Selection of Capacitors for Optimum Performance—Part II

PICKING CAPACITORS

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A somewhat lesser known performance parameter of capacitors called dielectric absorption (DA) is also a major contributor to sonic problems. Actually, in spite of the fact that DA is not generally understood, it may well be more important than DF.

This phenomenon is really a reluctance on the part of the capacitor dielectric to give up the electrons that it has stored within itself whenever the capacitor is discharged. Then, when the shorting mechanism is removed, these electrons that remained in the dielectric will, in time, accumulate on an electrode and cause a "recovery voltage" gradient to appear across the capacitor terminals. This has been referred to as a capacitor's "memory" of what was just previously applied. The recovery voltage, divided by the initial charging voltage, and expressed as a percent figure, is called the "percentage dielectric absorption" (% DA).

Conversely, there is also a reluctance on the part of the dielectric to accept all of the energy presented to it with a uniformity of speed. These factors may be understood by regarding the capacitor model of Fig. B2. The effect of DA is represented by the capacitor C2, with a series resistance, R_{DA}. The total capacitance seen externally is C = C1+C2. Variation of the relative size of C2 and C1, and R_{DA}, represents the equivalent of real capacitors, with varying degrees of DA. (Note that this model suggests that the externally perceived effects of DA might be controllable to some degree by manipulation of the relative impedances controlling charge and discharge of the real capacitance. Experimental evidence discussed later tends to support this contention.)

In addition to the "bound" electron phenomenon, a secondary factor in the magnitude of recovery voltage values is that of "free" electrons in random movement in the dielectric. These free electrons take finite time to move from the dielectric to the electrode, and therefore contribute to this recovery voltage.

Dielectric absorption becomes a critical factor in circuits which are highly dependent upon speed of response. As the a.c. signal goes to zero (as in a short circuit) the trapped or bound electrons within the dielectric do not follow as fast. These electrons take a finite time to move from the dielectric to the electrode. As capacitors are typically used in audio circuitry, we could translate these defects into loss of accuracy in reproducing the fine inner detail of music, as well as the music's dynamic structure.

It is quite illuminating to consider what effect a phenomenon such as DA will have on an a.c. signal consisting largely of transients (such as audio) might have. For example, when an a.c. voltage is applied, there is a tendency for the dielectric absorption phenomenon to *oppose* this change in polarity.

When music is the a.c. signal, the sonic degradation is one of compression or a restriction of the dynamic range. Also, a loss of detail results, and the sharpness is noticeably dulled. With dielectric types which have high DA, there is a definite "grundge" or hashy distortion added to the signal.

It is quite important to describe the sonic thumbprint that DA contributes to subjective audio. The effects of DF and DA can be perceived differently. DF is primarily a contributor to phase and amplitude modulation; DA reduces or compresses dynamic range. This it does by not returning the energy applied all at once. With signal applied to a capacitor with DA present, the amplitude is reduced by the percent DA. When this energy does get returned (later), it is unrelated to the music and sounds like noise or "garbage" being added; the noise floor is also raised. High-frequency and/or transient signals are audibly compressed the most. Signals that look like tail pulses (a lot of transient music information is of this nature) are blunted or blurred in their sound. "Dulling," "loss of dynamics," "added garbage or hash," and "an inability to hear further into the music" have been subjective terms used to describe the DA effect in capacitors.

All *polar* dielectrics have relatively high DA; the best examples of this pattern are tantalum and aluminum electrolytics, which can have DAs as high as several percent. There is also a general correlation between dielectric constant and DA, with the high K dielectric types being worst in terms of DA (we would like to thank T. Von Kampen of TRW Capacitors for

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making this point to us). For example, regarding Table BI, ceramics and both the Al and Ta oxides have high values for K, and also show correspondingly high values for DA.

Glass and mica dielectics have intermediate values for K, and also intermediate levels of DA. They are nowhere nearly as bad as ceramics or the Al and Ta oxides, but neither are they as good as the films.

Interestingly, it should be noted that there is also a general correlation between low values for DF and low DA, particularly among the film dielectrics. However, a low DF does not always go hand in hand with a low DA, and the glass and mica dielectrics are good examples of this fact. Both of these dielectrics have excellent properties with regard to DF, and also low capacitive variations with regard to frequency and temperature. Unfortunately, however, these excellent properties (which make these types highly desirable for such applications as resonant circuits and equalizers) are *not* realized concurrently with low DA. So, these types are therefore not ultimately as desirable for high-performance audio.

The film dielectrics, which are non-polar, are a different story with regard to DA and DF. All types listed in Table BI have relatively low values (3 or less) for K, and good to excellent performance with regard to DF and DA. Among the film dielectrics there can be found a direct correlation between K and DA, and even the relatively worst film dielectric (polyester) has a DA of less than 1 percent. The best of them, Teflon, has a DA on the order of 0.01 or 0.02 percent, while polypropylene and polystyrene are nearly as good.

Testing Capacitor DA

Measurement of the DA of a capacitor is a rather involved procedure when it is done in accordance with MIL-C-19978D [28]. This standard is widely used and referenced by the capacitor industry, and unless you test a particular type according to the MIL-C-19978D format, you are not likely to get comparable results (even though the relative quality relationship may still hold between different dielectrics).

The procedure outlined in this specification calls for a five-minute capacitor charging time, a five-second discharge, then a one-minute open circuit, after which the recovery voltage is read. The percentage of DA is defined as the ratio of recovery to charging voltages, times 100.

It should be understood that this is quite a stringent test, with regard to both the capacitor and the instrumentation. It takes an excellent dielectric to show small recovery voltages after a full charge, a five-second discharge, and a one-minute open circuit. It also takes some special low-current voltmeter techniques to read this voltage without introducing serious errors.

Table II — Dielectric absorption tests (after MIL-C-19978D).

Test 1

Device	V_o (V)	DA (%)
1) 4.7 μF/50 V Al	0.082	1.4
2) 6.8 μF/35 V Ta	0.170	2.8
3) 4.7 μF/250 V Metalized polyester	0.008	0.13
4) 5 μF/200 V		
Metalized polypropylene	0.001	0.017
Polypropylene foil	0.002	0.033

Test 2

Device	V_o (V)	DA (%)
1) 100 μF/3 V Ta	0.230	3.8
2) 100 μF/20 V Ta	0.095	1.6
3) 50 μF/10 V NP Al	0.065	1
4) μF/3 V Ta series, back to back	0.200	3.3
5) 6 μF/15 V NP Ta	0.148	2.5
6) 220 μF/35 V Al	0.086	1.4

To simulate a MIL-C-19978D type of test, we built the circuit of Fig. 11, which reads the recovered voltage (Vo) via a bench DVM. The capacitor being tested (D.U.T.) is charged to 0.6 V. This level might seem low, but was chosen because it represented a typical peak signal level, particularly for lower level circuits. (A slightly higher charging voltage would make measurements easier and more applicable to higher peak signal voltages, should this be desired.) A MOS FET input amplifier is used, the CA3160BT. This is done because only a few pA of bias current are allowable in the D.U.T. circuit; if the current were higher the D.U.T. voltage would vary, by being charged by this bias current, and not be distinguishable from the true DA-produced voltage. In the circuit here, the 3160 bias current begins to limit the accuracy of readings below about 0.1 percent DA.

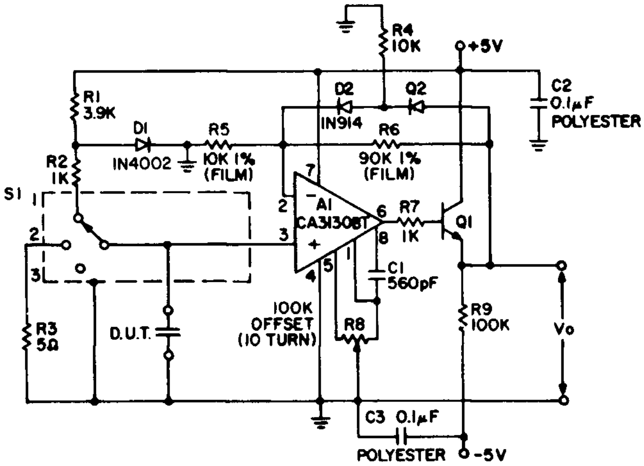
Fig. 11 — Dielectric absorption test circuit.

Test Procedure

1) Charge D.U.T. to 0.6 V for 5 minutes (S1, pos. 1).
2) Discharge D.U.T. for 5 seconds (S1, pos. 2).
3) Open S1 (pos. 3); after 1 minute, read Vo.
4) Calculate DA in percent, as DA (%) = Vo (16.7), where 16.7 is a scalor or constant unique to this test circuit.

Notes

1) Use clip-on heat sink for A1.
2) Trim offset for Vo = 0.0000 V prior to testing.
3) Use high-quality insulation to S1 and D.U.T. socket.
4) Q1, Q2=2N5089.



The test procedure is largely self-explanatory. However, the precautions listed in the notes should be followed, and we recommend no deviations from the parts specified if you want comparable results.

Two series of tests were run with this setup, as outlined in Table II. The first test compares four similar value capacitors with different dielectrics to see the differences in DA. As can be noted, both aluminum and tantalum electrolytics are very poor, with tantalum sample being slightly worse than the aluminum. This might be expected from their relative Ks.

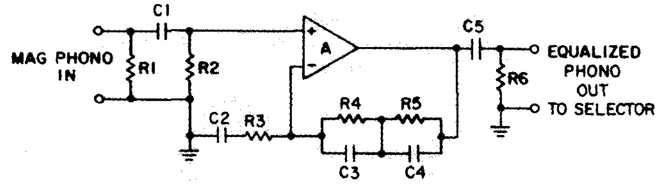
The metalized polyester unit is far better than either electrolytic, measuring less than 0.15 percent. This may be quite good for polyester types, as typical specification data available do not always show comparably low figures. The metalized polypropylene unit is extremely good in terms of DA with a measured figure which compares quite well with the manufacturer's data. The polypropylene foil unit is not quite as good, but is still excellent.

For both units 3 and 4 (or any other comparably low percentage DA type) the particular test conditions chosen are *very* sensitive to millivolt or sub-millivolt errors. This is simply because 0.1 percent of 0.6 V is only 600 μV— a voltage easily lost or obscured without very careful construction and calibration of the setup. Higher charging voltages (say 10 V) would ease this burden considerably, but we do not as yet know that such a test level can always be directly correlated to lower levels.

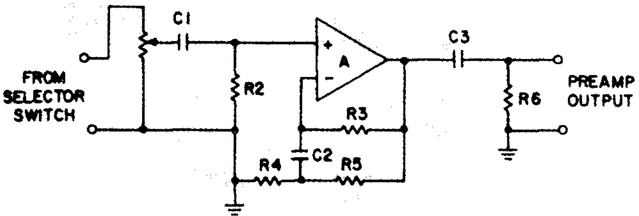
Test 2 examined a number of higher value aluminum and tantalum electrolytics. Comparison of units 1 and 2 shows that a higher voltage rated unit of the same value will tend to have a lower relative DA. This is an interesting point, as this

"Tuning" typically used audio circuits with quality capacitors

Fig. B5 — Capacitor "tune up" in typically used preamp circuits.



A) — Phono section.
B) — High-level section.



Since we would otherwise be endlessly asked "How can I improve my brand X preamp or power amp using the improved capacitor types recommended in this article?" it seems appropriate to make some comments as to the methods which would be typically used. First, readers should understand that we are not equipped to answer individual requests for consultation in these areas. If you cannot translate our general comments into the specific steps appropriate to modify your particular gear, please ask a more technically knowledgeable friend for some help. One should not attempt these changes without some prior experience in electronics and familiarity with the components used. Please be advised that if you choose to do so, you make such changes at your own risk, which is to say we cannot be responsible for any accidental damage you may incur. You should also be aware that the alteration of some equipment may result in invalidating a warranty and may also influence its potential resale value.

Since the minimum number of equipment blocks an audio system can be assembled with is two, preamp and power amp, we will discuss these two items as generally used. The basic ideas can be translated to any audio equipment using capacitors, which of course includes everything.

Figure B5 shows a block diagram of how a typical solid-state preamp is often realized. In the phono section of B5A, it can be noted that the signal path contains six capacitors, *all* of which can potentially degrade the signal's quality. The amplifier circuit is shown generally as a gain block A, which can be an op amp or discrete circuitry, and the comments on optimum capacitor usage apply to *any* active devices used (even those not yet invented!).

C1 is typically used to block d.c. from the cartridge, and is often a small electrolytic in the 1- to 10-μF range. It might better be a film unit such as a 2.2 μF, with a 0.01-μF polystyrene shunt. An interesting point here is that low bias current op-amp inputs (such as FET units like the TL071 or LF356) remove the requirement for C1 altogether, and the amplifier can be directly coupled to the cartridge. This, of course, will not be possible with the classic type of two-transistor topology, due to the inherent bias restrictions.

C2 is typically a large electrolytic, in the range of 10 to 100 μF or more, the large value necessary for extended bass response. This function can be optimized by selecting a low ESR type, using a back-to-back connection, and shunting with a film. The complete composite of Fig. 17B is useful.

C3 and C4 are the RIAA equalization capacitances and are *very* critical to fidelity as well as basic frequency response. If the network values are those appropriate for accuracy of the three RIAA time constants (see S. Lipshitz's article "On RIAA Equalization Networks," *Jour. of the Audio Eng. Soc.*, Vol. 27, No. 6, p. 458, June 1979), C3 and C4 should be realized with film types such as polystyrenes or polypropylenes (best) or at the least, polyesters. It is probably ill-advised to use a ceramic unit for equalization if quality results are to be expected. C5 is a simple output blocking capacitor and can be a composite such as Fig. 17B for best wideband response (or a large-value film type if the input impedance of the next stage is high).

The above comments can also be adapted to address tube-type phono sections, such as the Dynaco PAS series. In such cases, cathode bypasses (when used) are analogous to C2 and can be low ESR electrolytics, with film shunts. Interstage coupling caps should be the best-quality films, such as polypropylenes or polystyrenes, of appropriate voltage ratings. The output cap C6 cannot normally be an electrolytic because of d.c. leakage caused by the high bias voltages, so a composite film type such as several 5- to 10-μF units, shunted by a small polypropylene or polystyrene, is useful. This will be similar to Fig. 17A, but less the electrolytic. Be sure to use an adequate voltage rating and consider surges.

A point worth making is that it may be useful to minimize the grid resistances in tube circuits, while *increasing* coupling capacitance. This will tend to minimize the DA effects, by loading the capacitor as generally described with 17C. This idea also applies to the output capacitors used with cathode followers as well.

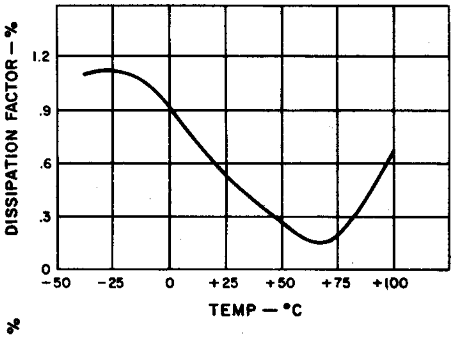
The high level preamp section of Fig B5B is typical of many modern solid-state preamps. C1 and C2 block the d.c. levels associated with the active devices used. If electrolytics are used, they should be low ESR types, with film shunts.

Depending upon the actual circuitry employed, C1 or C2 (or both) may even possibly be eliminated. For example, an LF357 op amp is often seen used for this amplification function, in which case its very low bias currents eliminate the need for C1 and C2, that is they can be jumpered out. Any residual offset of the IC used will still be blocked by C3, the output coupling cap. C3 would be selected, as was true for same consideration for selection criteria is also true with regard to DF. It means that wherever possible, if you must use an electrolytic, *use the highest practical voltage rating.* This applies to either aluminum or tantalum units. Units like number 1 should be avoided at all costs!

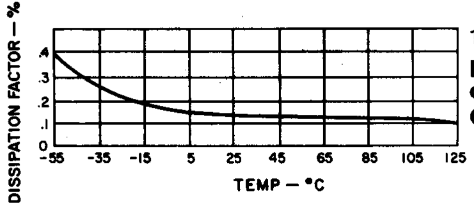
Unit three is a 50-μF non-polar aluminum electrolytic of a type often seen in solid-state audio circuits. As can be noted it has a somewhat lower DA. Apparently, a back-to-back connection tends to reduce the DA of a single unit. For example, unit 4, actually a series pair of two units like number 1, shows less DA than a single. This tends to say that non-polar units or non-polar connected conventional electrolytics will be better in DA relative to a conventional polar cap. However, this difference is largely academic we feel, since if you want really high-quality sound, you cannot tolerate more than a small fraction of a percent DA. Obviously this rules out all but the best of the film dielectrics. Unit 6 is an example of one of the better quality aluminum electrolytics (see also Fig. 7).

While studying the DA problem in tantalum and aluminum electrolytics, we also bench-tested a large number of various units in a much simpler, unbuffered test setup. The basic procedure was to charge a cap to 5 V for 10 seconds, discharge it (through a 1K) for 10 seconds, then open circuit it, and read the recovery voltage after 30 seconds. With this technique we could grade the various units into relative DA categories. The best would read less than 5 mV (or 0.1 per-

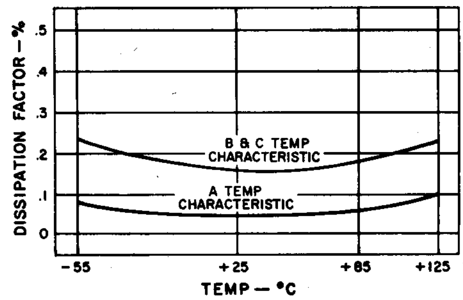
Fig. 12 — Dissipation factor vs. temperature, various dielectrics.



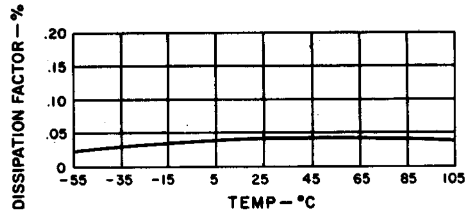
12A — Metalized polyester, courtesy Seacor, Inc.



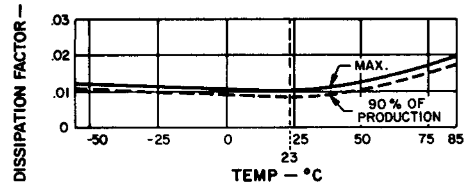
12B — Metalized polycarbonate, courtesy Union Carbide.



12C — Parylene (characteristics A,B, and C), courtesy Union Carbide.



12D — Metalized polypropylene, courtesy TRW.



12E — Polystyrene, courtesy PFC, Inc.

C6 in the phono section (a non-polar composite, such as Fig. 17B).

Not shown here are tone control functions which, if used, would couple into the feedback path of the amplifier. Comments similar to those on the RIAA equalization capacitors apply to tone control capacitors as well. Since relatively high values will often be employed, polypropylenes will likely be effective here.

Power Amplifiers

In solid-state power amplifiers as are typically used today, the capacitor numbers are reduced due to the more simple function required.

A typical power amp signal path is as shown in Fig. B6. The amplifier circuit itself is direct coupled to the speaker to eliminate a huge blocking capacitor and to simplify biasing. C1 serves as an input coupling capacitor of 1 to 10μF in value, while C2 may be 100 to 1000 μF. Both of these capacitors should be optimized similar to the method described for the preamp. C2 usually must be an electrolytic, but should be an optimized composite type. In some cases, depending upon the value of R2, C1 might possibly be a film (only) unit, but with typical input impedances of 10-50K, it will usually need to be 10μF or more for adequate LF response.

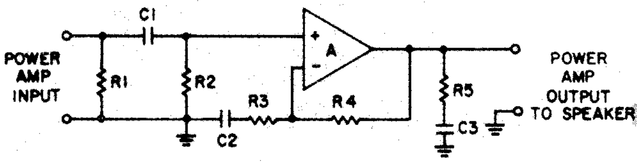


Fig. B6 — Capacitor "tune up" in typically used power amplifier circuits.

C3 and R5 form an output compensation network for the power devices, and C3 may in some cases be a ceramic disc. An equivalent value film unit is likely to be profitable here as a substitution.

In summarizing these comments, it is perhaps important to underscore the point that capacitors as used in the audio signal path can be optimized mostly independent of the circuit topology or devices used. This is simply to say that while our generalized guidelines have addressed more popular examples of circuit types, good-quality capacitors go well in other circuits also; crossover networks are an example of passive circuits, an equalizer could be a good example of active ones. Both functions have performance basic to capacitors. In making such changes as outlined above, a logical approach is to upgrade all the poorer quality capacitors first, for example the ceramic capacitors if used, and in particular those in the signal path.

Table III—Capacitor dielectric comparison.

Dielectric	Glass	Mica	Polyester	Metalized Polyester	Polycarbonate	Metalized Polycarbonate	Parylene	Polypropylene	Metalized Polypropylene	Polystyrene	Teflon
Parameter/ Characteristics											
DF, %	0.1	0.1	0.3-1.0	0.3-1.0	0.1-0.3	0.1-0.3	0.1	0.01-0.03	0.03-0.1	0.01-0.03	0.01-0.03
DA, %	≅5	≅5	0.3-1.0	0.3-1.0	0.1-0.3	0.1-0.3	<0.1	<0.1	<0.1	<0.1	<0.1
IR, 25°C	High	Med./High	Med/High	Med/High	High	High	Very High	Very High	High	Very High	Very High
ΔDF/freq.	Very Low	Very Low	Medium	Medium	Medium	Low	Low	Very Low	Very Low	Very Low	Very Low
ΔC/freq.	Very Low	Very Low	Medium	Med/High	Medium	Low	Low	Very Low	Very Low	Very Low	Very Low
ΔDF/temp.	Low	Low	Med/High	Med/High	Medium	Medium	Low	Very Low	Very Low	Very Low	Very Low
ΔC/temp.	Low	Low	High, Non-Linear		Med/Low	Med/Low	Low, Linear	Med/Low	Med/Low	Low, Linear	Low, linear
Stability	Excellent	Excellent	Poor	Poor	Good	Good	Excellent	Excellent	Excellent	Excellent	Excellent
Tolerances Available, %	1-10	1-10	5-20	5-20	1-20	1-20	0.5-10	1-20	1-20	0.5-10	0.5-10
Range of Values	1-10,000 pF	1-10,000 pF	0.001-10 µ F	0.1-50 µ F	0.001-5 µ F	0.01-50 µ F	0.001-1 µ F	0.001-5 µ F	0.01-50 µ F	10 pF-5 µ F	0.001-5 µ F
Relative Size Of Higher Values	Large	Large	Medium	Small	Medium	Small	Large	Large	Large/Med	Large	Large
Relative Cost	High	Medium	Lowest	Low	Medium	Med/High	High	High	High	High/Low	Highest

Notes: The outstanding performers among those listed are in the shaded areas. Highest performance is obtained from polycarbonate and those listed to its right.

cent) for this test, the worst over 20 mV (0.4 percent). Obviously, this simple test does not compare *directly* with the Fig. 11 test results, but it still can grade units *relatively*. And we would invariably find that lower DA units would sound better in an audio circuit. However, the clincher is that no electrolytic known to us, aluminum or tantalum, sounds like a wire in even so simple an application as a coupling cap. Once you try some of these tests for yourself in a good audio system, one free of masking, you may begin to abhor capacitors and seek means to eliminate them where at all possible. And, indeed, where it is possible this is perhaps the most effective method of eliminating these distortions. However, it is not always practical to eliminate capacitors, therefore ways to minimize their degrading of the signal are valuable and will be discussed.

Performance Comparison of Various Dielectrics

At this point we are ready to survey the various capacitor dielectrics with regard to their parameters relevant to audio. This we will do for all dielectrics mentioned thus far, with the exception of ceramic and the electrolytics, since for the highest-quality audio these dielectrics should not be used if at all possible. Where an electrolytic type is a must because of a time constant or filter criteria, some qualified recommendations can be made for aluminum types which make them quite useful; this will be covered at the end.

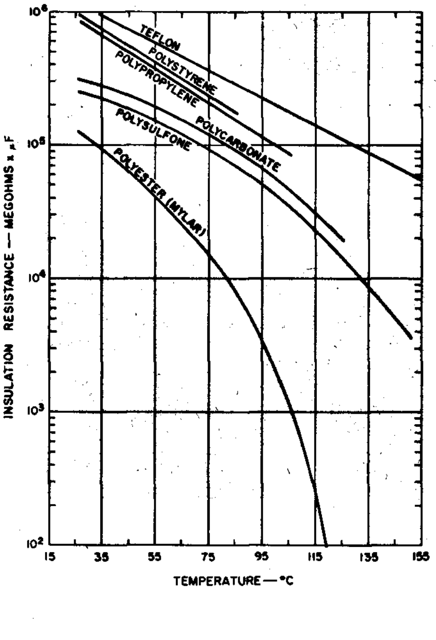


Fig. 13 — Insulation resistance vs. temperature, various dielectrics, courtesy F-Dyne Electronics.

Table III is a summary of the various dielectrics most useful for consideration, with typical specifications listed for each major performance parameter (left column). These specs are really *ranges,* as are typically available from average suppliers, and are not meant to represent a given type or series in specific terms. They are, however, broadly representative of what is generally available. For a given electrical parameter, the dielectric type (or types) which are outstanding are noted by shaded areas.

While Table III summarizes comparative data in discrete form, Figs. 12 through 16 illustrate graphically a selection of these different characteristics.

Dissipation factor of the various dielectrics is usually given at 25° C, but there is always some temperature dependence. Figure 12 shows that polyester is the worst of the films in this regard, but the better ones show very flat DF change with temperature.

Insulation resistance (Rp) has not been strongly addressed in this discussion, because it is not often a critical parameter in audio (at least from a *distortion* point of view). Figure 13 is an excellent summary of how the dielectrics compare for Rp. As can be noted, all show decreases in Rp with increasing temperature.

While DF is an important parameter for capacitors, it is also important that DF remain low for different frequencies. However, in many dielectrics there is substantial frequency dependence exhibited by DF, as shown in Fig. 14. The better dielectrics in this regard are parylene, polystyrene, polypropylene, and Teflon (not shown). A related parameter is capacitance variation with frequency, shown in Fig. 15. Again, parylene, polystyrene, polypropylene, and Teflon (not shown) are best in this regard. These variations are due to the variation in K versus frequency for the different materials.

Film capacitors are generally quite good with regard to capacitance variation with temperature, as is shown by Fig. 16. The better a capacitor in this regard, the more stable a tuned circuit based on it will be when undergoing changes in temperature. Of the films, polyester is the poorest, followed by polycarbonate. The lowest TC is exhibited by polystyrene.

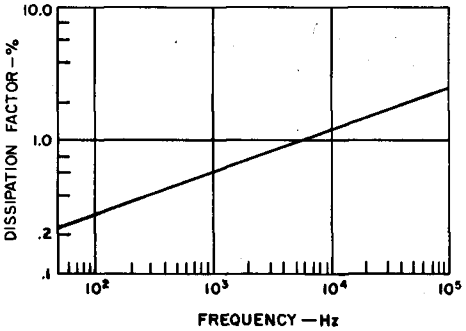
One should view TC minimization with some caution with regard to audio use, as in certain dielectrics optimization techniques which minimize TC *raise* DA. A good example of this factor is the characteristic "B & C" parylene dielectrics, which have nominally 0 TCs, but a DA several times that of characteristic A parylene, which has a 0.1 percent DA but a TC of -200 ppM/°C. For audio use, the A characteristic would be preferred, since you can't "compensate" for zero DA, whereas for TC you can (where necessary). One should, incidentally, check for a possible compromise in DA for any "0 TC" capacitor; they often occur, and we do not mean to imply the DA compromise is peculiar to parylene.

The remaining parameters of Table III are not illustrated by graphical data, but also deserve comment. For example, the available tolerances and range of values can strongly influence the selection of a capacitor, aside from the electrical specs. Generally, very tight tolerances are available in most films, to below 1 percent on special order. The range of values is a difficulty, though, particularly when large sizes are needed.

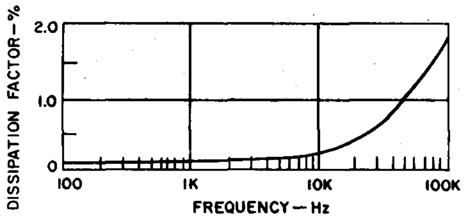
Most film capacitors are readily available, many off the shelf, in sizes up to 1 µF. Above 1 µF they become very hard to obtain, and almost non-existent for some dielectrics, such as polystyrene.

In the larger values, any film capacitor will be quite large, relatively speaking. So, to make use of the excellent electrical properties and ultimate sound quality, we must be prepared to accommodate a largish capacitor when 1 µF or more is needed. A factor which can help minimize the final size is the metalized dielectric. Most film capacitors (except polystyrene) are available in metalized types, as opposed to the foil-wound variety. The metalized dielectric uses a very thin metalized layer for the electrode and thus conserves space. A danger area of metalized caps is the lead attachment, which

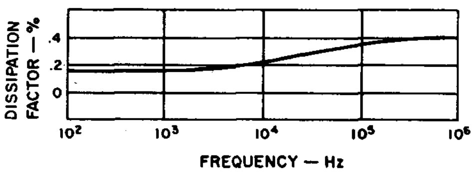
Fig. 14 — Dissipation factor vs. frequency, various dielectrics.



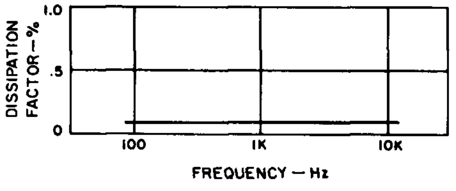
14 A — Metalized polyester, courtesy Seacor, Inc.



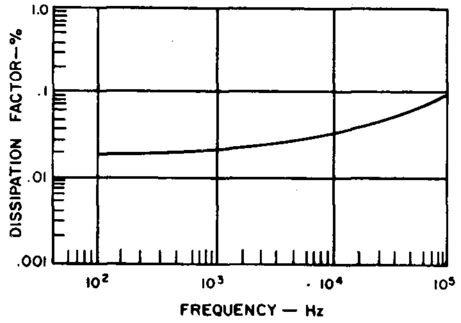
14B — Metalized polycarbonate, courtesy Union Carbide.



14C — Parylene, courtesy Union Carbide.

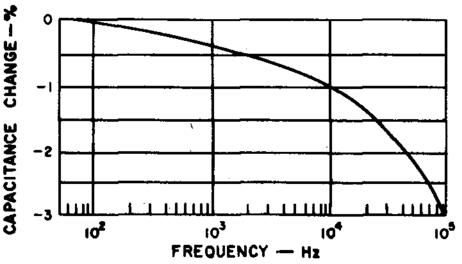


14D — Polystyrene, courtesy Midwec.

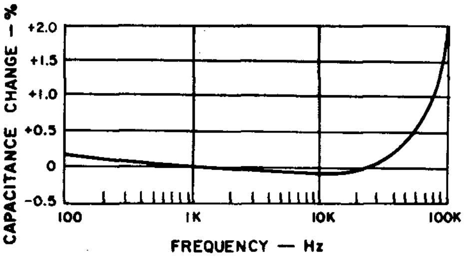


14E — Metalized polypropylene, courtesy Seacor, Inc.

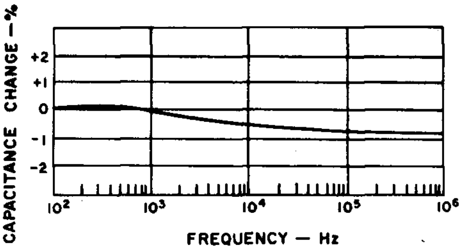
Fig. 15 — Capacitance vs. frequency, various dielectrics.



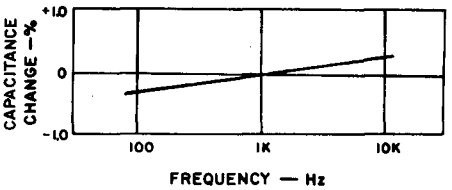
15A — Metalized polyester, courtesy Seacor, Inc.



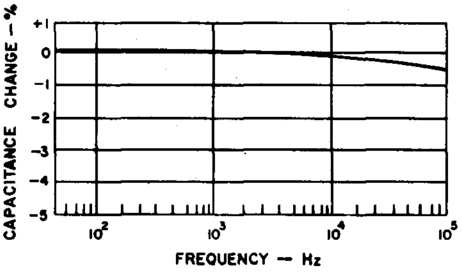
15B — Metalized polycarbonate, courtesy Union Carbide.



15C — Parylene, courtesy Union Carbide.



15D — Poly-styrene, courtesy Midwec.

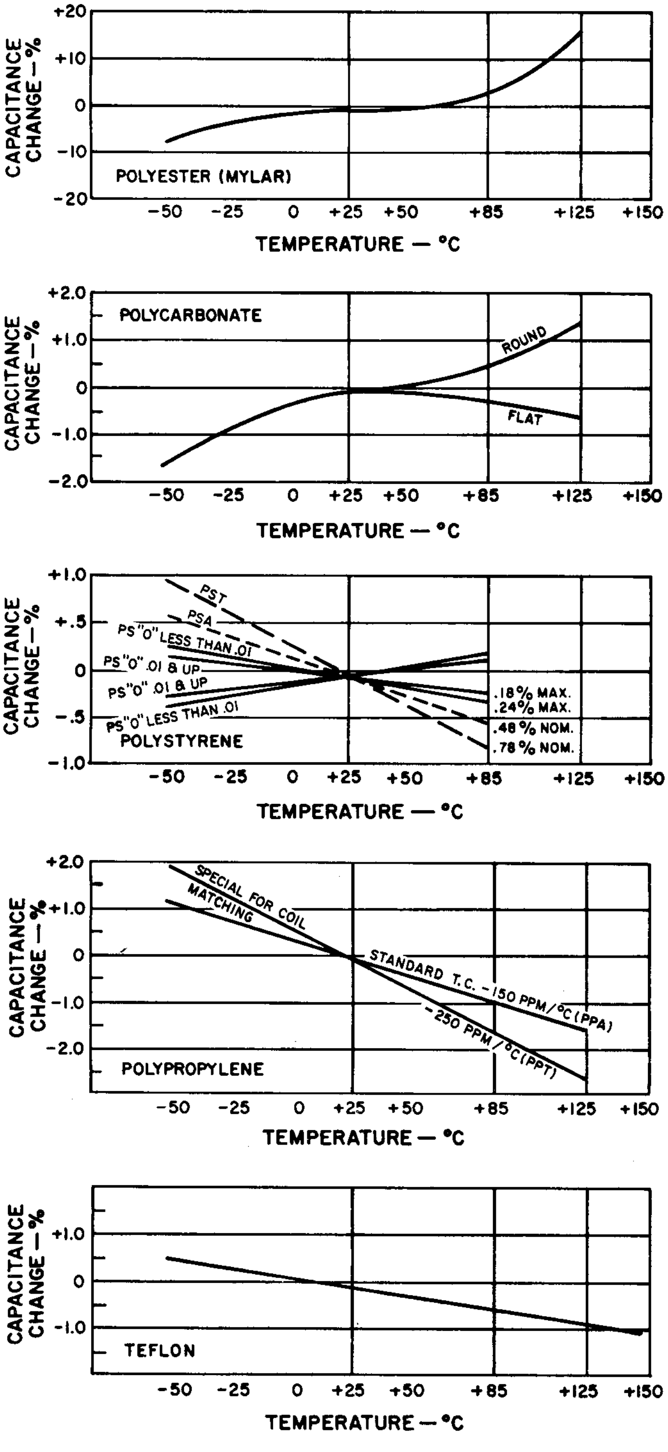


15E — Metalized polypropylene, courtesy Seacor, Inc.

is tricky. If it is not done adequately, a high (or worse, intermittent) Rs can occur. As a result, metalized caps will usually show somewhat higher levels of DF than a foil unit. However, they can still be of excellent quality, and the best advice here is simply to thoroughly check a given type before use.

The final "parameter" of Table III is the relative cost of the various dielectrics. A statement that is unquestionably true here is that you do get what you pay for — the "super dielectric" films will cost you more money for a given value. For example, a small-quantity of price for a 5-μF polypropylene will be on the order of $8.00, whereas a 5-μF aluminum electrolytic will cost about 20 cents.

Fig. 16 — Capacitance vs. temperature, various dielectrics, courtesy F-Dyne Electronics.



This kind of comparison is a sobering one, and the authors would be foolish to think it will not scare many off. However, we should not attempt to kid ourselves that "cheaper is better," as it simply is not *if you want the best quality.* As time progresses and more become aware of the advantages of these excellent capacitors, we hope volume usage will help their price reduction. Where it is inevitable that a cap be used, we should be prepared to pay more for the quality unit necessary. If this seems like a harsh, unrelenting statement, the final summation should give you better perspective for why we feel the true audiophile must be prepared to bite the bullet with regard to capacitors.

Summary

If we have done a good job on this article, a glance at Table III and considerations of the distortion discussions should allow the reader to easily select a good capacitor. For reasons of practicality and other rationalizations, there are the inevitable trade-offs. However, here is the way we see it.

Up to values of about 10,000 pF, polystyrene is the best all-around choice, as it has reasonable size and is readily available in many sizes, with tight tolerances available. Above 10,000 pF, and up to 0.1 μF, it still can be used but is much harder to obtain.

Above, 0.1-μF polypropylene (or metalized polypropylene) is the dielectric of choice, as it has nearly the same relative qualities of DF and DA as polystyrene. Tight tolerances are available (but will be special order), and you can get capacitors up to 10 μF or more.

Teflon may well be the best dielectric of all for audio, but is produced in limited volume and is generally not practical. Parylene is an excellent dielectric also, but limited in electrical size (1 μF or less) and not widely available. Polycarbonate is perhaps the next best all-around choice behind these and is generally available in a wide range of values.

Polyester types are the most widely available for all the films and are already widely used in many audio circuits. There is no doubt that this is due to the generally low cost of these capacitors, but convenience and low cost should not be primary selection criteria to a critical audiophile. *Polyester capacitors can be readily heard in good systems,* with defects similar to those described for tantalum but, of course, reduced in magnitude.

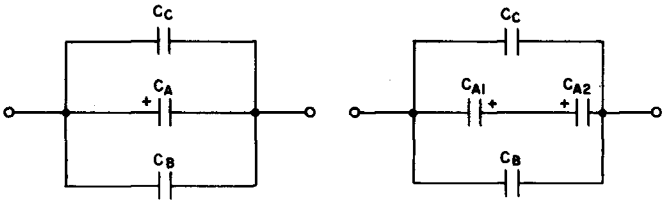
In our opinion, polyester capacitors should be very carefully applied in an audiophile's system, and any system using them in the signal path may potentially benefit by the substitution of (equal value, voltage and tolerance) polypropylenes or polycarbonates. We have done this ourselves on different items of equipment, tube and transistor, with always the same result — a stunning upgrade in sound quality. Further, we have observed others do similar things, either completely independently or at our direction, with the same type of results.

It is not surprising to us that this type of reaction occurs, since one *single* polyester or electrolytic (or other polar type) can be heard, and a typical update to an old preamp or amp might replace a dozen or more! If you did nothing more than take an old (stock) Dynaco PAS preamp and change the capacitors to polypropylenes, you can be literally astounded at the results. All of this is available at moderate cost to anyone who can solder, and you need not send your amp off to the specialty audio shop either! (Capacitor sources are listed in the appendices.)

More Specific Recommendations

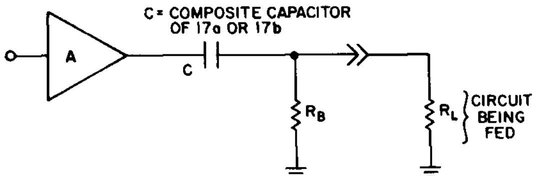
Beyond the above described substitutions (which are basically of a one-to-one variety), we'd also like to show how to use aluminum electrolytics effectively, so as to minimize their sound degradation.

Fig. 17 — Using aluminum electrolytics with film shunts.



A) — Defined polarity. **B) — Arbitrary polarity.**

C_A=330 μF/50 V or 220 μF/35 V aluminum electrolytic (Panasonic), see text.
C_B=5 μF/200 V 20 percent polypropylene (TRW X363UW, Seacor 125 or Electro-Cube W950)
or 4.7 μF/250 V 10 percent metalized polyester (Transcap).
C_C= 0.47 μF polypropylene (Transcap).



C) — Optimizing loading.

Notes
1) R_L is net input resistance of next stage load.
2) R_B is local bleeder or shunt resistance, adjusted to minimize leakage and load impedance.

In Fig. 17 are shown two types of connections which might need to employ higher capacity value, 100 μF or more. The trick is to select a low Rs electrolytic, such as one of the two specifically mentioned for C_A (see Fig. 7 again). Either of them may be considered overkill from a time constant standpoint, as 50 μF may be all that is necessary. But, the high value and voltage listed will minimize Rs, and the relatively high voltage also minimizes DA. At the higher frequencies where the electrolytic becomes inductive, the film shunt carries the signal and minimizes the audible degradation.

Figure 17A is used where the capacitor will always see a defined polarity and can thus be correctly polarized. Figure 17B uses two of the specified types to form a low Rs, low DA non-polar electrolytic. For the film cap C_B, use a polypropylene if at all possible; if not, use a polyester. In either case, a smaller polypropylene shunt C_c helps even further. Optionally, an even smaller polypropylene or polystyrene (in addition) in the range 0.01 to 0.1 μF may be useful in some circumstances.

Figure 17C illustrates how the composite capacitors of 17A or 17B would be best applied as a coupling capacitor (d.c. blocking) within an actual circuit typical of such use. The load resistance which the capacitor must feed into is comprised of R_L (which may be the input resistance of, say, a power amp) plus the local bleeder resistance, R_B. The net load resistance will be R_B and R_L, added in parallel fashion.

For two reasons, this impedance should be minimized. First, and most obvious, a low impedance is necessary to bleed off any d.c. leakage of the large electrolytics (which can for certain conditions be on the order of 1 μA or more). Selecting a load resistance of 10K or less will, for example, reduce the leakage-induced d.c. offset at the output to 10 mV or less for a leakage of 1 μA.

The second reason is to minimize the audible effects of whatever DA may exist in the capacitors actually used for C_A and C_B. A low load (and source) resistance presented to a coupling capacitor tends to minimize sonic deterioration.

In a single blind listening test using such various capacitor dielectric types as mica, polyester, tantalum, and polypropylene, it was found that a simple coupling capacitor can degrade sound quality quite strongly if the load impedance is high. In this test R_L was 50K and R_B was varied from infinity down to 1K, and the source impedance for C was 1K.

A tantalum capacitor (Table II, Test 2, sample 1) feeding the 50K load distorted the sound very strongly, with severe hashy sound and loss of detail. However, the same capacitor under 1K load conditions improved in sound quality appreciably (it did not become transparent, but it did improve). The other dielectrics mentioned followed similar patterns: Poor performance into the higher impedance, improvement in clarity with the lower impedance. However, even the best dielectric on hand in a usable size (5-μF polypropylenes) sounded much better into a lower impedance load.

Of course, one cannot lower load resistance arbitrarily from this general viewpoint, as low-frequency response will suffer sooner or later. But the evidence of these tests and also the general pattern of bench tests for DA (which show reduced recovery voltage for low R_L) indicate that it is worthwhile to lower load resistance (within allowable bounds) to minimize DA effects. This factor can very logically explain points of disagreement on whether or not capacitors really do sound bad, as it tends to say they sound bad (within a given dielectric type) to the degree that the DA is allowed to manifest itself. Minimizing load resistance tends to optimize the circuit in terms of suppressing the DA. General procedural guidelines for "tuning" typical audio circuits with capacitor improvements are described in the sidebar.

Interestingly enough, there is very strong indication to us that in many situations the *power supply electrolytics* also need the same careful attention as do signal path units. The general rule of selection is the same: Use a low Rs unit and bypass it with a film (such as in Fig. 17A). While the degree to which this problem may be apparent is surely related to the circuit topology, it is certainly worth consideration in all instances of amplifier circuits, tubes or transistors.

For those readers unfamiliar with the "sound" of capacitors or this general subject area, much of the above might sound like mad ravings to some degree or another. We'd like to leave some implication of what we feel the magnitude of this problem really is.

After we had gone through all of the above exercises and exorcised our complete system of unnecessary or poor-quality capacitors, the total degree of improvement was greater than any other improvement measure ever employed. With no capacitors (or *clean* capacitors), you begin to hear the music in a new light, one which is much more like the sound of the real thing. In fact, you will be able to differentiate subtleties you never before even realized *existed*. Your system simply becomes a new system, in terms of resolution and definition. The "solid-state sound" we've all heard discussed may be largely due to lousy electrolytics — which by and large never got used in the signal path in the tube days.

Acknowledgements

The authors would like to acknowledge private discussions with John Curl and J. Peter Moncrieff on the subject of capacitors in audio circuits and how they might influence subjective testing. W.J. would like to acknowledge the contributions of Dave White on capacitor problems, and thank him for participating in listening tests. We also found the discussions by Dow [32] to be particularly useful in relating the phenomenon of DA to audio circuit behavior.

In addition, we would like to thank those manufacturers who have allowed use of their data in this article. Technical information as well as price and delivery data can be obtained by writing manufacturers direct (see appendix), mentioning this article.

Appendix I — Capacitor manufacturer index.

Code for types, A= aluminum electrolytic; F= film, and T= tantalum electrolytic.

Company	Types
Custom Electronics, Inc. Browne St. Oneonta, N.Y. 13820 607/432-3880	F
Elpac Capacitors 3131 S. Standard Ave. Santa Ana, Calif. 92705 714/979-4440	F
Electro-Cube, Inc. 1710 So. Del Mar Ave. San Gabriel, Calif. 91776 213/283-0511	F
F-Dyne Electronics 449 Howard Ave. Bridgeport, Conn. 06605	F
Mallory Capacitor Co. 4760 Kentucky Ave. Indianapolis, Ind. 46241 317/856-3731	A,F,T
Mepco/Electra Columbia Rd. Morristown, N.J. 07960 201/539-2000	A,F
Mial 165 Franklin Ave. Nutley, N.J. 07110 201/667-1600	F
Midwec Box 417 Scotts Bluff, Neb. 69361 308/632-4127	F
Nichicon (America) Corp. 6435 No. Proesel Ave. Chicago, Ill. 60645 312/679-6530	A,F
Panasonic Electronic Components Div. One Panasonic Way Secaucus, N.J. 07094 201/348-7000	A,F,T
Precision Film Capacitors 100 Community Drive Great Neck, N.Y. 11022 516/487-9320	F
Sangamo Capacitors Box 128 Pickens, S.C. 29671 803/878-6311	A
Seacor, Inc. 123 Woodland Ave. Westwood, N.J. 07675 201/666-5600	F
Siemens Corp. 186 Wood Ave. Iselin, N.J. 08830	A,F,T
Sprague Electric Co. 449 Marshall St. North Adams, Mass. 01247 413/664-4411	A,F,T
Transcap Capacitors Box 2536 El Cajon, Calif. 92021 714/449-6650	F
TRW Capacitors 301 West "O" St. Ogallala, Neb. 69153 308/284-3611	F
Union Carbide/Kemet Box 5928 Greenville, S.C. 29606 803/963-6300	F,T
West-Cap Capacitors 2201 E. Elvira Rd. Tucson, Ariz. 85706 602/294-2646	F

Appendix II — Distributors with shelf stock of audio grade capacitors.

Digi-Key
P.O. Box 677
Thief River Falls, Minn. 56701
800/346-5144

Hanifin Electronics
P.O. Box 188
Bridgeport, Penna. 19405
800/523-0334

Mouser Electronics
11511 Woodside Ave.
Lakeside, Calif. 92040
714/449-2222

National Capacitor Supply
11731 Markon Drive
Garden Grove, Calif. 92641
800/854-2451

Old Colony Sound
P.O. Box 243
Peterborough, N.H. 03458