

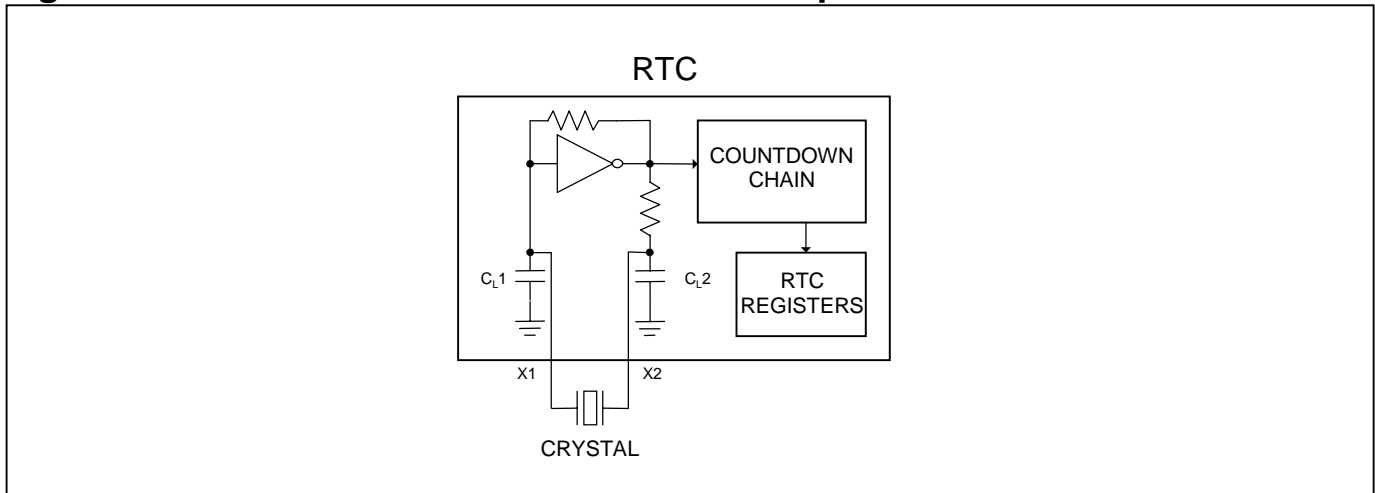
OVERVIEW

This application note describes crystal selection and layout techniques for connecting a 32,768Hz crystal to a real-time clock (RTC). It also provides information about oscillator circuit-design criteria, system design, and manufacturing issues.

OSCILLATOR BASICS

The oscillator used in Dallas Semiconductor RTCs is a CMOS inverter variation of a Pierce-type oscillator. Figure 1 shows a general configuration. These RTCs include integrated load capacitors (C_{L1} and C_{L2}) and bias resistors. The Pierce oscillator uses a crystal operating in parallel mode. Crystals used in parallel mode are specified for a certain frequency with a specific load capacitance. The crystal is trimmed at the factory to operate at the specified frequency for the specified capacitive load. For the oscillator to run at the correct frequency, the oscillator circuit must load the crystal with the correct capacitive load.

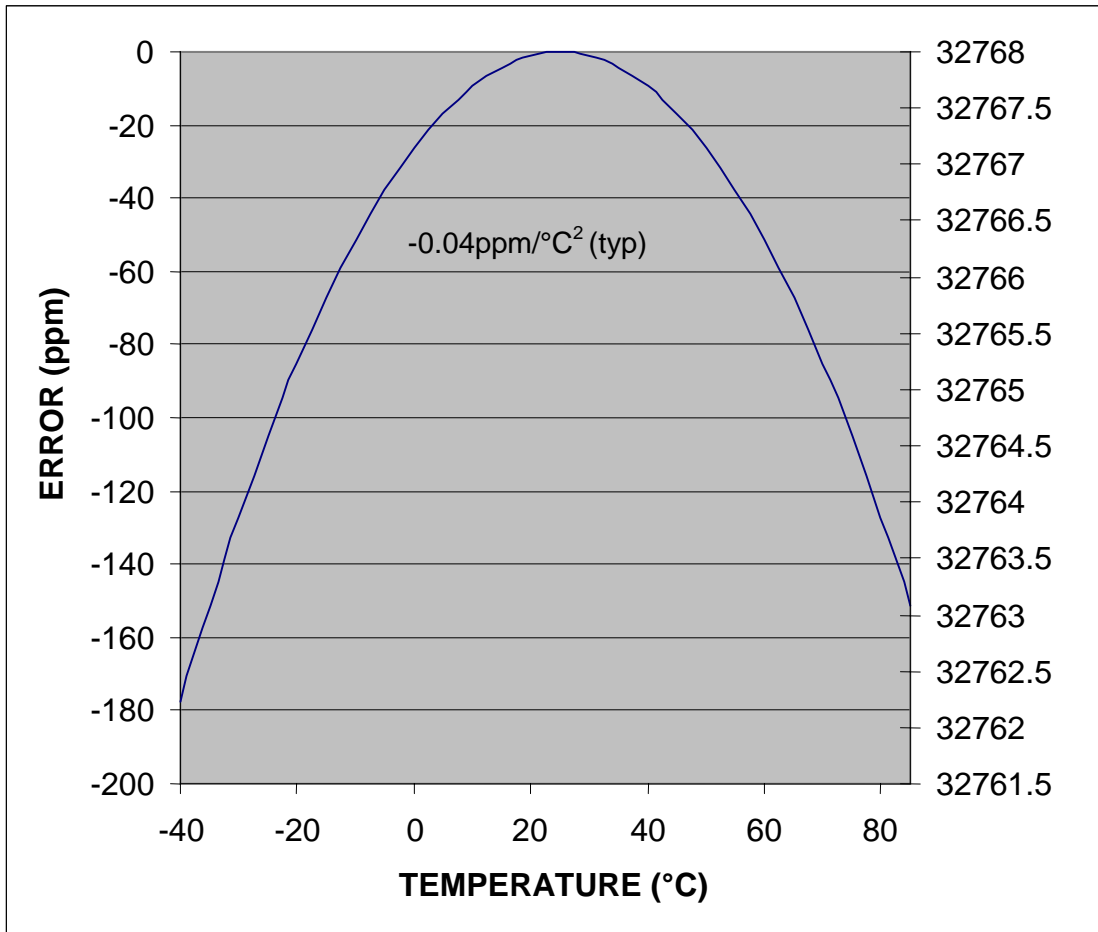
Figure 1. RTC Oscillator with Internal Load Capacitors and Bias Resistors



ACCURACY

The frequency accuracy of a crystal-based oscillator circuit is mainly dependent upon the accuracy of the crystal and the accuracy of the match between the crystal and the oscillator capacitive load. If the capacitive load is less than the crystal was designed for, the oscillator runs fast. If the capacitive load is greater than what the crystal was designed for, the oscillator runs slow.

In addition to the errors from the crystal and the load match, crystals vary from their base frequency as the ambient temperature changes. Dallas RTCs use “tuning fork” crystals, which exhibit an error over temperature, as shown in Figure 2. An error of 20ppm is equivalent to approximately 1 minute per month.

Figure 2. Crystal Frequency vs. Temperature

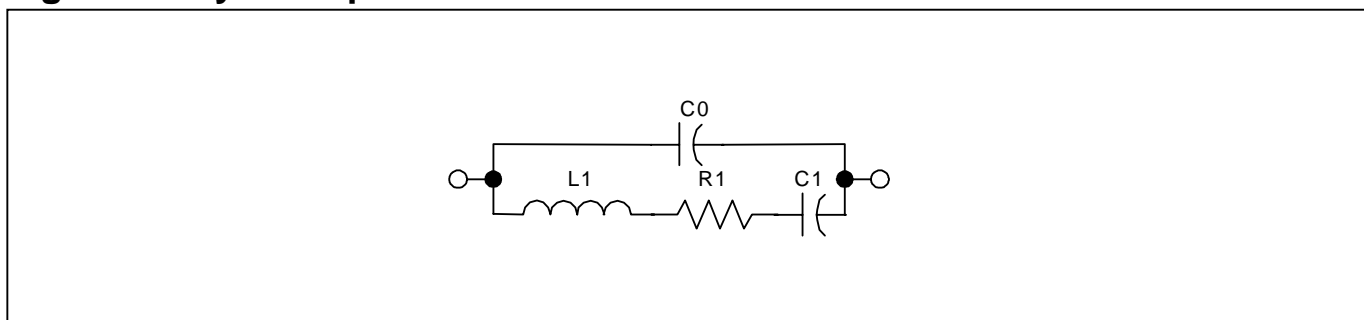
Note: If better accuracy is required, a TCXO such as the DS32kHz can be used.

CRYSTAL PARAMETERS

Crystals have several fundamental characteristics that are important to the design of an oscillator circuit. Figure 3 shows the equivalent circuit for a crystal. Near the resonant frequency the circuit consists of a series circuit including motional inductance L_1 , motional resistance R_1 , and motional capacitance C_1 . The parallel component C_0 is the shunt capacitance of the crystal.

The equivalent series resistance (ESR), also known as motional resistance, is the impedance of the crystal when the reactive components of the crystal cancel, i.e., at the resonant frequency. ESR and quality factor (Q-Factor or Q) are inversely proportional. The lower the ESR, the less energy that is lost in the crystal. A crystal with a high ESR requires more power to operate and takes longer to start.

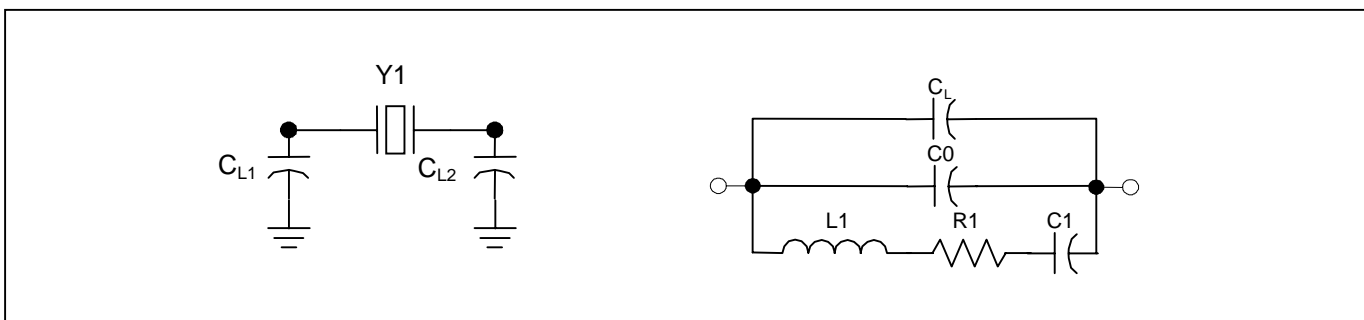
Figure 3. Crystal Equivalent Circuit



The load capacitance C_L is the capacitive load of the oscillating circuit as seen from the pins of the crystal. Figure 4 shows C_L as a capacitance in parallel with the crystal. The load capacitors used in an oscillator circuit, C_{L1} and C_{L2} , plus any stray capacitance in the circuit, combine to create the overall load capacitance. All Dallas RTCs have integrated C_{L1} and C_{L2} capacitors. Care should be taken to minimize stray capacitance in the PC board layout. The following formula shows the relationship between C_L and load capacitor values:

$$C_L = [(C_{L1} \times C_{L2}) / (C_{L1} + C_{L2}) + C_{STRAY}]$$

Figure 4. Crystal Load Capacitors and Equivalent Parallel Load



Most crystals allow a maximum drive level of $1\mu\text{W}$. All Dallas RTCs run under $1\mu\text{W}$. Drive level may be determined using the following formula:

$$P = 2R_1 \times [\pi \times 32,768(C_0 + C_L)V_{RMS}]^2,$$

where V_{RMS} is the RMS value of the voltage across the crystal.

OSCILLATOR STARTUP TIME

Oscillator startup times are highly dependent upon crystal characteristics, PC board leakage, and layout. High ESR and excessive capacitive loads are the major contributors to long startup times. A circuit using a crystal with the recommended characteristics and proper layout usually starts within one second.

Table 1. Crystal Specifications

| PARAMETER | SYMBOL | MIN | TYP | MAX | UNITS |
|------------------------------|------------------|--------|----------|-------|-------------------------|
| Nominal Frequency | F_O | | 32.768 | | kHz |
| Frequency Tolerance | $\Delta F / F_O$ | | ± 20 | | ppm |
| Load Capacitance | C_L | | 6 | | pF |
| Temperature Turnover Point | T_0 | 20 | 25 | 30 | $^{\circ}\text{C}$ |
| Parabolic Curvature Constant | k | | | 0.042 | ppm/ $^{\circ}\text{C}$ |
| Quality Factor | Q | 40,000 | 70,000 | | |
| Series Resistance | ESR | | | 45 | k Ω |
| Shunt Capacitance | C_0 | | 1.1 | 1.8 | pF |
| Capacitance Ratio | C_0/C_1 | | 430 | 600 | |
| Drive Level | D_L | | | 1 | μW |

Table 2. Crystal Suppliers

| MANUFACTURER | PART | FREQUENCY TOLERANCE (ppm) | ESR (k Ω) | Q k Ω (min) typ* | DRIVE LEVEL max (μW) | C_L -pF | ALTERNATE C_L ? | TEMP RANGE ($^{\circ}\text{C}$) | SURFACE OR THRU-HOLE |
|--------------|---------|---------------------------|-------------------|-------------------------|-----------------------------------|-----------|-------------------|-----------------------------------|----------------------|
| Citizen | CFS-145 | ± 20 | 40 | 80,000* | 1.0 | 8.0* | yes | -10~+60 | TH |
| Citizen | CFS-206 | ± 20 | 35 | 70,000* | 1.0 | 12.5 | yes | -10~+60 | TH |
| ECS, Inc. | ECS-3X8 | ± 20 | 35 | 90,000 | 1.0 | 12.5 | ? | -10~+60 | TH |
| ECS, Inc. | ECS-2X6 | ± 20 | 35 | 90,000 | 1.0 | 12.5 | ? | -10~+60 | TH |
| ECS, Inc. | ECS-1X5 | ± 20 | 35 | 90,000 | 1.0 | 8 | ? | -10~+60 | TH |
| KDS/Daiwa | DT-26 | ± 20 or ± 30 | 40 | 40,000 | 1.0 | 12.5 | yes | -10~+60 | TH |
| KDS/Daiwa | DT-38 | ± 20 or ± 30 | 30 | 50,000 | 1.0 | 12.5 | yes | -10~+60 | TH |
| Pletronics | WX15 | ± 20 | 40 | | 1.0 | 8.0 | yes | -10~+60 | TH |
| Pletronics | WX26 | ± 20 | 40 | | 1.0 | 12.5 | 6.0 | -10~+60 | TH |
| Fox | NC-38 | | 35 | | 1.0 | 12.5 | 6.0 | -20~+60 | TH |
| Seiko | C-001R | ± 20 | 45 | | 1.0 | 12.5 | 6 | -10~+60 | TH |
| Seiko | C-2 | ± 20 | 35 | | 1.0 | 12.5 | 6 | -10~+60 | TH |

| MANUFACTURER | PART | PACKAGE DIMENSIONS (mm) | ESR (k Ω) | MANUFACTURER ORDERING NUMBER |
|--------------|---------|-------------------------|-------------------|------------------------------|
| Citizen | CFS-145 | 1.5 x 5.1 | TH | |
| Citizen | CFS-206 | 2.1 x 6.2 | TH | |
| ECS, Inc. | ECS-3X8 | 3.1 x 8.2 | TH | |
| ECS, Inc. | ECS-2X6 | 2.1 x 6.2 | TH | |
| ECS, Inc. | ECS-1X5 | 1.5 x 5.1 | TH | |
| KDS/Daiwa | DT-26 | 2.0 x 6.0 | TH | 1TB602G00 |
| KDS/Daiwa | DT-38 | 3.0 x 8.0 | TH | |
| Pletronics | WX15 | 1.5 x 5.1 | TH | WX15-32.768k-6pF |
| Pletronics | WX26 | 2.1 x 6.2 | TH | WX26-32.768k-6pF |
| Fox | NC-38 | 3.0 x 8.3 | TH | |
| Seiko | C-001R | 3.1 x 8.0 | TH | |
| Seiko | C-2 | 2.0 x 6.0 | TH | |

*Cylinder-type dimensions are barrel diameter and length. They exclude leads. All dimensions are approximate.

POWER CONSUMPTION

Many RTCs are designed to operate from a battery supply. In a typical application, a small lithium battery can be used to run the oscillator and clock circuitry while the main supply is off. To maximize battery life, the oscillator must run using as little power as possible. To accomplish this, some design tradeoffs must be made.

Negative Resistance

For typical high-frequency oscillator circuits, it is normal for the circuit to be designed with a 5 or 10X margin for the ESR. Low-frequency crystals typically have higher ESRs. An RTC oscillator may have less than a 2X margin for negative resistance. An oscillator circuit with a low margin normally consumes less current. As a result, an RTC oscillator often is sensitive to relatively small amounts of stray leakage, noise, or an increase in ESR.

The C_L of the oscillator circuit influences the power consumption. An RTC with 12.5pF internal loads consumes more power than one that has 6pF loads. However, the oscillator with 12.5pF load capacitors is usually less susceptible to noise.

NOISE AND CRYSTAL LAYOUT GUIDELINES

Since the crystal inputs of Dallas RTCs have very high impedance (about $10^9\Omega$), the leads to the crystal act like very good antenna, coupling high-frequency signals from the rest of the system. If a signal is coupled onto the crystal pins, it can either cancel out or add pulses. Since most of the signals on a board are at a much higher frequency than the 32.768kHz crystal, it is more likely to add pulses where none are wanted. These noise pulses get counted as extra clock “ticks” and make the clock appear to run fast.

The following steps illustrate how to determine if noise is causing the RTC to run fast:

- 1) Power the system up and synchronize the RTC to a known accurate clock.
- 2) Turn the system power off.
- 3) Wait for a period of time (two hours, 24 hours, etc.). The longer the time period, the easier it is to measure the accuracy of the clock.
- 4) Turn the system on again, read clock, and compare to the known accurate clock.
- 5) Resynchronize the RTC to the known accurate clock.
- 6) Keep the system powered up and wait for a period of time equal to the period in Step 3.
- 7) Read the clock after waiting for the above period of time and compare it to the known accurate clock.

By using the above steps, the accuracy of the clock can be determined both when the system is powered up and when the system is powered down. If the clock proves to be inaccurate when the system is powered up, but is accurate when the system is powered down, the problem is most likely due to noise from other signals in the system. However, if the clock is inaccurate both when the system is powered up and when it is powered down, then the problem is not due to noise from the system.

Since it is possible for noise to be coupled onto the crystal pins, care must be taken when placing the external crystal on a PC board layout. It is very important to follow a few basic layout guidelines concerning the placement of the crystal on the PC board layout to ensure the extra clock ticks do not couple onto the crystal pins.

- 1) It is important to place the crystal as close as possible to the X1 and X2 pins. Keeping the trace lengths between the crystal and RTC as small as possible reduces the probability of noise coupling by

reducing the length of the antenna. Keeping the trace lengths small also decreases the amount of stray capacitance.

- 2) Keep the crystal bond pads and trace width to the X1 and X2 pins as small as possible. The larger these bond pads and traces are, the more likely it is that noise can couple from adjacent signals.
- 3) If possible, place a guard ring (connected to ground) around the crystal. This helps isolate the crystal from noise coupled from adjacent signals. See Figure 2 for an illustration of using a guard ring around a crystal.
- 4) Try to ensure that no signals on other PC board layers run directly below the crystal or below the traces to the X1 and X2 pins. The more the crystal is isolated from other signals on the board, the less likely it is that noise is coupled into the crystal. There should be a minimum of 0.200 inches between any digital signal and any trace connected to X1 or X2. The RTC should be isolated from any component that generates electromagnetic radiation (EMR). This is true for discrete and module type RTCs.
- 5) It may also be helpful to place a local ground plane on the PC board layer immediately below the crystal guard ring. This helps to isolate the crystal from noise coupling from signals on other PC board layers. Note that the ground plane needs to be in the vicinity of the crystal only and not on the entire board. See Figure 4 for an illustration of a local ground plane. Note that the perimeter of the ground plane does not need to be larger than the outer perimeter of the guard ring.

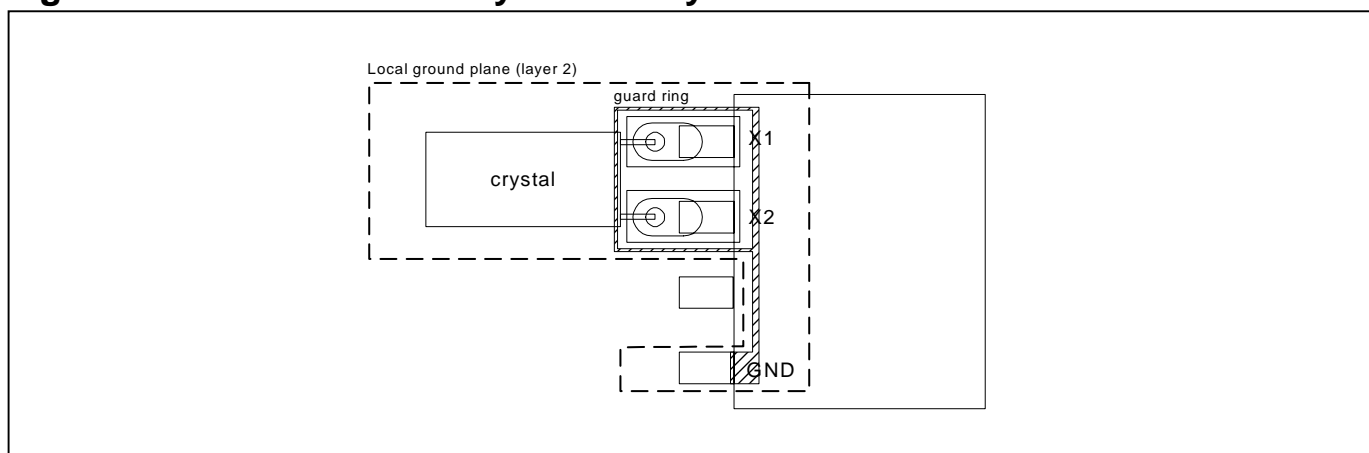
Note that care must be taken concerning the use of a local ground plane because of the stray capacitance that it introduces. The capacitance between the traces/pads and ground plane is added to the internal load capacitors (C_{L1} and C_{L2}). Therefore, some factors must be taken into account when considering adding a local ground plane. For example, the capacitance due to the ground plane can be approximated by the following equation:

$$C = \epsilon A/t, \text{ where}$$

ϵ = dielectric constant of the PC board
 A = area of the traces/pads
 t = thickness of the PC board layer

Therefore, to determine if a ground plane is appropriate for a given design, the above parameters must be taken into account to ensure that the capacitance from the local ground plane is not sufficiently large enough to slow down the clock.

Figure 4. Recommended Layout for Crystal



Fast Clocks

The following are the most common scenarios that cause a crystal-based RTC to run fast.

- 1) Noise coupling into the crystal from adjacent signals. This problem has been extensively covered above. Noise coupling usually causes an RTC to be grossly inaccurate.
- 2) Wrong crystal. An RTC typically runs fast if a crystal with a specified load capacitance (C_L) greater than the RTC-specified load capacitance is used. The severity of the inaccuracy is dependent on the value of the C_L . For example, using a crystal with a C_L of 12pF on an RTC designed with a 6pF C_L causes the RTC to be about 3 to 4 minutes per month fast.

Slow Clocks

The following are the most common scenarios that cause a crystal-based RTC to run slow.

- 1) Overshoots on RTC input pins. It is possible to cause a RTC to run slow by periodically stopping the oscillator. This can be inadvertently accomplished by noisy input signals to the RTC. If an input signal rises to a voltage that is greater than a diode drop ($\sim 0.3V$) above V_{DD} , the ESD protection diode for the input pin will forward bias, allowing the substrate to be flooded with current. This, in turn, stops the oscillator until the input signal voltage decreases to below a diode drop above V_{DD} .

This mechanism can cause the oscillator to stop frequently if input signals are noisy. Therefore, care should be taken to ensure there is no overshoot on input signals.

Another situation that is common to overshoot problem is having an input to the RTC at 5V when the RTC is in battery-backup mode. This can be a problem in systems that systematically shut down certain circuits but keep others powered up. It is very important to ensure there are no input signals to the RTC that are greater than the battery voltage (unless stated otherwise in the device data sheet) when the device is in battery-backup mode.

- 2) Wrong crystal. A RTC typically runs slow if a crystal with a specified C_L is less than the C_L of the RTC. The severity of the inaccuracy is dependent on the value of the C_L .
- 3) Stray capacitance. Stray capacitance between the crystal pins and/or to ground can slow an RTC down. Therefore, care must be taken when designing the PC board layout to ensure the stray capacitance is kept to a minimum.
- 4) Temperature. The further the operating temperature is from the crystal turnover temperature, the slower the crystal oscillates. See Figures 3 and 4.

Clock Does Not Run

The following are the most common scenarios that cause a RTC to not run.

- 1) The single most common problem when the clock does not run is that the CH (clock halt) or EOSC (enable oscillator) bit has not been set or cleared, as required. Many Dallas RTCs include a circuit that keeps the oscillator from running when power is first applied. This allows a system to wait for shipment to the customer, without drawing power from the backup battery. When the system is powered for the first time, the software/firmware must enable the oscillator and prompt the user for the correct time and date.
- 2) Surface mount crystals may have some N.C. (no connect) pins. Make sure that the correct pins from the crystal are connected to the X1 and X2 pins.

CRYSTAL MANUFACTURING ISSUES

Tuning fork crystals should not be exposed to ultrasonic cleaning. They are susceptible to damage from resonant vibration.

Crystals should not be exposed to temperatures above their maximum ratings. Exposure to excessive temperatures may damage the crystal, and usually increase the ESR. Crystal “cans” should not be soldered to a PC board. This is sometimes done to ground the case of the crystal. Soldering directly to the case of the crystal usually subjects the unit to excessive temperatures.

RTCs should generally be used in noncondensing environments. Moisture forming around the oscillator conductors can cause leakage, which can cause the oscillator to stop. Conformal coatings can be used to protect the circuit, however, conformal coating may by itself cause problems.

Some conformal coatings, especially epoxy-based materials, can have unacceptable levels of ionic contamination. In addition, conformal coatings can, if the PC board surface is not sufficiently cleaned prior to conformal coating, cause contaminants to concentrate around leads and traces.

Solder flux residue can cause leakage between pins. RTC oscillator circuits are especially sensitive to leakage because of their low-power operation. Leakage between the oscillator input and output, or leakage to ground, often keep the oscillator from running.

REFERENCES

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