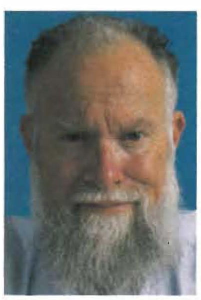
BOB PEASE

What's All This Soakage Stuff, Anyhow?

Of course, this column is going to be talking about the *Dielectric Absorption* of capacitors. But that is much too long a phrase, so we'll call it soakage, or DA. The earliest manifestation of DA was found when old experimenters had a capacitor such as a Leyden jar (a glass jar with metal foil electrodes inside and out) charged up to a large number of volts. They knew if they shorted out the capacitor, the charge would go away. But if they shorted out the capacitor for only a short time, the voltage would recover.

For example, if a 2000-V, 0.1µF capacitor was discharged through 220 kΩ for just 20 seconds, you would expect it to be well discharged. So, if you came back a few minutes later and got a really big jolt from that capacitor, you would be surprised. This was well known as early as the 1700s, and was documented 100 years ago as "residual charge," in my 1894 *Encyclopedia Britannica.*



BOB PEASE OBTAINED A BSEE FROM MIT IN 1961 AND IS STAFF SCIENTIST AT NATIONAL SEMICONDUCTOR CORP., SANTA CLARA, CALIF.

In the early 1900s, the theory of dielectrics provided a fairly good explanation of how the molecules were slowly polarized to store charge—and how they were slow to let loose of their polarization when the original voltage was removed. All capacitors have some DA, but there are many octaves of relative goodness (or badness). When you have filled up the capacitor with charge, after you try to short that charge out, the *soakage* charge just keeps coming out of the capacitor. (Of course, if you thought you had charged a capacitor up to a new value, it would take a while before it stopped needing extra charge. Soakage is a fairly linear effect: It's just as hard to charge a capacitor *up* as it is to charge it *down.*)

The original definitions of DA were only spelled out in terms of hours. If you charge up a capacitor for an hour, then discharge it for a minute, and come back an hour later, what is the voltage? The oil-filled capacitor used in the high-voltage power supplies of old radios, was pretty bad—as much as a 20% voltage error. That's a lot of hidden charge. But many good capacitor materials such as polystyrene were 100 times better than that. So, you didn't have to accept 20% errors. A darned good thing!

Where is a practical example of where soakage is important? Well, if you turn your color TV off and open up the back, what's the first thing you have to do before you start working on it? Put a grounding strap on a screwdriver and reach under the rubber shroud on the HV plug to discharge the CRT. OK, now that capacitance has been discharged, how much voltage will "soak" back into the "capacitance" of the picture tube if you let it sit for about 10 minutes? Enough to make a *visible arc* when you discharge it the SECOND time...now that's what *I* call dielectric absorption. So, you don't want to fool around with a real high-voltage capacitor, if it has only been discharged once.

Still, if you know what happens every time you charge up a capacitor for an hour, how can you tell what will happen when you charge it up for one second, or a millisecond, or 10 microseconds? This isn't obvious.

The model for a capacitor with soakage is a big capacitor, in parallel with several small capacitors in series with various large resistors *(see the figure).* If we put a dc voltage on the capacitor for 0.1 second, some of those smaller capacitors will be charged up, but some of the bigger ones will take more time.

Back in the 1960s, I fooled around with some rather good capacitors, and a few mediocre ones. At Philbrick, I made some very good integrators. I started with teflon capacitors, and FET switches to reset the integrator after it had been integrating for a while. We had several different reset circuits and sample-and-hold circuits.

The fun circuit for resetting your integrator was an old circuit from the early 1950s, that used vacuum tubes and a neon lamp. When you wanted to reset the integrator, a pentode was turned on, and a small RF oscillator started up. The output of the oscillator was fed to a wire wrapped around an NE-2 neon lamp. Presumably the neon lamp was induced into conductance, went to low impedance, and reset the integrator. I have never built this up, but maybe I'll do it. I wonder if it works well at all. But, I suspect, not.

When the integrator was reset, the main capacitance was shorted out. Some of the faster RC networks would be discharged, but the slower ones would cause significant errors. So I engineered some compensator networks to compensate out, cancel that charge.

I have a pretty good write-up on my web pages. There, I wrote that nobody ever talks about soakage or dielectric absorption in any detail. Recently I received letters and e-mails from readers, one of which pointed out that *The Art of Electronics*, by Horowitz and Hill, has a neat little explanation of DA.

I tried looking it up in that book (the original 1980 edition), and I nearly went blind looking for it. Nothing in there. Finally I got suspicious and went to our library, to look in the second edition (1989). OK, there is some mention there, but they don't say much quantitative about soakage. Then other people wrote to me, pointing out some of the seminal work in the field, by Paul C. Dow, Jr., in 1958, and Robert Guyton and Joe McKay in 1968.

Dow, in the *IRE Transactions on Electronic Computers* (analog computers, in those days, of course), March 1958, pp. 17-22, measured the soakage of the best capacitors of the day—polystyrene. His data resulted from measuring the current flowing out of a capacitor after it had been charged for a long time, and discharged for a short time. His model of the soakage showed that a basic 1-μF polystyrene capacitor might appear to have a series RC network across it, such as 140 pF in series with 3.5 Mega Megohms (MMΩ), a 200 pF in series with 250 kiloMegohms (kMΩ), a 270 pF in series with 20 kMΩ, a 190 pF in series with 3 kMΩ, and another of 120 pF in series with 330 MΩ. (Figure 4 at my web site is quite comparable, but the losses are worse because it's a model for a mylar capacitor.) Dow indicated how much trouble these RC networks would cause for various analog-computer and integrator circuits, such as unwanted phase shifts and errors when making an oscillator out of a couple integrators.

But Dow looked at the soakage in time-frames from 1000 seconds to just 0.1 second. Hey, it's a fact that the official definition of dielectric absorption requires a capacitor to be charged up for 10 minutes, discharged for 1 minute, and then monitored for another 10 minutes. But that doesn't tell you much about how your sample-and-hold circuit will "distort" if you're looking at a small signal just 10 or 1 ms after it was discharged from a large voltage!

So, in my studies, I ran charge and discharge times from 100 seconds down to 100 μs. You can look at the characteristics of various different types. I must admit, I did run all of my tests with a T_{CHARGE}:$T_{DISCHARGE}$ of about 10:1. But the results over wide dynamic ranges showed that the accuracy of a sample-and-hold capacitor tends to get better as you go faster.

The other guys—Guyton at Mississippi State University, and McKay at Redstone Arsenal—engineered a compensating network for an integrator, to make it closer to perfection. However, while their integrator did have greatly improved phase and amplitude errors during integration, their compensation circuit wouldn't help in trying to reset the integrator to zero quickly. It only worked by changing the phase shift of the input resistor to compensate for the phase and gain errors in the capacitor. If you wanted to short out the capacitor, to reset the integrator, their paper provided no help at all.

The circuits in my tech paper show how you can get good, quick settling from capacitors in integrators or sample-and-hold circuits, where you need fast reset action. Where is that web site? It's at *www.national.com/rap.* Then, at the bottom of my home page, click on the "good technical stuff." It's one of three papers there. If you can't get on the web, write me a letter, and I'll send you a copy of that paper.

Can you hear the advantage of low-soakage capacitors in your hi-fi amplifier? Lots of experts say "yes"...those golden-ears again. If an amplifier is "capped" by taking all electrolytic capacitors out of the signal path, and replacing them with good film capacitors, it has to sound better. All the experts say it sounds better.

Tom Nousaine (who did ABX testing on speaker cables) says the golden-ears cannot hear a difference, in truly blind tests. I believe him. Of course, that does not mean that there are no differences. Nousaine is careful, after all, not to leave all the controls "flat," because this might let out all sorts of differences in frequency response. He makes sure that the gains of both amplifiers are matched within 0.1 dB at 0.1, 1, and 10 kHz. If one did not do that, one might hear a difference.

Now, that does NOT mean we can't hear the effects of a tantalum capacitor in a poorly-designed circuit, with improper bias. I'll run some tests on those, soon. But it's well-known that tantalum caps can sound pretty weird if they are ever allowed to get biased the wrong way during part of a cycle. I bet even *I* can hear that kind of distortion.

I heard a great story about some extreme tests on capacitors. The engineers took a 1-uF mylar cap and charged it up to its rated voltage, say 50 V. Then, they heated it to 150 °C, for a while, afterward cooling it down to room temperature, still maintaining 50 V. Next, they shorted out the capacitor and measured the charge. Of course, they got 50 μC, or Q = C × V. That's what you'd expect.

Then, they held the capacitor at 0 V, and heated it back up to 150 °C. The amount of charge that flowed out of the cap, as it was heated, was larger than 50 μC! Of course, 150 °C is considerably outside of the normal working range for mylar capacitors, but it did not cause any problems, other than this huge amount of residual charge stored on the molecules of the dielectric!

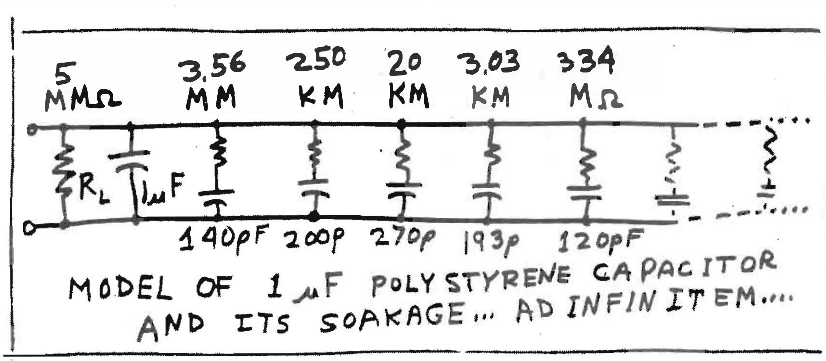
Recently I read an e-mail from an old friend, who said that one web expert asserted that speaker cables made with low-soakage materials will sound better than cables made with high-soakage insulation. He claimed that since Pease explained how soakage works, the better cables must sound better. My friend asked me if there would be any audible difference.

I thought about it, and I reached into my wallet. I've been carrying around a photocopy of some facts about different types of speaker cables for many months. I don't think I carried them the 200 mi. around Annapurna, but other than that, I've been carrying them for over a year.

Let's assume we are talking about 10 yd. of cable; anything less than that would be sub-negligible. Some of the simple, low-capacitance ones have 10 to 30 pF/ft. Some of the good, low-impedance ones, which I like (made of 32 pairs of wires), have as much as 300 to 700 pF/ft., or 9000 pF to 21,000 pF/30 ft. Let's talk about those.

If you used a 30-ft. length of cable as the storage capacitor in a sample-and-hold circuit, a teflon cable would look pretty good. And the cheap rubber or plastic-insulated cable might make a rather poor sample-and-hold. A 20,000-pF capacitor made of teflon-insulated wire might have, at 1 or 2 kHz, as much as 20 pF in series with 8 MΩ.

A cable made with poor plastic might have 50 times worse than this, such as 1000 pF in series with 160 kΩ. Mind



you, I have not yet measured *lamp cord*, as a hold-capacitor in a sample-and-hold, but still, this is a ball-park worst-case kind of soakage. Let's see where this leads us.

If you measure the loss factor and settling tails of a sample-and-hold circuit, due to the resistance, the poor cable might look a LOT different. Now, take this poor, lossy cable out of the sample-and-hold, and connect it to an 8-Ω load. Then, drive it from an audio amplifier with 1 Ω of output impedance. If you put 160 kΩ across 8 Ω, it would definitely make a tiny, but measurable difference in impedance—perhaps 0.005%, or 0.0005 dB. It would be different from a teflon cable, all other things being equal. But not a heck of a lot. And, if you consider that the low-impedance amplifier (1 Ω) is driving this 160 kΩ in parallel with the 8 Ω, that would sound like a 0.00005-dB warpage of the frequency response. I would not call that audible.

So, I replied to my concerned friend, that the "expert" who thinks that speaker cables will sound "different" or "better" if they are made with low-DA materials, will probably have a very thin chance of telling any difference.

I told him this relevant esaeP's Fable: Do you know the Celluloid Cat? That is the Celluloid Cat being chased by the Asbestos Dog. Well, that "expert" has about as good of a chance of hearing any difference, as the Celluloid Cat being chased by the Asbestos Dog through the Fires of Hell.

In the week after this analysis, I came across two other cases where the parable of the Celluloid Cat came up, because it was a perfectly applicable case. I figured, three times in a row, that it was trying to tell me something. So here is that fable. NOTE, to young kids and people who cannot remember back 40 years, photographic film and ping-pong balls used to be made from celluloid, and they were REALLY flammable. These days, they are NOT made of celluloid, and not very flammable.

All for now. / Comments invited!
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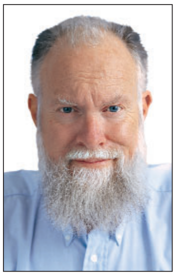


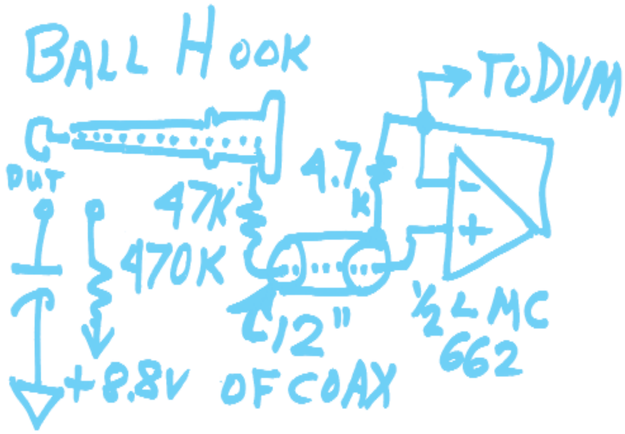
What's All This Capacitor Leakage Stuff, Anyhow?

We all know that capacitors have a shunt resistance (leakage) and that leakage resistance should be pretty easy to measure, right? Wrong! I've measured a lot of capacitors for short-term soakage (dielectric absorption) per *www.national.com/rap/Application/0,1570,28,00.html*.

After the short-term soakage stops, it's possible (not easy) to measure the leakage. For example, if you charge a good cap up to 9 V for a few seconds, it will start discharging shortly for several millivolts. If you wait long enough, you may see leakage slow down to a few millivolts per hour. But you will see the long-term soakage. Is that different from the short-time leakage? Maybe not.

Now I will charge up some of my favorite low-leakage capacitors (such as Panasonic polypropylene 1 µF) up to 9.021 V dc (a random voltage) for an hour. I will read the V_{OUT} with my favorite high-input-impedance unity-gain follower (LMC662, Ib about 0.003 pA) and buffer that into my favorite six-digit digital voltmeter (DVM) (Agilent/HP34401A) and monitor the V_{OUT} once a day for several days.

Why did I choose 9 V? Because that's within the common-mode range of the op amp and the DVM at highest resolution. I keep the input ball hook connected to +8.8 V dc between readings. I also keep my left hand grounded to +8.8 V.



DAY BY DAY ¥ One of my e-mail colleagues had been monitoring some good 0.1-µF polystyrenes, and he was impressed that they got down to a leak rate of better than a year after several months. Well, I could see that my polypropylenes had their leak rate improve even better than that in just a few days. Refer to the list of voltages below:

Day 0: 9.0214 V
Day 1: 9.01870 V
Day 2: 9.01756 V
Day 6: 9.0135 V
Day 7: 9.0123 V
Day 8: 9.01018 V
Day 9: 9.00941 V
Day 11: 9.00788 V
Day 12: 9.00544 V
Day 13: 9.00422 V

The first day after soaking for an hour, their leak rate was as good as 2.7 mV per day. Not bad.

If you had a 1 million-MΩ resistor across a 1-µF capacitor at the 9-V level, it would draw 9 pA, which would pull down the capacitor 778 mV per day. All the capacitor types I tested were better than this, except some "oil-and-paper" caps that supposedly had special qualities for audio signals.

If you had a 10-meg-meg resistance, that would cause the cap to leak down 78 mV/day. With 100 meg-megs, it would be 7.8 mV per day. Several good capacitors soon began to leak slower than that. After a mere week, some of the best caps were leaking at a rate down near 1 mV/day. Quite good. So, what's the big deal?

The big deal is that a time constant of 31.5 meg seconds is one year! So any capacitor leaking less than 2.5 mV per day is leaking at a tau (rate) of 10 years or more. If you had to wait a few months to get this leak rate, well, that's not bad. But achieving this leak rate in less than two weeks is, I would say, quite good. Less than a *day*? Spectacular.

So I'm finding that good polypropylene caps are better than the best (old) polystyrenes, in terms of soakage or dielectric absorption (early or late) and in terms of leakage, early or late. Are Teflons any better? Not much. I may have to buy a couple to find out.

Comments invited! *rap@galaxy.nsc.com —or:*
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