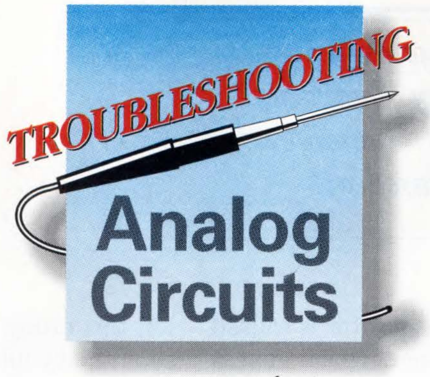


PART 4

A knowledge of capacitor subtleties helps solve capacitor-based troubles

Earlier installments of this series have described a good analog troubleshooter's mindset, armamentarium of test equipment, and requisite knowledge of resistors, inductors, and transformers. Now, ace troubleshooter Pease reveals some of the secrets of an often-underestimated class of components—capacitors. And much of what you need to know to troubleshoot capacitor-related problems is not in any book—it's not even in data sheets.

Robert A Pease, *National Semiconductor Corp*

Capacitors are rather remarkable. We consider capacitors, like resistors, to be "passive." But if you charge up a good as capacitor to 10V and take a 2-week vacation, when you come back the voltage may not have decreased by as much as 20 or even 10%. The capacitor may have stored and retained enough energy to run a micropower circuit for hours or to light an LED for a shorter interval. Calling components with such exceptional properties "passive" is more than a little unfair.

Ordinary, aluminum, electrolytic capacitors are most often used for power-supply filtering and bypassing. In the old vacuum-tube days, electrolytic capacitors were often used at levels of 150, 300, 500V, or more. There are several basic problems with these old circuits. First, if the voltage across a capacitor is much higher than 350V, the part's reliability is not nearly as good as that of devices operated below 350V. Also, if a piece of old equipment has not been powered up for years, it is advisable to apply the ac power gradually by cranking up the line voltage slowly with a variable transformer so that the electrolytic film has a chance to "form" up. If you hit it with full voltage instantly, an old capacitor may fail. Of course, if you are hit by high voltage, you may fail, too.

At this point, I should remind you that when working on high-voltage circuits, probe with one hand only and keep the other hand in your pocket. Avoid grounding your body at any other place and stand or sit on an insulating slab of dry material. These precautions can prevent a shock from causing you serious harm. When I start work on a high-voltage circuit, I solder a neon lamp in series with a 100-kΩ resistor across the high-voltage power supply as a glowing reminder that this circuit is powered by a voltage much higher than 15V.

After you operate a high-voltage power supply at full voltage, if you turn off the power and decide that for safety's sake you should short out the filters with a few hundred ohms, be careful. A few minutes later, the voltage on the capacitors may come back up to 60 or 80V and give you a shocking experience. The partial

The partial recovery of voltage on a discharged capacitor is caused by "soakage," which causes the dielectric to "remember" the voltage it was recently biased at.

recovery of voltage on a discharged capacitor is caused by "soakage," or dielectric absorption, which causes the dielectric of the capacitor to "remember" the voltage it was recently at. In high-voltage equipment, it is wise to install a 2W resistor of a few hundred kilohms across each large high-voltage filter capacitor to bleed off the charge and decrease the chance of shocks **(Ref 1)**.

The last problem with old vacuum-tube equipment is that the heat tends to dry up the capacitors' electrolyte, thus causing their capacitance to decrease. This decrease is evidenced by excessive ripple, or "hum," on various signals and, of course, on the power-supply output of unregulated supplies. Although I have presented these maladies as problems afflicting old equipment, you should consider them even in new designs.

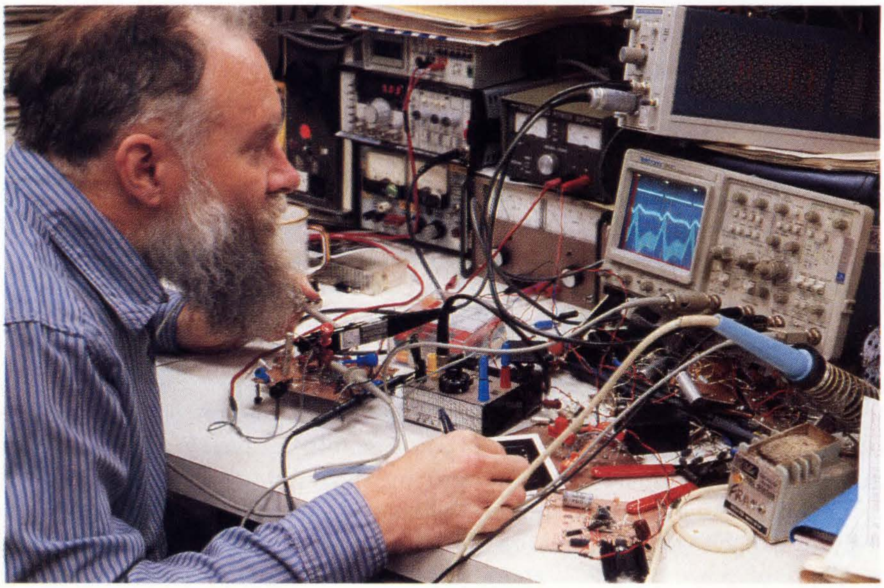
In modern power-supply designs, it is critical that you choose a filter capacitor whose effective series impedance is low at all rated temperatures. Otherwise the rms filter current multiplied by the resistive component of the series impedance can cause excessive self heating. And if the heat can't flow out of the capacitor, the temperature will rise and cause poor reliability. Excessive heating is one of the most common causes of failure in electrolytic capacitors.

For instance, at 120 Hz, which is the frequency of the ripple current flowing in the filter capacitors that follow a full-wave rectifier operated from a 60-Hz ac source, some manufacturers rate their capacitors at 2A rms for each 1000 μF. Because the rms current in the capacitor is nearly 2A rms when the dc output is 1A, this rating is consistent with the rule of thumb for an ordinary full-wave bridge rectifier: Provide at least 1000 μF of filter capacitance for each 1A of dc output. At 20 or 40 kHz, which is the ripple-current frequency in many switch-mode power-supply filters, the capacitor will have a higher series resistance. Thus, the capacitor won't be suitable for handling even 1A rms. If you insist on using a 120-Hz-rated capacitor as a filter in a switch-mode supply, you will probably have to contact the capacitor vendor for data or advice.

Of course, if you install an electrolytic capacitor with reversed polarity and apply working voltage, the reliability will be poor and the failure mode will probably be dramatic. So, please be careful working with big power supplies and big filter capacitors that store large amounts of energy. Wear protective goggles or glasses with safety lenses for protection because a capacitor in a high-energy supply might decide to blow up while you are peering at it. In fact, a friend of mine pointed out that a 6V electrolytic capacitor of even a few microfarads can blow out as explosively as a shotgun blast if you apply 6V dc of the wrong polarity or 6V ac to it. So, again, be very careful with your polar electrolytic capacitors.

Nonpolar capacitors can be a bear

You can buy nonpolar electrolytic capacitors made of either aluminum or tantalum. They are bigger and more expensive than ordinary, polar capacitors, so they are fairly uncommon. But, have you seen the little 3-leaded electrolytic types recently brought to market?



***That's funny,** it worked just fine the last time I tried it.*

The lead in the center is the positive terminal and the other two leads are negative. This configuration not only gives you lower inductance but also allows you to insert the device into a board two ways—and *both* are correct.

Tantalum capacitors have many characteristics similar to those of aluminum electrolytic capacitors; and, for the extra price you pay, you can get less leakage and somewhat lower series resistance. Designers often try out a timing circuit using a tantalum capacitor and a high-value resistor. But when they try to buy a tantalum capacitor with leakage guaranteed low enough to make the circuit work every time, they get quite angry when nobody is interested in selling such a device. Of course, if you were a manufacturer of tantalum capacitors and someone asked you to measure the leakage, you would refuse the business, too, because testing is so difficult. Even though this leakage is usually quite low, nobody wants to have to measure it in production.

Wound-film and stacked-film capacitors cover wide ranges, from small signal-coupling capacitors to large high-power filters. The different dielectrics are their most interesting ingredients. Often a designer installs a polyester capacitor (technically, polyethylene terephthalate, often called Mylar—a trademark of DuPont Corp) and wonders why something in the circuit is drifting 2 or 3% as the circuit warms up. What's drifting is probably the polyester capacitor; its TC of 500 to 800 ppm/°C is 10 times as high as that of a metal-film resistor.

If you give up on polyester and go to polystyrene, polypropylene, or Teflon, the TC gets better—about −120 ppm/°C. Polystyrene and polypropylene have low leakage and good dielectric absorption—almost as good as Teflon's, which is the best **(Ref 1)**. But Teflon is quite expensive and much larger in package size than the other types. Be careful with polystyrene; its maximum temperature is +85°C, so you can damage it during ordinary wave soldering. Polycarbonate has a TC of 150 ppm/°C but has inferior soakage.

Foiled again!

Now let's discuss the difference between a polyester foil capacitor and a metallized polyester capacitor. The foil capacitor is made of alternating layers of film and foil, where both the delicate film and the metal foil are just a couple of tenths of a mil thick. This construction makes a good capacitor at a nominal price and in a nominal size. The metallized-film capacitor is made with only a very thin film of polyester—the metal is deposited on the polyester. This construction leads to an even smaller size for a given capacitance and voltage rating, but the deposited metal is so thin that its current-carrying capacity is much less than that of the metal in the foil capacitor. If a pinhole short develops in the metallized-polyester capacitor's plastic film, the metal layer in the vicinity of the pinhole will briefly carry such a high current density that it will vaporize like a fuse and "clear" the short.

For many years, metallized polyester capacitors were popular in vacuum-tube television sets. These metallized capacitors would recover from pinhole flaws not just once but several times. However, at low voltages, the energy stored in the capacitors would often prove insufficient to clear a fault. Thus, the capacitors' reliability at low voltages was often markedly worse than it was at their rated voltage. You could safely use a cheap, compact, metallized-polyester capacitor in a 100V TV circuit but not in a 2V circuit. Fortunately, there are now classes of metallized-polycarbonate, metallized-polyester, and metallized-polypropylene capacitors that are reliable and highly suitable for use at both low and high voltages.

When the old metallized-polyester capacitors began to fail in a TV set, the "clearing" of the shorts would make the signals very noisy. Likewise, when used as audio coupling capacitors, "dry" tantalum capacitors would sometimes make a lot of noise as they "cleared" their leaky spots. These parts have therefore become unpopular for audio coupling. Similarly, you can use an electrolytic capacitor with a small reverse voltage—perhaps 0.5V—with no harm or problems. But a friend told me of a time an electrolytic capacitor used as an audio coupling capacitor with 2V of reverse bias produced all sorts of low-frequency noise and jitter. So, excess noise is often a clue that something is going wrong.

Extended foil offers extensive advantages

Another aspect of the film capacitor is whether or not it uses "extended-foil" construction. The leads of many inexpensive wound-foil capacitors are merely connected to the ends of the long strip of metal foil. However, in an extended-foil capacitor, the foils extend out on each end to form a direct low-resistance, low-inductance path to the leads. This construction is well suited for capacitors that must provide low ESR (equivalent series resistance) in applications such as high-frequency filters. But if you substitute a capacitor without extended foil, the filter's performance will be

It is critical to choose a filter capacitor whose effective series impedance is low at all rated temperatures.

drastically degraded.

So there are several methods of construction and several dielectrics that are important for most capacitor applications. If an aggressive purchasing agent wants to do some substituting to improve cost or availability, the components engineer or design engineer may have to do a lot of work to make sure that the substitution won't cause problems. If a substitution is made, the replacement part is a good place to start looking for trouble. For example, a capacitor with higher-than-planned-for ESR can cause a feedback loop to oscillate—for example, when a capacitor without extended-foil construction is substituted for one with such construction. Substitution of capacitors with higher ESR than the designer intended can also cause filters to fail to properly attenuate ripple. Another consequence of excessive ESR is the overheating and failing of capacitors—capacitors may be passive components, but they are not trivial.

Not only does extended-foil construction lower a capacitor's ESR, it also lowers the component's inductance. As a friend pointed out, "Pease, you understand things really well if they are at dc or just a little bit faster than dc." I replied, "Well, that's true, but what's your point?" His point was that in RF circuits, and many other kinds of fast circuits, you should use capacitors and other components dressed closely together, so that the inductance is small and well controlled. He was absolutely right—the layout of a high-speed, fast-settling or a high-frequency circuit greatly affects its performance. Capacitors for such circuits must be compact and not have long leads. Ceramic and silvered-mica capacitors are often used for that reason.

Every year, billions of ceramic capacitors find their way into electronic products of all kinds. There are basically three classes of these parts: the "high-K" and "stable-K" types and the C0G or NP0 types.

The high-K types, such as those with a "Z5U" characteristic, give you a lot of capacitance in a small space—for example, 10^6 pF in a 0.3-in. square that is 0.15-in. thick. That's the good news. The bad news is that the capacitance of parts with this Z5U characteristic drops 20% below the room-temperature value at 0 and 55°C; it drops 60% below the room-temperature value at −25 and +90°C. Also, the dielectric has a poor dissipation factor, mediocre leakage, and a mediocre voltage coefficient of capacitance. Still, none of these drawbacks prevents capacitors of this type from being used as bypass capacitors across the supply terminals of virtually every digital IC in the whole world. That's a lot of capacitors!

These ceramic capacitors have a feature that is both an advantage and a drawback—a typical ESR of 0.1Ω or lower. So, when a digital IC tries to draw a 50-mA surge of current for a couple of nanoseconds, the low ESR is a good feature: It helps to prevent spikes on the power-supply bus. However, when you have 10 ICs in a row and 10 ceramic bypass capacitors, you've got a long L-C resonator **(Fig 1)** with the power-supply bus acting as a low-loss inductor between each pair of bypass capacitors. When repetitive pulses excite this resonator, ringing of rather large amplitude can build up and cause an excessively noisy power-supply bus.

The standard solution is to add 2 μF of tantalum electrolytic bypass capacitors or 20 μF of aluminum electrolytic capacitors for every three to five ICs. The

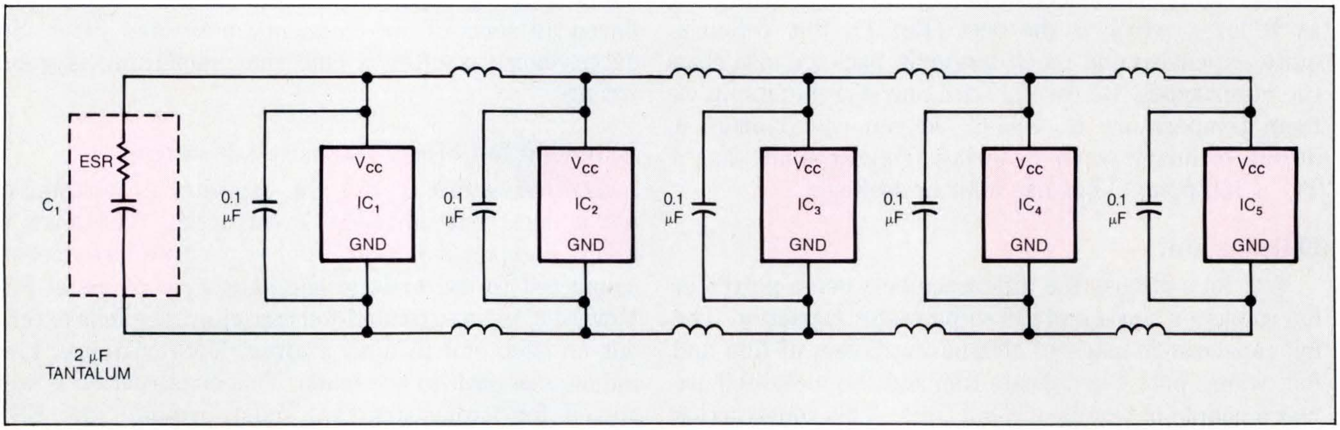


Fig 1—Low ESR in a decoupling capacitor *is a 2-edged sword. Though a capacitor with low ESR stabilizes the supply bus when the ICs draw short-duration current spikes, the low dissipation encourages ringing by allowing the decoupling capacitance to resonate with the bus inductance. One cure is to place an electrolytic capacitor, such as C_1, across the bus. C_1's ESR of approximately 1Ω damps the ringing.*

ESR of the electrolytic capacitors, typically 1Ω, is essential to damp out the ringing. I have read a few ads in which some capacitor manufacturers claim that their ceramic bypass capacitors are so good that ringing is no longer a problem, but I find the claims hard to believe. I invite your comments.

ESR, friend or foe?

Specifically, some capacitor manufacturers claim that the series resistance, R_S, is so low that you won't have a problem with ringing. But low R_S would seem to exacerbate the ringing problem. Conversely, I've heard that one capacitor manufacturer is proposing to market ceramic capacitors whose series R_S has a lower limit—a few ohms—to help damp out any ringing. I'm going to have to look into that. But if you have bypass capacitors with a very low R_S, you can lower the Q of the resonator you have inadvertently constructed around them by adding a resistor of 2.7 to 4.7Ω in series with each capacitor. Adding resistance in series with bypass capacitors might seem a bit silly, but it's a very useful trick.

High-K ceramic capacitors also can exhibit piezoelectric effects: When you put a good amount of ac voltage across them, they can hum audibly; if you rattle or vibrate them, they can kick out charge or voltage. (Other types can do the same thing, but high-K types are worse.) Be careful when using these capacitors in a high-vibration environment.

The capacitance of stable-K capacitors, such as X7R, typically decreases by 15% from the room-temperature value over the −55 to +125°C range. These capacitors are general-purpose devices and are usually available in the 100- to 10,000-pF range; in the larger packages, you can get as much as 300,000 pF. However, you can buy a 10,000-pF capacitor in either a high-K or a stable-K type; and you can't be sure of the kind you're getting unless you check the catalog and the part number.

The last type of ceramic capacitor was originally called "NP0" for Negative-Positive-Zero and is now usually called "C0G." The C0G capacitor is really a high-grade capacitor with a guarenteed TC of less than ±30 ppm/°C. Their dissipation factor, dielectric absorption, and long-term stability are not quite as good as those of Teflon capacitors but are comparable to those of other good precision-film capacitors. So, if you want to make a S/H circuit usable over the military temperature range, you'll find that C0G capacitors are more compact and less expensive then Teflon parts. Many, but not all, ceramic capacitors smaller than 100 pF are made with the C0G characteristic. You can get a 22,000-pF C0G capacitor in a 0.3-in.-square package.

Recently, a customer called me about a drift problem: His V/F converter had a poor TC, even though he said that he had put in a C0G 0.01-µF capacitor as the main timer. Troubleshooting by phone—it's always a wonderful challenge. I asked him, "This C0G-ceramic 0.01-µF capacitor . . . is it . . . as big as your little fingernail?" He said, "Oh no. It's a lot smaller than that." I replied, "Well, that's too small; it can't be a C0G." Problem solved.

One observed failure mode for ceramic capacitors can arise when the capacitor's leads are attached to the dielectric with ordinary, low-temperature solder. When the capacitor goes through a wave-solder machine, the lead may become disconnected from the capacitor. If this problem occurs, you'll have to switch to capacitors from a manufacturer that uses high-temperature solder.

Don't forget silvered mica

Silvered-mica capacitors have many features similar to C0G capacitors. They have low ESR and a TC of 0 to 100 ppm/°C. They can also work at temperatures above 200°C if assembled with high-temperature solder. Unfortunately, they have poor soakage characteristics.

A major problem with silvered-mica capacitors is their marking. The silvered-mica capacitors in old radios had completely inscrutable markings—six color dots. Some of the new ones have such odd codes that even if the marking on the capacitor hasn't rubbed off, you can never be sure whether "10C00" means 10, 100, or 1000 pF. You really need to use some kind of capacitance meter. Similarly, in the old days, some ceramic capacitors were marked in an inscrutable way. I remember two little capacitors both marked "15K." One was a 15-pF capacitor with a 'K' characteristic, and the other was a 15,000-pF capacitor—yet they were both the same size and had the same marking.

I must also mention that, in the past, you could buy a pretty good capacitor that had never been tested for its capacitance. About 99% of the time, they were excellent, reliable capacitors. But once in a while, some of the capacitors came through with a completely different value. One time I saw a whole box of "capacitors" in which the two leads were still made of one loop of wire that had not been snipped apart. Obviously, the manufacturer wasn't interested in testing and measuring these capacitors before sending them out the door.

A 6V electrolytic capacitor of even a few microfarads can blow out as explosively as a shotgun blast if you apply 6V dc of the wrong polarity to it.

So, if you are buying capacitors to a 1% AQL (Acceptance Quality Level) and not 0.1% or 0.01%, you should be aware that some low-priced parts have not even been sample tested.

Variable capacitors have finite rotational lives

Variable capacitors are usually made of low-K material with characteristics similar to those of C0G capacitors. Their performance is excellent. The dielectric doesn't cause much trouble, but the metal sliding contacts or electrodes on some types are very thin; after only a small number of rotations—hundreds or even dozens—the metal may wear out and fail to connect to the capacitance.

In general, capacitors are very reliable components; and, if you don't fry them with heat or zap them mercilessly, the small-signal ones will last forever and the electrolytic ones will last for many years. (Old oil-filled capacitors aren't quite that reliable and have probably been replaced already—at least they should have been replaced.) The only way you can have an unreliable capacitor is to use a type that is unsuitable for the task. And that's the engineer's fault, not the capacitor's fault. Still, some troubleshooting may be required; and if you recognize the clues that distinguish different types of capacitors, you've taken a step in the right direction.

What procedures are best for troubleshooting capacitors? I use two basic procedures, the first of which is the add-it-on approach. Most circuits are not hopelessly critical about capacitor values, as long as the capacitors' values are large enough. So, if there is a 0.01-μF capacitor that I suspect of not doing its job, I just slap another 0.01-μF capacitor across it. If the ripple or the capacitor's effect changes by a factor of two, the original capacitor was probably doing its job and something else must be causing the problem. But if I observe little or no change or a change of a factor of three, five, or ten, I suspect that capacitor's value was not what it was supposed to be. I pull the capacitor out and measure it. Of course, the capacitor substitution boxes I mentioned in the section on test equipment can be valuable here; they let me fool around with different values. But in critical circuits, the lead length of the wires going to the substitution box can cause crosstalk, oscillation, or noise pickup; so I may have

But is this really troubleshooting?

When I passed the first draft of this article around to a few friends, one guy asked, "Why are you telling us all these things about weird capacitors? What does that have to do with troubleshooting?" I gave him the same answer I give you here: If you had a mediocre coupling capacitor and you didn't realize that it could keep on "leaking" for many seconds or minutes longer than a good coupling capacitor would, you wouldn't look for problems traceable to that capacitor. I cannot foresee every problem you will have in a circuit, but I can point out that similar-looking components can have startlingly different characteristics.

You can't learn about these characteristics from looking in books, or even in data sheets. So, if you get in trouble, I'm trying to suggest clues to look for to help you get out. Conversely, if you study these precautions and think about what can happen, you may be able to avoid getting into trouble in the first place. That's even better than being able to get out.

In fact, maybe some of the warnings I have presented here will explain why you once had a problem whose cause you could never figure out. Every once in a while, I learn something that stops me in my tracks: "That explains why the oscillator I made two years ago never worked right." If you stand on my shoulders, you may be able to get to places that neither of us could get to alone.

I certainly didn't figure out every one of these ideas by myself. I am passing along many ideas that I gleaned from other people's experience. Furthermore, I doubt if they invented all those ideas themselves. Surely, they benefited from other peoples' ideas that they picked up along the way. I am just trying to pass along insights that are not book learning but that I learned in the College of Hard Knocks. It may or may not be troubleshooting, but it's close enough for me.

Be careful with polystyrene; its maximum temperature is +85°C, so you can damage it during ordinary wave soldering.

to just "touch in" a single capacitor to a circuit.

Suppose, for example, that I have a polyester coupling capacitor that seems to be adding a big, slow "long tail" to my circuit's response. I don't expect the performance with the polyester capacitor to be perfect, but a tail like this one is ridiculous! So, I lift up one end of the polyester capacitor and install a polypropylene unit of the same value. I expect the new capacitor's characteristics to be a lot better than those of the old capacitor. If the tail gets a lot smaller, either my plan to use polyester was not a good one or this particular polyester capacitor is much worse than usual. It's time to check. But usually, I'd expect to find that the polypropylene capacitor doesn't make the circuit perform much better than the polyester capacitor did, and I'd conclude that something else must be causing the problem.

For either of these techniques to work, it is helpful to have a large stock of assorted capacitors. In our lab, we have several cartons of used—but not too badly beaten up—components left over from old experiments: One is a box of small mica and ceramic capacitors, one holds various electrolytic capacitors, and one is a tray of assorted wound-film capacitors. These boxes are extremely valuable because if I need an odd type, I can usually fish in one of those cartons and find something close. Or I can find some capacitors that give the right value if I parallel two or three of them. I can use these capacitors per the add-it-on or the substitution method to find out what my unhappy circuit is trying to tell me. In addition, I keep a couple of Teflon capacitors in my file cabinet for when I need a super-good capacitor.

A technique that nobody talks about but is as old as the hills is a favorite trick of mine. Sometimes it drives my technicians wild, but then they learn the trick and find it awfully useful. Let's say I want to compare a Mylar capacitor with a ceramic capacitor in a small, precision circuit. The technician starts to remove the Mylar capacitor and install the ceramic one. Wrong! Instead, remove one lead of the first capacitor and lift it up slightly. Then tack solder one end of the second capacitor to the circuit. At this point, neither capacitor is actually in the circuit—both capacitors are just waving in the breezes.

After the solder thoroughly cools down, I can use the springiness of the leads to let me "touch in" one of the capacitors or the other or both, as needed. It only takes a second to go from one mode to the other. (Of course, I'm assuming there's not enough voltage to "bite" my finger.) If I actually desolder and resolder the capacitors and allow enough time for these temperature-sensitive components to cool off, I'll probably forget what the difference between them looks like. So, this technique can save a lot of time and greatly facilitates A-B comparisons—it lets me use my eyeball to evaluate the nuances of small performance changes.

Of course, if I have two or three of these spring-loaded options at one time and they begin to get wobbly, it may be time to tack solder down the ones that I am not actively pursuing. In general, though, this technique is extremely valuable, and I've never seen it in any book. Use it with my compliments. It works with diodes, resistors, and transistors, too. Just make sure that solder flux doesn't prevent the spring-loaded component lead from contacting the conductor. And make sure that your finger doesn't add a lot of capacitance, impedance, or noise into the circuit. If you do have this problem, push on the component with the edge of a fingernail instead of a finger. A fingernail adds less than ½ pF. **EDN**

Reference

1. Pease, R A, "Understand capacitor soakage to optimize analog systems," *EDN*, October 13, 1982, pg 125.

Author's biography

For more information about Bob Pease, see the ***box****, "Who is Bob Pease, anyway?" in the January 5, 1989, edition of EDN.*

Article Interest Quotient (Circle One)
High 494 Medium 495 Low 496