. H. Weisel, Jr.) (F) **Check 419**

International Crystal Manufacturing, 10 N. Lee St., Oklahoma City, Okla. 73102. (405) 236-3741 (C) **Check 420**

Keamos, Inc., 104 N. Church St., Lizton, Ind. 46149. (317) 994-5394. (Paul Angleton) (PC) **Check 421**

Linden Laboratories, Inc., Box 920, State College, Pa. 16801. (814) 355-5491. (James W. Anderson) (PC) **Check 422**

McCoy Electronics Co., Chestnut & Watts St., Mount Holly Springs, Pa. 17065. (717) 486-3411. (M.L. Myers) (Q), (F) **Check 423**

Microsonics Inc., Div. Sangamo Electric Co., 60 Winter St., Weymouth, Mass. 02188. (617) 337-4200. (J. Klayman) (F) **Check 424**

Monitor Products, 815 Fremont Ave., South Pasadena, Calif. 91030. (213) 682-3761. (J.W. Blasler) (Q), (F) **Check 425**

Motorola Inc., Box 90241, Phoenix, Ariz. 85036. (602) 244-3465. (Chuck Johnson) (W) **Check 426**

M-tron Inds., Inc., Box 630, 100 Douglas St., Yankton, S.D. 57078. (605) 665-9321. (L. Tally) (Q) **Check 427**

Murata Corp. of America, 2 Westchester Plaza, Elmsford, N.Y. 10523. (914) 592-9180. (J. Alterescu) (PF) **Check 428**

Northern Engineering Labs., 357 Beloit St., Burlington, Wis. 53105. (414) 763-3591. (J.D. Holmbeck) (C) **Check 429**

Omnitec Corp., Nytronics Filter Div., 2405 S. 20th St., Phoenix, Ariz. 85034. (402) 348-9500. (J. Matejka) (F) **Check 430**

OPT Industries, Box F, Alpha, N.J. 08865. (201) 454-2600. (J. Smith) (F) **Check 431**

Peterson Radio, 2800 W. Broadway, Council Bluffs, Iowa 51501. (712) 323-7539. (N. Anderson) (Q) **Check 432**

Piezo Crystal Co., 100 "K" St., Carlisle, Pa. 17013. (717) 249-2151. (W. Wilson) (C), (F) **Check 433**

Piezo Technology Inc., Box 7877, 2400 Diversified Way, Orlando, Fla. 32804. (305) 425-1574. (J. Dinnan) (F) **Check 434**

Quaker Electronics, Box 215, Hunlock Creek, Pa. 18621. (717) 256-3477. (Q) **Check 435**

Radio Materials Co., 4242 W. Bryn Mawr Ave., Chicago, Ill. 60646. (312) 478-3600. (R. Merritt) (PC), (PF) **Check 436**

Reeves-Hoffman Div., Dynamics Corp. of America, 400 W. North St., Carlisle, Pa. 17013. (717) 243-5929. (J.D. Harlin) (C) **Check 437**

Sawyer Research Products, Inc., 35400 Lakeland Blvd., Eastlake, Ohio 44094. (216) 942-8747. (D.P. Larsen) (Q) **Check 438**

Seacor, Inc., 598 Broadway, Norwood, N.J. 07648. (201) 768-6070. (M. Davis) (PC) **Check 439**

Seg Electronics, 120-30 Jamaica Ave., Richmond Hill, N.Y. 11418. (212) 441-3200. (F) **Check 440**

Sherold Crystal Products, Tyco Labs., 1510 McGee Trafficway, Kansas City, Mo. 64108. (816) 842-9792. (Q) **Check 441**

Standard Crystal Corp., 1111 S. Fremont Ave., Alhambra, Calif. 91803. (213) 284-4176. (J. B. Fischer) (C) **Check 442**

Statak Corp., 1200 Alvarez Ave., Orange, Calif. 92668. (714) 639-7810. (M. Nusbaum) (Q), (W) **Check 443**

Tedford Crystal Labs., 4914 Gray Rd., Cincinnati, Ohio 45232. (513) 542-5555. (J.A. Vella) (C), (F) **Check 444**

Thermal American Fused Quartz, Change Bridge Rd., Montville, N.J. 07045. (201) 334-7770. (J. F. von Sternberg) (O) **Check 445**

TMC Systems, 930 West 23rd St., Unit 26, Tempe, Ariz. 85282. (D. R. Robinson) (C), (F) **Check 446**

Torotel, Inc., 13402 S. 71 Hwy., Grandview, Mo. 64030. (816) 761-6314. (R. Osborne) (Q), (F) **Check 447**

TT Electronics Inc., 2214 S. Barry Ave., Los Angeles, Calif. 90064. (213) 478-8224. (J.F. Sodar) (F) **Check 394**

Tyco Filters Div. Inc., 3940 W. Montecito St., Phoenix, Ariz. 85019. (602) 272-7945. (H. Schinaman) (F) **Check 395**

Valpey Fisher, 1400 Highland St., Holliston, Mass. 01746. (617) 429-4322. (T. Gallagher) (Q) **Check 448**

Vernitron Piezoelectric Div., 232 Forbes Rd., Bedford, Ohio. 44146. (216) 232-8600. (Mark Rickman) (PC), (PF) **Check 449**

X-Tron Electronics, 1869 National Ave., Hayward, Calif. 94545. (415) 783-2145. (R.M. Hossack) (Q) **Check 450**