Understanding precision crystal time bases

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☐ Precision crystal time bases are the heart of a wide variety of test and measurement instruments. Frequency counters and synthesizers in particular depend on them to meet increasingly stringent demands for accuracy and stability. In addition, instruments like oscilloscopes and pulse generators have started using precision timing to broaden their range of applications.

The basic control element of a precision time base is the quartz crystal itself. In its natural formation, the crystal has a hexagonal cross section and terminates longitudinally in a point. From the base crystal, thin slices, or plates, are cut, having the property that each plate will resonate when excited by an alternating voltage tuned to its natural frequency. This frequency is primarily a function of the plate's thickness and original lattice orientation, or "cut," in the base crystal. Unfortunately, for high frequencies the plates are so thin that they are difficult to cut, as well as very fragile.

Crystals may also be operated at odd mechanical overtones of their natural frequency. (The odd mechanical overtone of a crystal, although not exactly equal to the odd harmonic of the natural frequency, is very close to it.) A major factor to consider in choosing an overtone crystal is its number of spurious vibrating modes, which increase with plate thickness and degrade the crystal's performance.

Types of cut

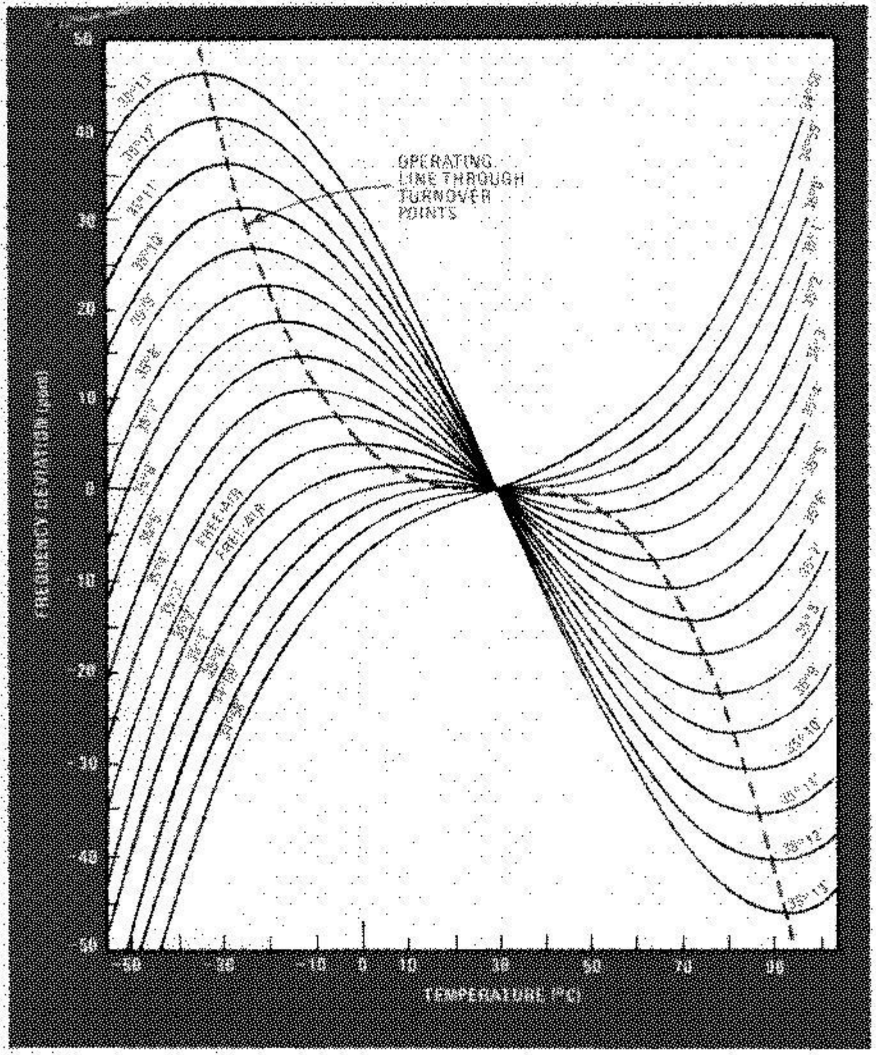
The cut angle of a crystal also determines the long-term frequency stability and basic temperature characteristics of the time base. Several cut types are available, and the designer can select the one that will best meet the frequency and stability specifications required. The AT-cut crystal has a frequency range of 1 to 150 megahertz and is the type most often used in time bases (10 MHz being the most popular choice) because of its frequency and temperature characteristics. The curves in Fig. 1 relate the performance of several AT cuts in terms of the frequency deviation versus temperature for a nominal frequency of 10 MHz.

Once cut to the appropriate angle, the crystal is processed and mounted in a metal or a glass container (Fig. 2). The container may be sealed with either glass or solder and evacuated or filled with an inert gas.

The packaged crystal may then be used in any of a variety of time bases depending on the end performance requirements. There are three basic types, listed in order of increasing frequency stability and price (see table):

- Simple, or "free air," time bases, in which the ambient temperature noticeably affects crystal performance.
- Temperature-compensated crystal oscillators (TCXOs),

This is part 3 of the continuing "Microseconds and megahertz" series, which is designed to bring engineers up to date on the latest techniques of time and frequency measurement. Part 1, which appeared in the March 30 issue, pp. 81–88, covered the use of digital counters and timers. Part 2, in the June 22 issue, pp. 138–144, discussed methods of eliminating time-base errors from oscilloscope measurements. Follow-up articles will describe other modern instruments like microprocessor-controlled spectrum analyzers and triggering oscilloscopes.



1. AT type. A crystal's frequency stability depends on the cut angle and the operating temperature, as illustrated by the family of curves generated by crystal cuts for a nominal frequency of 10 MHz. Varying the cut angle by a few minutes changes the performance significantly.

which utilize an electrical network to regulate the frequency as ambient temperature varies.

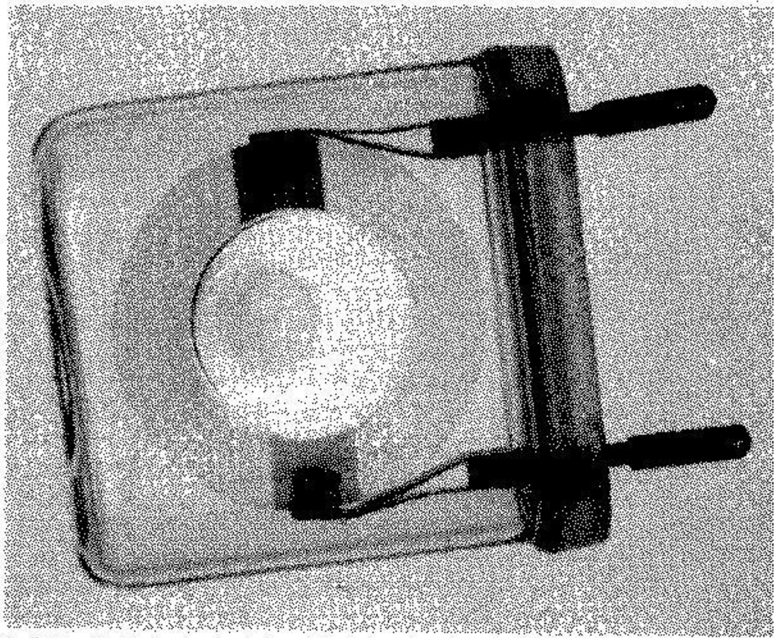
- "Ovenized" time bases, which have an internal heating element to provide a controlled operating temperature higher than the external ambient temperature.

Free-air time bases

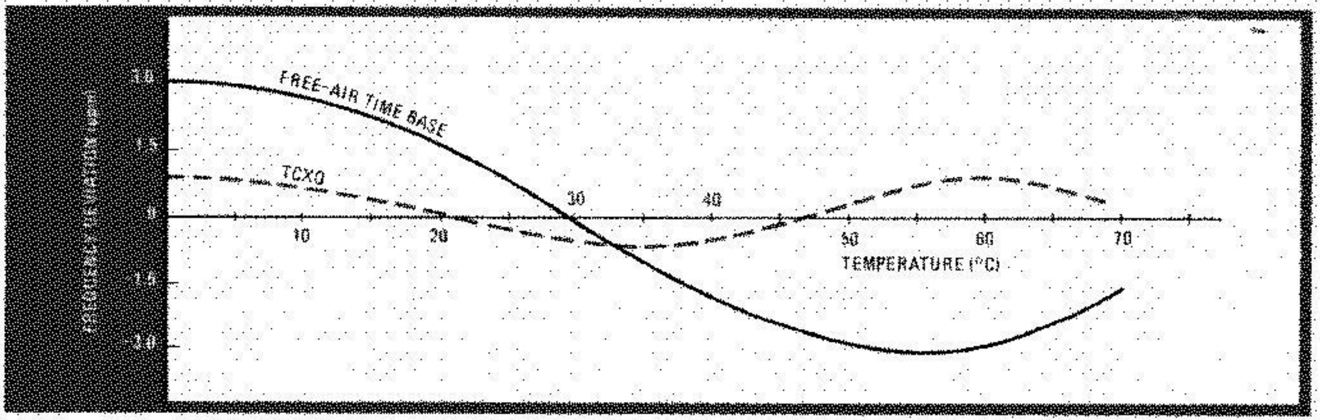
The free-air type of time base, as the name implies, does not rely on an external temperature-compensating circuit or an oven to achieve its overall performance. It is used when moderate performance and small size at low cost are required.

Proper oscillator design and crystal cut angle will yield moderate temperature stability. For an AT-type crystal used in a free-air time base, cut angles of 35°2′ and 35°3′ are typical. A temperature dependence of ±5 parts per million (±50 hertz for a 10-MHz crystal) over the 0°-to-65°C range is readily obtainable, with ±2.5 ppm over a range of 0° to 50°C the optimum available at a reasonable cost.

A free-air time base's aging rate, that is, the rate at which the crystal drifts off frequency, is determined almost solely by the crystal's characteristics. Cleanliness in processing, the type of mount, and the type of seal all affect the final drift performance. Typically, an initial



2. Free-air package. In order to limit environmental influences, the crystal is mounted and sealed either in a glass container, shown here, or in a metal one. Glass-enclosed crystals tend to increase in frequency with aging; a decrease occurs with metal enclosures.



3. Improved stability. The performance of a TCXO is superior to that of a free-air time base in terms of both maximum deviation from and tracking of the nominal frequency over a wide temperature range. A total yearly drift of less than ± 1.0 ppm can be expected for TCXOs.

COMPARING TIME BASES

	Free air	TCXO	Ovenized
Frequency drift factors			
Aging rate	$\pm 5 \times 10^{-7}$ per month	$\pm 3 \times 10^{-7}$ per month	$\pm 5 \times 10^{-9}$ per day
Temperature (max shift, 0° – 50°C)	$\pm 5 \times 10^{-6}$	$\pm 2 \times 10^{-6}$	$\pm 1 \times 10^{-8}$ per °C*
Line voltage (max shift, 10% change)	$\pm 1 \times 10^{-7}$	$\pm 1 \times 10^{-7}$	$\pm 1 \times 10^{-9}$
Warm-up time (until deviation is $\leq 1 \times 10^{-8}$ ppm)	not specified	not specified	20 min
Relative price	X	X + $150	X + $550

* Refers to oven temperature.

aging rate of 0.5 ppm/month can be expected, and this figure declines substantially with time in operation.

Temperature-compensated crystal oscillators bridge the gap between free-air time bases and expensive, higher-performance ovenized ones. They are possible because a crystal's resonant frequency may be altered by placing a reactance in series with the crystal, and therefore a temperature-sensitive impedance can be used to compensate for frequency drift.

TCXOs

Once the cut has been made for the desired variation over the specified temperature range, the crystal is placed in a thermal test chamber and its actual frequency variation with temperature is plotted. With the aid of computer analysis, circuit parameters are selected that will counteract as closely as possible the crystal's inherent frequency variation with temperature.

Compensation schemes using analog, digital, and hybrid circuits are available, with some employing microprocessor control. The great majority, however, use analog techniques, the two most common being the thermistor-varactor compensation and the temperature-compensating capacitor network. The choice depends primarily on the operating conditions inside the instrument containing the time base. Typical temperature dependences of ±0.5 to ±2 ppm from 0° to 70°C may be obtained at reasonable cost.

The aging rate of a TCXO is largely dependent on crystal quality, as is the case with free-air time bases. Usually, crystals with an initial aging rate of less than 0.3 ppm/month are used in TCXOs, and total yearly drift can be less than ±1.0 ppm.

Because of the imperfect cancellation of temperature effects, the time base's final plot of frequency vs temperature will vary from unit to unit. Figure 3 illustrates the frequency drift of a temperature-compensated crystal oscillator compared with that of a free-air time base over a typical temperature range.

The advantages of a TCXO are good temperature performance, small size, fast warm-up, and low power consumption at a moderate price.

Calibration of TCXOs, however, can be a problem. Since the oscillator will almost always be embedded in an instrument with a 5°-to-15°C heat rise, calibration at room temperature requires careful calculation based upon the known frequency-temperature characteristics for that TCXO.

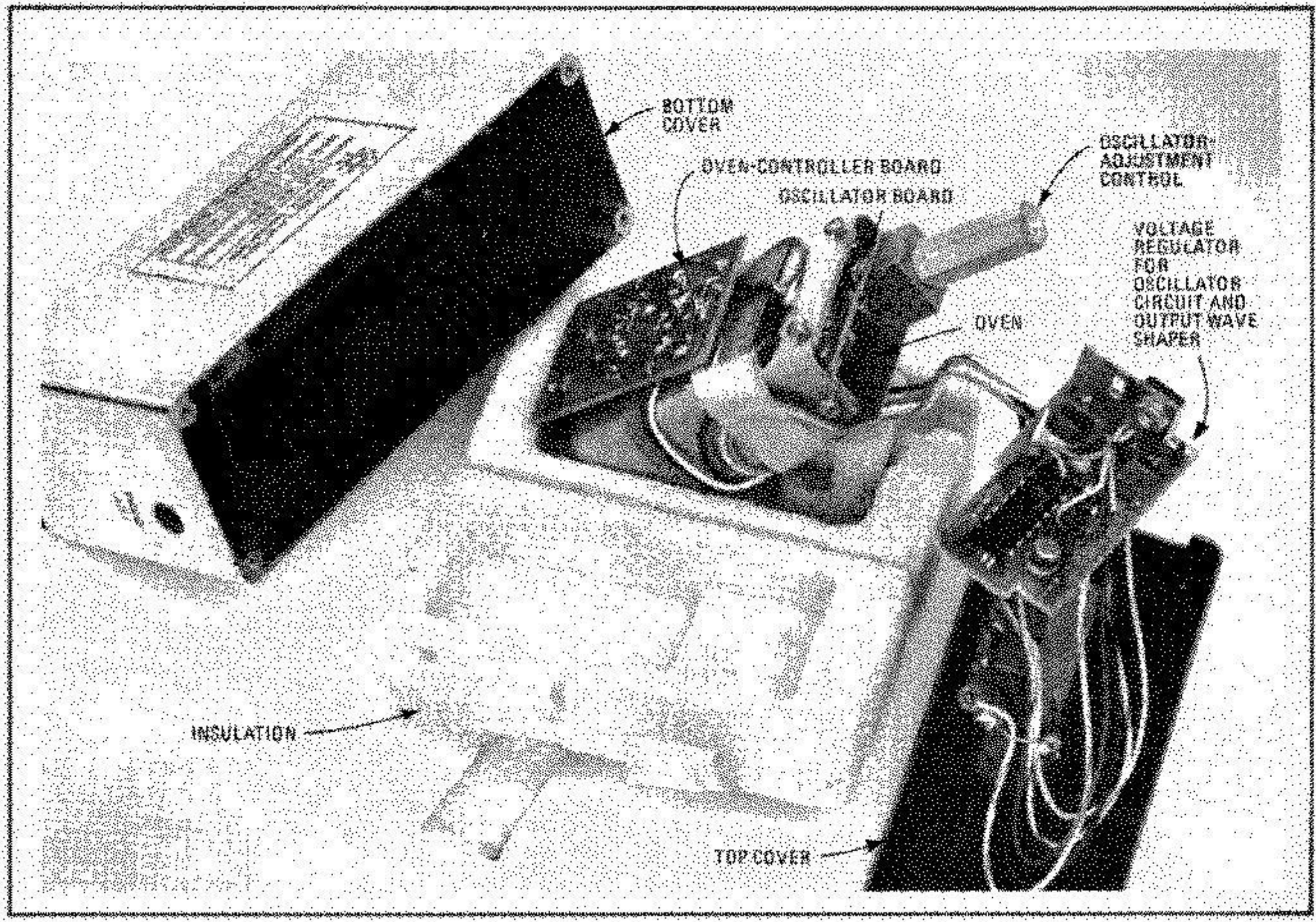
Calibration methods

A more common method, which eliminates the need to account for the heat rise, is to operate the instrument at a known ambient temperature (usually 25°C) and to adjust the frequency to an offset, both specified by the time-base manufacturer. The manufacturer then guarantees that the TCXO will meet specifications across the full temperature range.

Both calibration methods leave a lot to be desired from the customer's standpoint. Calculating heat rise is complicated and providing a fixed ambient temperature is difficult to do outside a well-controlled calibration laboratory. But the instrument manufacturer can elimi-

What to look at in considering a crystal time base's performance

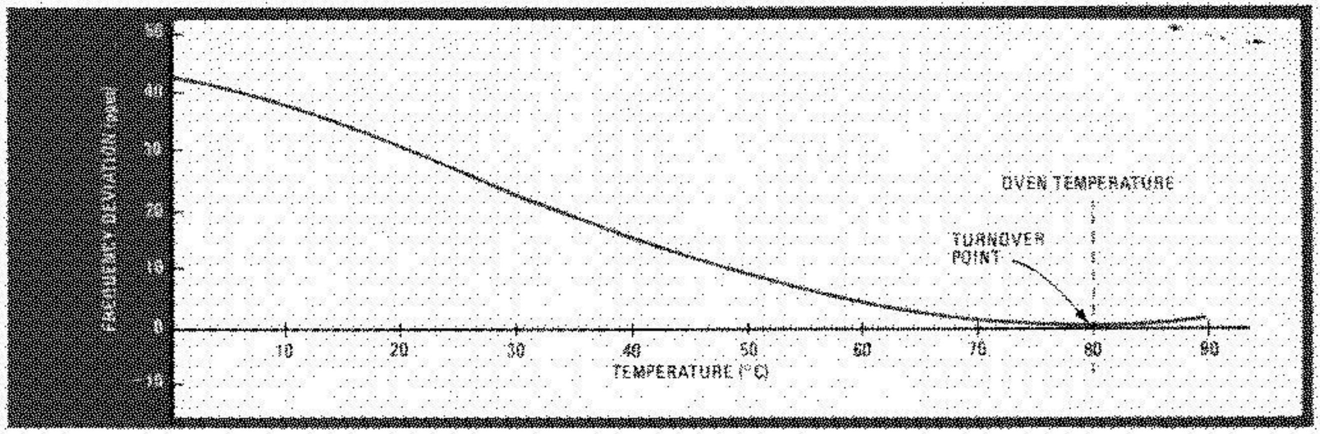
Aging rate	the rate at which a crystal drifts off frequency with time
Power-supply dependence	the amount of frequency variation with change in line or battery voltage
Restabilization	the time it takes an oscillator to return to a given aging rate following a period of nonoperation
Retrace error	the offset (after warm-up) from the frequency prior to turn-off, when an oscillator is turned off for a period of time and then turned back on
Shock, vibration, humidity, and gravitational dependence	the amount of frequency variation resulting from, respectively, shock, vibration, humidity, and the physical positioning of the time base
Short-term stability	the amount of frequency variation during short periods of time due to random frequency fluctuations—typically specified at 1 or 10 s; in synthesizer applications, it may be specified as phase noise
Temperature dependence	the amount of frequency variation with change in temperature.



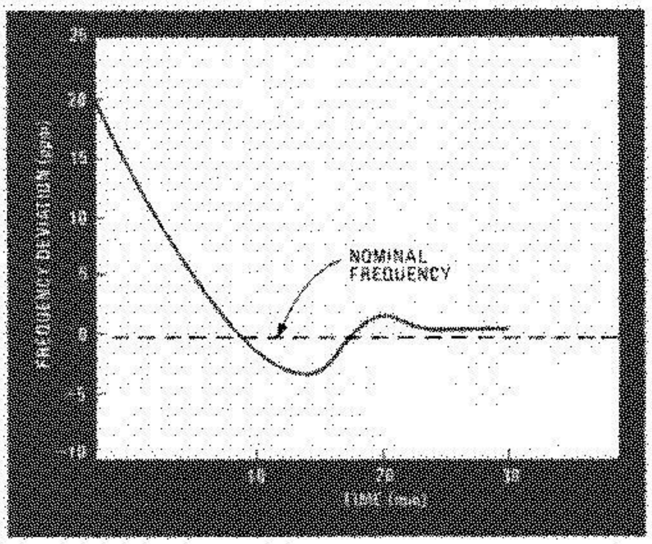
4. Ovenized time base. Both the crystal-oscillator board and the temperature-controller board are insulated to minimize outside thermal influences. The voltage-regulator–wave-shaper board is mounted outside the insulation to limit additional heating and to provide dissipation.

nate these problems by using a time base with a tighter tolerance and specifying that calibration of the instrument be performed at any ambient temperature between, for example, 20° and 30°C. The instrument with its high-performance TCXO should then meet specifications across the full temperature range.

Ovenized time bases use a controlled-temperature oven to insulate the crystal from ambient temperature changes (Fig. 4). The crystal itself is cut at a high angle so that the higher temperature bend in the curve, called the turnover point (see Fig. 1 again), is at the operating temperature of the oven. The oven temperature is set 10° to 15°C above the highest temperature ever expected at the location of the time base within the instrument, and



5. Hot operation. An ovenized time base can be expected to track its nominal frequency exactly upon reaching and maintaining the designated operating temperature. Ovens typically maintain the specified temperature to within 0.2°C to provide superior performance.



6. Warm-up. Although frequency deviation decreases significantly as warm-up time approaches the 30-minute mark, it may take much longer, even days or weeks, to return to the specified aging rate (restabilize) if the oscillator has been off for months.

the oscillator is adjusted to be exactly on frequency at that oven temperature (Fig. 5).

Ovenized time bases offer outstanding temperature stability because of tight thermal control of the crystal. An oven crystal will generally vary about 1 part in 10^8/°C if the oven has been set to within ±1°C of its turnover point. Ovens typically maintain temperature to within about 0.2°C to provide superior performance. Therefore temperature stabilities as good as ±5 parts in 10^9 from 0° to 50°C can be expected.

Other considerations

However, because ovenized time bases have extremely good temperature stability and aging rates, a variety of considerations that are unimportant in free-air time bases and TCXOs become significant.

For one, since the crystal is to be operated at an elevated temperature, its frequency at initial turn-on will be far off the intended operating frequency. As can be seen in Fig. 5, an ovenized oscillator with an internal temperature of 25°C at turn-on will start out 25 ppm off frequency, because the oscillator has been designed and adjusted to be on frequency when the crystal is at the designated 80°C operating temperature. As the oven and crystal warm up, this offset decreases, as shown in Fig. 6.

After initial warm-up, other factors emerge. Restabilization, or the time it takes for the oscillator to reach its specified aging rate, must be known so that the user can calculate total drift. The time depends primarily on how long the oscillator was off before power-up: the longer the oscillator is off, the longer it will take to reach its specified aging rate. This period can be as much as several weeks if the oscillator has been off for months. In practice, typical aging rates for an ovenized time base will range from 1 part in 10^8 per day to 5 parts in 10^{10} per day, depending on the type of crystal used. (Note that restabilization refers to the return to the aging rate and says nothing about return to frequency.)

Frequency retracing

Frequency retracing defines how closely an oscillator will return to its original frequency after a lengthy on time and a specified off time and subsequent warm-up period. A typical retrace specification might be: "The time base will return to within 1 part in 10^8 of previous frequency following a long period of operation, 2 hours off, and 5 hours subsequent warm-up."

Retrace errors and restabilization times both must be carefully taken into consideration when deciding whether to use an ovenized time base or a TCXO. If the time base is to be turned off for long periods and expected to perform quickly on turn-on, a TCXO may be a better choice.

Time-base literature rarely gives specifications for deviations caused by shock and vibration. Since a shock of 20 g for 15 ms or a vibration of 5 g can cause typical frequency variations of 1 to 2 parts in 10^8, such effects can be especially significant when calibrating an ovenized time base.

Typically, an instrument containing a time base is unplugged, shipped to a calibration laboratory, adjusted to frequency, unplugged, reshipped, and finally plugged in again and operated. The possibilities of shock- and vibration-induced errors in this cycle are numerous and can easily defeat the entire calibration effort. Therefore proper calibration should include special handling of the instrument. ☐