

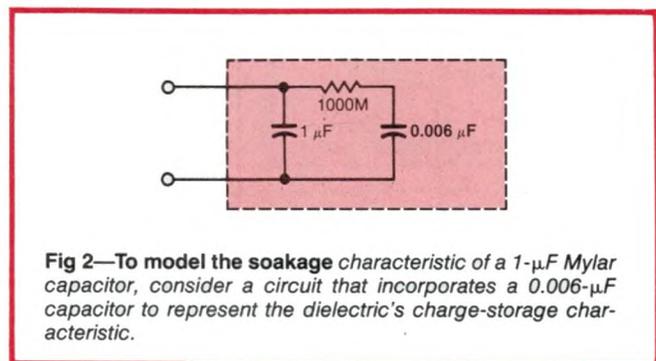
# Understand capacitor soakage to optimize analog systems

*Dielectric absorption can cause subtle errors in analog applications such as those employing S/H circuits, integrating ADCs and active filters. But knowing how to measure this soakage and compensate for it helps you minimize its effects.*

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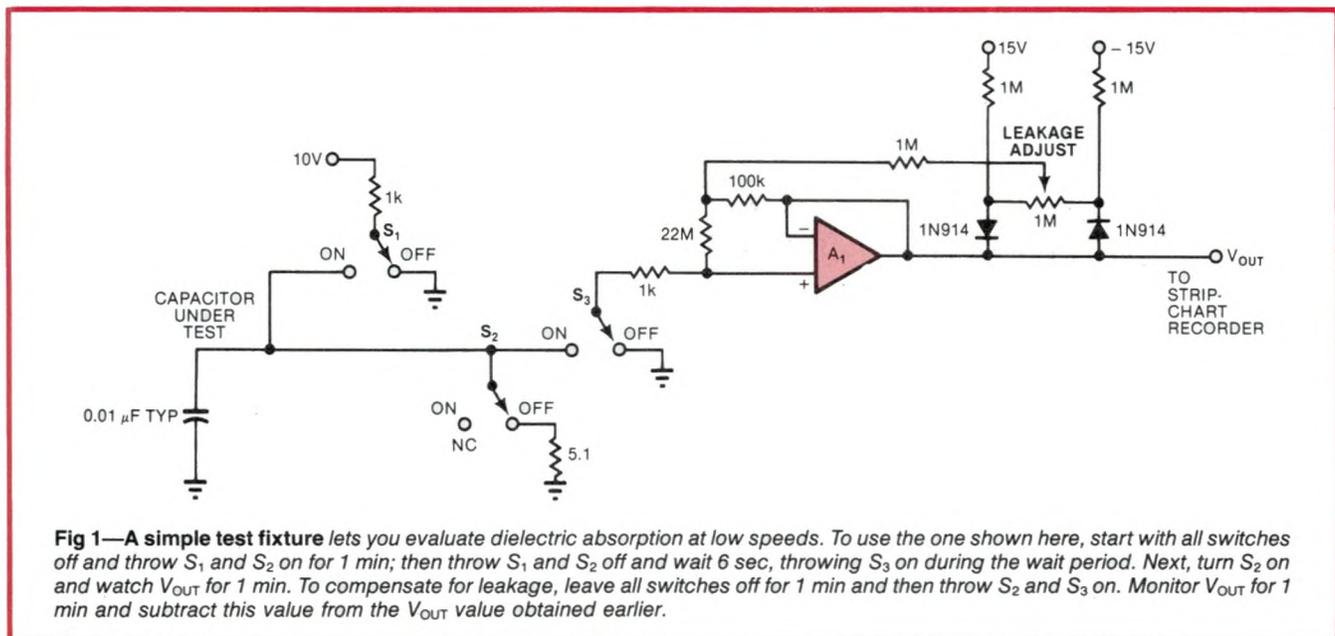
Veteran circuit designers often got a shocking introduction to dielectric absorption when supposedly discharged high-voltage oil-filled paper capacitors reached out and bit them. Indeed, the old oil-filled paper capacitors were notorious for what was once called soakage—a capacitor's propensity to regain some charge after removal of a momentary short. Today, you won't find very many of these capacitors in use, but you will still encounter soakage. Do you know how to deal with it?

Nowadays, you're more likely to notice the effects of dielectric absorption in some more subtle way, perhaps in the performance of an integrator that can't be reset to zero or a sample/hold that refuses to work correctly. But whether you literally feel its effects or merely observe them in a circuit's behavior, dielectric absorption is an undesirable characteristic that every capacitor possesses to some degree. This characteristic is

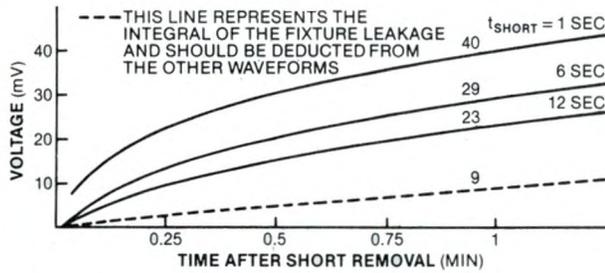


inherent in the dielectric material itself, although a poor manufacturing procedure or inferior foil electrodes can contribute to the problem.

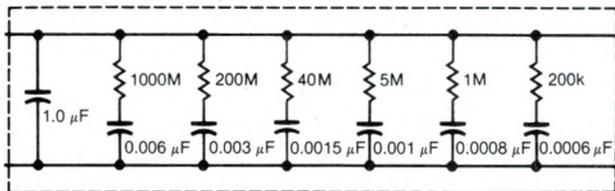
Indeed, soakage seems an apt term for dielectric absorption when you note what the capacitor seems to be doing. Consider a typical example: A capacitor charges to 10V for a long time  $T$  and then discharges through a small-value resistor for a short time  $t$ . If you



# Soakage introduces errors into sample/hold circuits



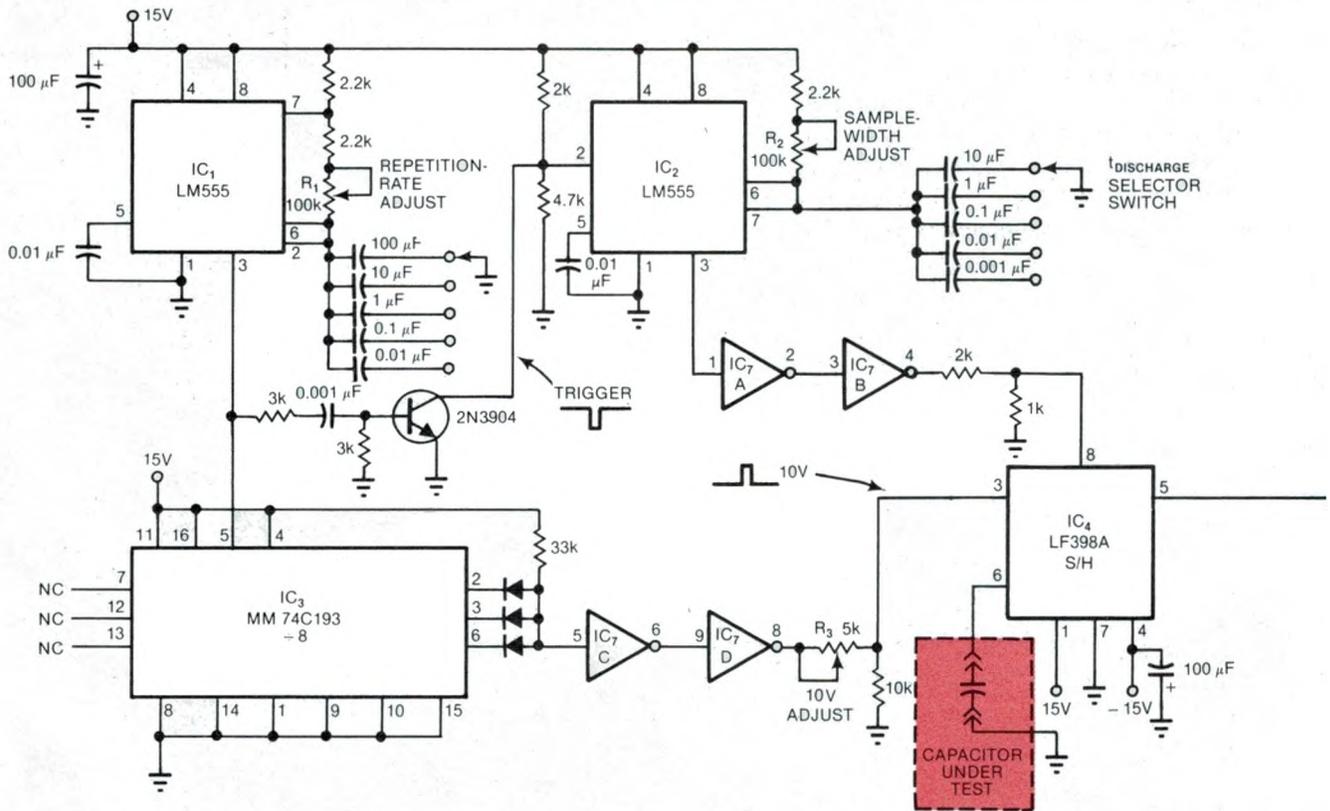
**Fig 3**—Obtained using Fig 1's test circuit, these dielectric-absorption-measurement results for a 1- $\mu$ F capacitor show that longer  $t_{DISCHARGE}$  times reduce soakage-caused errors.



**Fig 4**—More precise than Fig 2's equivalent circuit, a capacitor model employing several time constants proves valid for a wide range of charge and discharge times. This model approximates a Mylar capacitor.

remove the short circuit and monitor the capacitor terminals with a high-impedance voltmeter, you see the capacitor charge back to 0.1%, 1% or as much as 10% of the original voltage. For example, a 1- $\mu$ F Mylar capacitor charged to 10V for 60 sec ( $T_{CHARGE}$ ) and discharged for 6 sec ( $t_{DISCHARGE}$ ) charges to 20 or 30 mV after 1 min ( $T_{HOLD}$ ). **Fig 1** shows a simple evaluation circuit for measuring this characteristic.

A capacitor exhibiting dielectric absorption acts as if during its long precharge time the dielectric material has soaked up some charge that remains in the dielectric during the brief discharge period. This charge then bleeds back out of the dielectric during the relaxation period and causes a voltage to appear at the capacitor terminals. **Fig 2** depicts a simple model of this capacitor: When 10V is applied for 1 min, the 0.006- $\mu$ F capacitor gets almost completely charged, but during a 6-sec discharge period it only partially discharges. Then, over the next minute, the charge flows back out of the 0.006  $\mu$ F and charges the 1- $\mu$ F capacitor to a couple of dozen millivolts. This example indicates that a longer discharging time reduces soakage error but that discharging for only a small fraction of that time results in a larger error. Illustrating this point, **Fig 3** shows



**Fig 5**—Capable of automatically sequencing the dielectric-absorption tests, a circuit employing timers, a sample/hold and limiting stages allows you to make measurements for a wide range of  $T_{CHARGE}$ ,  $T_{HOLD}$  and  $t_{DISCHARGE}$  values. **Fig 7** shows results obtained using the circuit shown here.

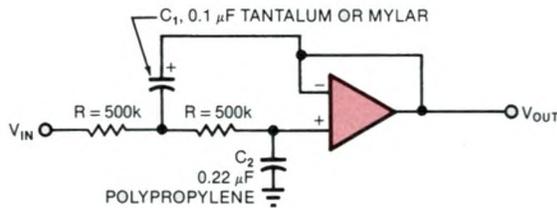


# Multiple-time-constant model represents dielectric absorption

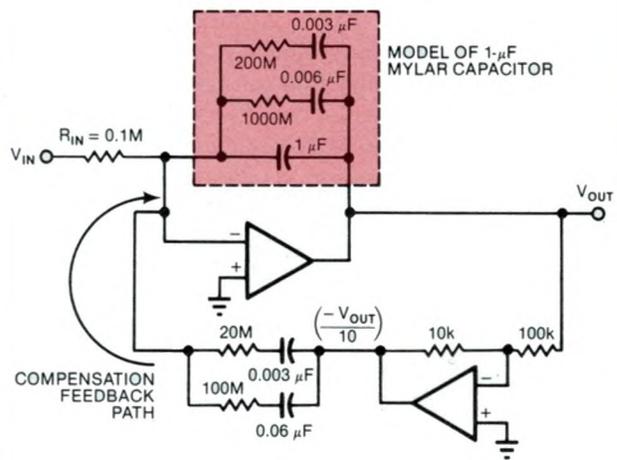
achieve a low temperature coefficient (a spec not usually significant for a S/H but one that might prove advantageous for precision integrators or voltage-to-frequency converters). Teflon is rather expensive but definitely the best material to use when high performance is important. Furthermore, only Teflon and NP0 ceramic capacitors suit use at 125°C.

If you look at Fig 7's dielectric-absorption values, you can see wide differences in performance for a given dielectric material. For example, polypropylene sample

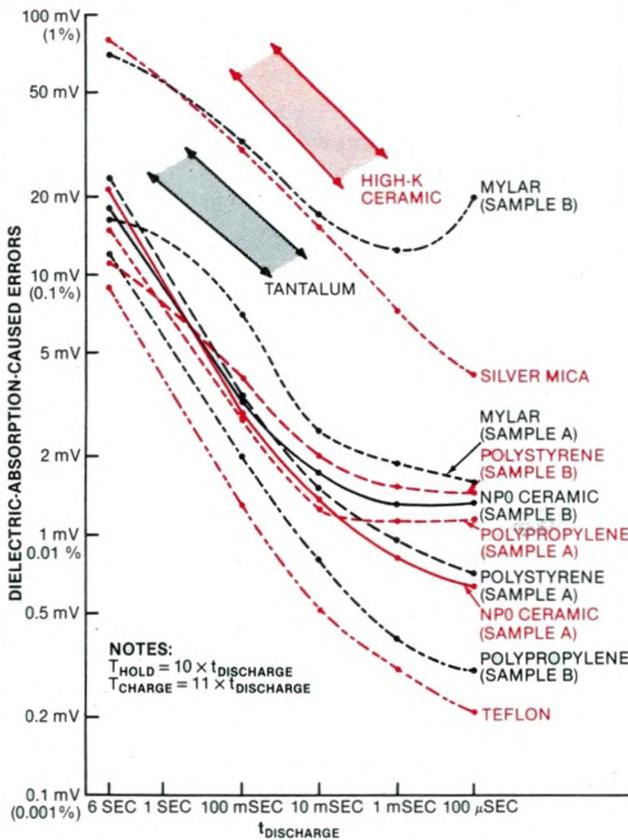
A is about as good as B at  $t=6$  sec, but B is four times better at high speeds. Similarly, NP0-ceramic sample A is slightly worse than NP0-ceramic sample B at low speeds, but A is definitely better at high speeds. And some Mylar capacitors (sample A) get better as speed increases from 1000 to 100  $\mu$ sec, but others (sample B) get worse. So if you want consistently good performance from your capacitors, evaluate and specify them for the speed at which they'll be used in your application. Keep in mind that because most sample/



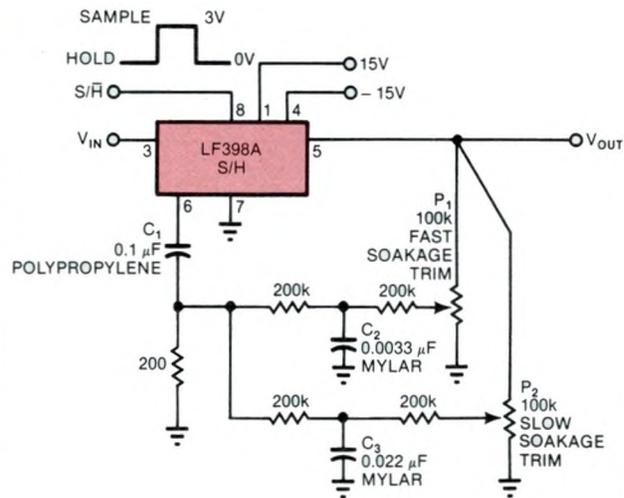
**Fig 6—Soakage can present problems when you're designing a fast-settling amplifier or filter. In the circuit shown here, for example,  $C_1$  can be a Mylar or tantalum unit, but making  $C_2$  a polypropylene device improves performance.**



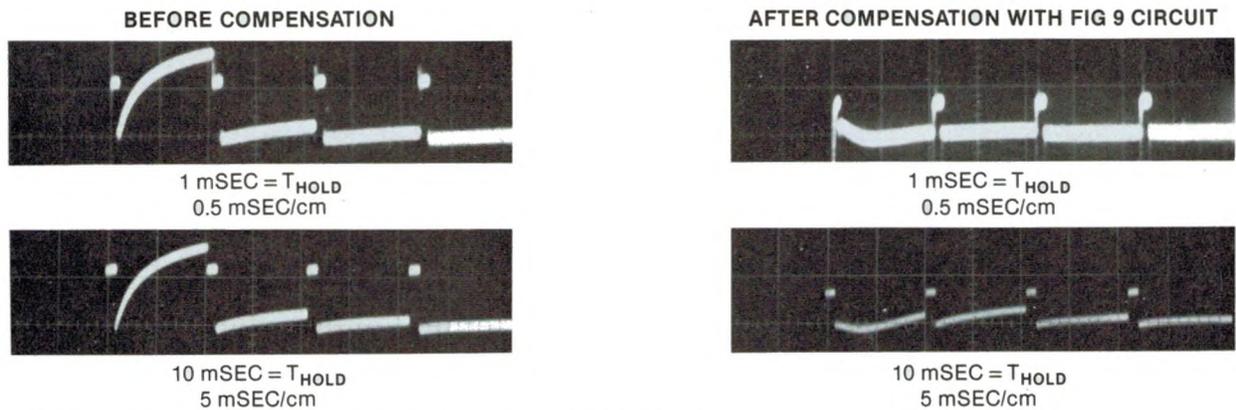
**Fig 8—You can compensate an integrator for dielectric absorption by feeding its inverted output back to the input through one or more experimentally chosen RC networks, which cancel the equivalent network inherent in the capacitor's dielectric material.**



**Fig 7—Soakage-measurement results for a variety of capacitors illustrate the effects of  $t_{\text{DISCHARGE}}$  values on dielectric-absorption-caused errors. Note that the curves for two different samples of NP0 ceramic capacitors intersect.**



**Fig 9—Adding compensation circuitry to a sample/hold yields better-than-Teflon performance with a polypropylene capacitor. Using Teflon capacitors in such circuits can yield a 15- to 17-bit dynamic range.**



NOTES: 1. DIELECTRIC ABSORPTION ERRORS WITH GOOD POLYPROPYLENE CAPACITOR

2. ALL WAVEFORMS AT 1 mV/cm;  $\frac{T_{\text{SAMPLE}}}{T_{\text{HOLD}}} = \frac{1}{10}$

**Fig 10**—Adding Fig 9's compensation network to a sample/hold circuit yields a 10-fold performance improvement for sample times of 50 to 2000  $\mu\text{sec}$ ; additional RC networks and trimming pots can extend the time range. The short pulses represent normal S/H jumps and occur during the sample time. The exponentially rising waveform during the hold time results from soakage. Note that soakage effects are still visible during the second hold period.

holds are used at much faster speeds than those corresponding to the 1- or 5-min ratings usually given in data sheets, a published specification for dielectric absorption has limited value.

In addition, other dielectrics furnish various levels of performance:

- Because any long word that starts with poly seems to have good dielectric properties, how about polycarbonate or polysulfone? No—they are about as bad as Mylar.
- Does an air or vacuum capacitor have low soakage? Well, it might, but many standard capacitors of this type are old designs with ceramic spacers, and they might give poor results because of the ceramic's hysteresis.
- If a ceramic capacitor is not an NP0 device, is it any good? Most of the conventional high-K ceramics are just terrible—20 to 1000 times worse than NP0 and even worse than tantalum.
- Is silicon dioxide suitable for small capacitances? Although Fig 5's test setup, used in preparing Fig 7's chart, only measures moderate capacitances (500 to 200,000 pF), silicon dioxide appears suitable for the small capacitors needed for fast S/Hs or deglitchers.

#### Cancellation circuit improves accuracy

A practical method of getting good performance with less-than-perfect capacitors is to use a soakage-cancellation circuit such as one of the form shown in Fig 8, in which a capacitor of the type modeled in Fig 4 serves as an integrator. (Only the first two soakage elements are shown.) The integrator's output is invert-

ed with a scale factor of  $-0.1$ , and this voltage is then fed through one or more experimentally chosen RC networks to cancel the equivalent network inherent in the capacitor's dielectric material.

Fig 9 shows a practical sample/hold circuit with an easily trimmed compensator. This network provides about a 10-fold improvement for sample times in the 50- to 2000- $\mu\text{sec}$  range (Fig 10). Although this compensation is subject to limitations at very fast or slow speeds, the number of RC sections and trimming pots employed can be extended.

Simple circuits similar to Fig 9's or Fig 8's have been used in production to let inexpensive polypropylene capacitors provide better-than-Teflon performance. In turn, using these compensator circuits with a good Teflon capacitor furnishes a dynamic range of 15 to 17 bits.

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#### Author's biography

**Robert A Pease** is a staff scientist at National Semiconductor Corp (Santa Clara CA). Before joining National, he designed op amps and analog modules for Teledyne Philbrick. Bob earned a BSEE degree at MIT and holds five patents.



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