

Getting rid of hook: the hidden pc-board capacitance

Those previously unexplained discrepancies in circuitry output
can be traced and measured and then designed out

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□ Lurking beneath the apparently stable surface of many printed-circuit boards is a mysterious and relatively unknown phenomenon: hook. What this seemingly capricious and thoroughly confusing effect can do to an electronic circuit is a design tragedy: apparently well-designed high-impedance circuitry performs below the specifications that both theory and experience firmly establish as reasonable claims. Even perfectly designed and assembled test instruments read incorrectly.

Hook may be defined as the effect on a signal's voltage caused by a change in pc-board capacitance with frequency. Board capacitance is created between pc-board conductors separated by dielectric material. It can change the response time of a square wave and can bring about erroneous responses at certain frequencies of sine waves.

In an effort to lay bare the mysteries of hook, Tektronix and Norplex undertook investigations of the phenomenon [*Electronics*, July 6, p. 41]. The results tell a great deal about the causes and the effects of this hidden menace. They also make it imperative that designers no longer ignore the electrical parameters of the laminates onto which their brainchildren's components and printed wiring go.

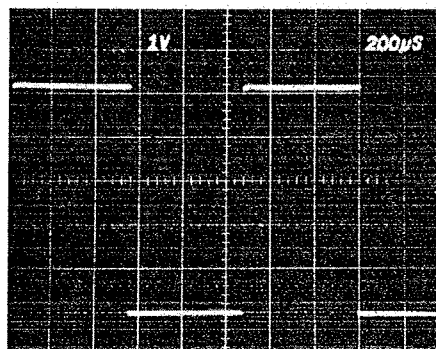
To that end, this article will discuss the nature of hook and will look at its causes and methods of measurement. It will show how precise measurements are clearing the way to understanding the variables that bring about hook, and it will suggest what both the users and the makers of the laminates can do.

Variance with frequency

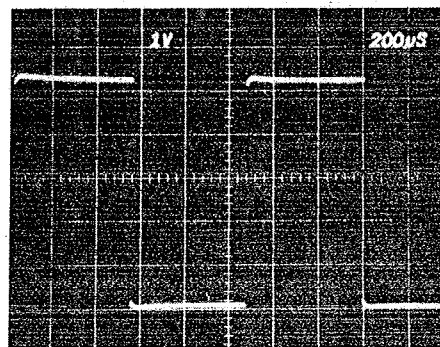
The investigations have discovered that the board capacitance that brings about hook varies inversely with frequency, up to about 10 kilohertz. From 10 to 100 kHz, it appears to be relatively flat.

Apparently, above certain frequencies the molecular orientation and dipole-to-dipole alignment of the polymers used for pc boards do not change rapidly enough to cause variations in board capacitance. Below these

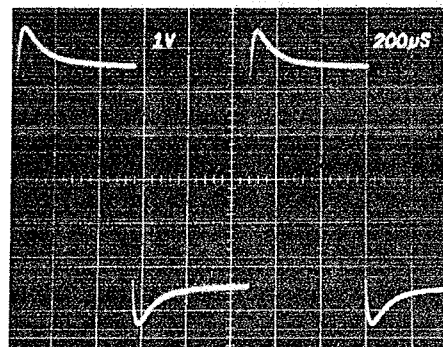
1. Hook. These waveforms are at the outputs of three identical high-impedance networks, each mounted on its own pc board. One board (a) has low hook, a second (b) has moderate hook, and the third (c) has a large amount of hook.



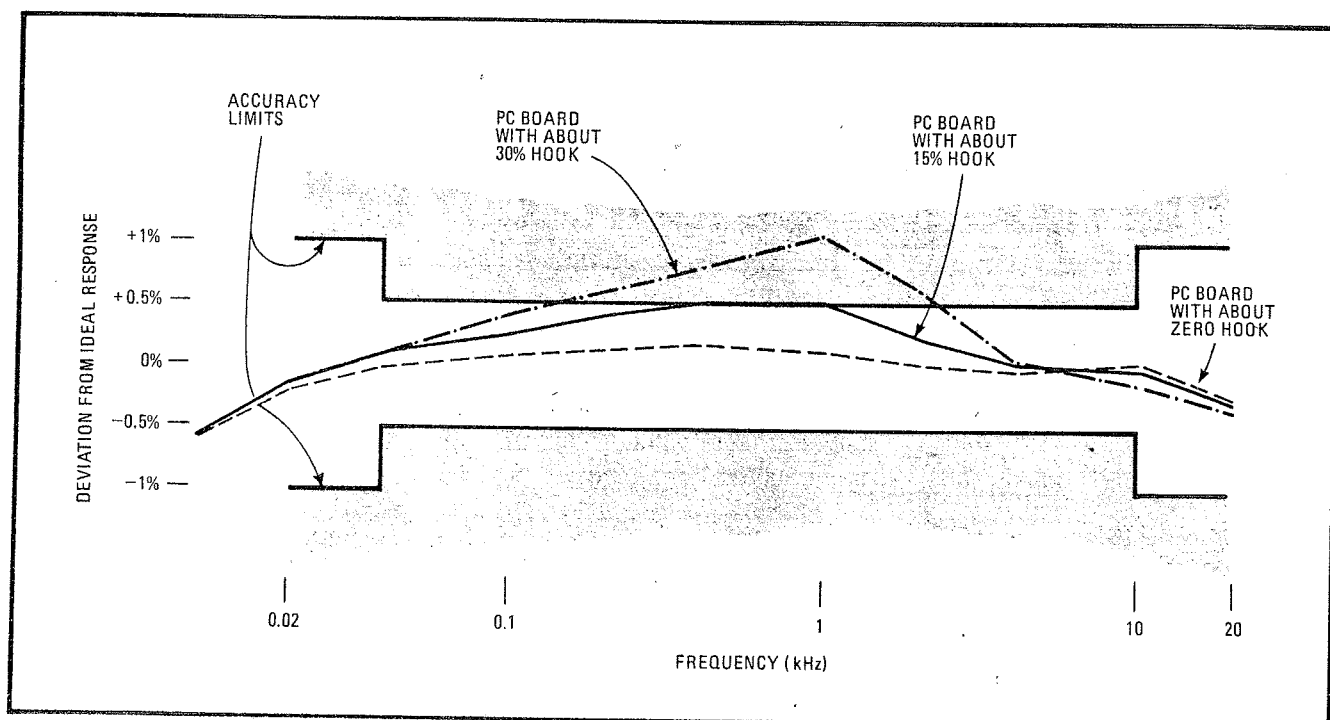
(a) LOW HOOK



(b) MODERATE HOOK



(c) LARGE AMOUNT OF HOOK



2. Digital deviation. Digital multimeters are particularly vulnerable to large and medium values of hook, which can result in out-of-tolerance deviation measurements. This plot was taken for an ac voltmeter, using 100:1 high-impedance attenuators.

frequencies, the various molecular components orient themselves at differing time constants. Hence, capacitance varies with frequency.

The variable capacitance compounds the circuit designer's difficulties, for example, in the construction of high-impedance attenuators for oscilloscopes and digital multimeters. These attenuators are networks of resistors and capacitors connected to provide a diminished output proportional to the input signal's amplitude for all frequencies within the bandwidth of the instrument. The most frequently used method of interconnecting the components is with a pc board. Hook prevents the attenuator from giving outputs proportional to the inputs for the frequencies of interest.

Hook in scopes and DMMs

Tektronix assigns "hook" to describe a particular type of distortion seen on a waveform displayed on an oscilloscope. Figure 1a shows the proper response of a scope's attenuator to an input square wave. The leading edge should be square, with no overshoot and no undershoot.

The waveforms of Figs. 1b and 1c come from attenuators on printed-circuit boards with a moderate and a large amount of hook, respectively, and leading edges are no longer square. The deviation from a square wave is measured as a percentage of the latter's full amplitude, with an acceptable level of distortion being less than 0.5% to 1.5%, depending on the oscilloscope's performance requirements.

In digital multimeters, hook raises its ugly head in the ac voltmeter section. Attenuators in these meters generally use higher-value resistors than those of an oscilloscope, making the circuits even more susceptible to the high impedance of the board capacitance. The ac voltmeter function of a DMM is most accurate when measur-

ing undistorted sine waves. Its measurement accuracy is usually specified as $\pm X\%$ of the reading within a given bandwidth. Hook distortion for this function is best viewed by plotting a graph of the deviation of the displayed reading from the true input-signal amplitude.

Effects on accuracy

The effects of various amounts of hook on three DMMs of the same type are shown in Fig. 2. An ideal response curve plotted in this graph would be a straight line following the 0% deviation axis. With two of the DMMs, accuracy limits were exceeded between 700 hertz and 1 kHz. Hook in the pc boards renders these two instruments unsalable.

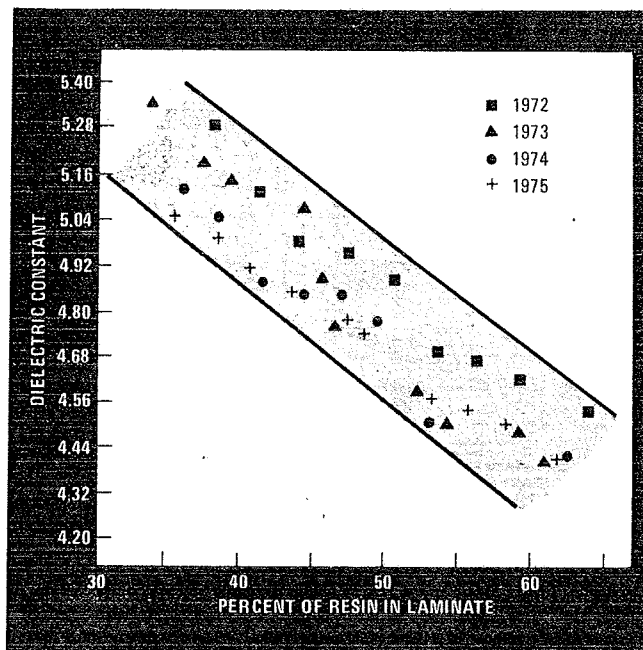
Hook can affect other circuits as well. In general, it will affect those in which all of the following occur:

- Resistors have high values (between 500 kilohms and 1 megohm).
- Board capacitance is an appreciable portion of the total circuit capacitance.
- Frequencies of interest are below 10 kHz.
- Required accuracy is better than 2% to 5%.

For such circuits, a quick way to gauge the effect of hook is to see if the board capacitance conducts an appreciable part of the signal current at frequencies below the 1-to-10-kHz range. If so, look for improper circuit operation with frequency variation.

Hook is not restricted to pc-board materials. It has been observed in dielectric materials used in some types of switches and capacitors, as well as in the junction capacitance and reverse-biased diodes and in metal-oxide-semiconductor capacitors. The investigations leading to this article, however, have been limited to pc-board capacitance.

Anything that affects board capacitance will affect



3. Dielectric constant. The dielectric constant decreases as the percentage of resin in the laminate increases. This data is from more than 600 samples of Norplex FR-4 laminates produced from 1972 to 1975, with resin contents varying from 30% to 75%.

hook. Thus the board's dielectric constant and its dissipation factor were early objects of the investigation into hook. Inquiry centered on the effects of such factors as resin content upon these two parameters.

Previous work showed that the dielectric constant (ϵ) and the dissipation factor (ϵ') of FR-4 (flame-resistant epoxy-glass) laminates to be proportional to resin content; ϵ decreases while ϵ' increases with increasing resin content. With F_r = fraction of retained resin in a given laminate, then:

$$\epsilon = 6.2 - 3 F_r$$

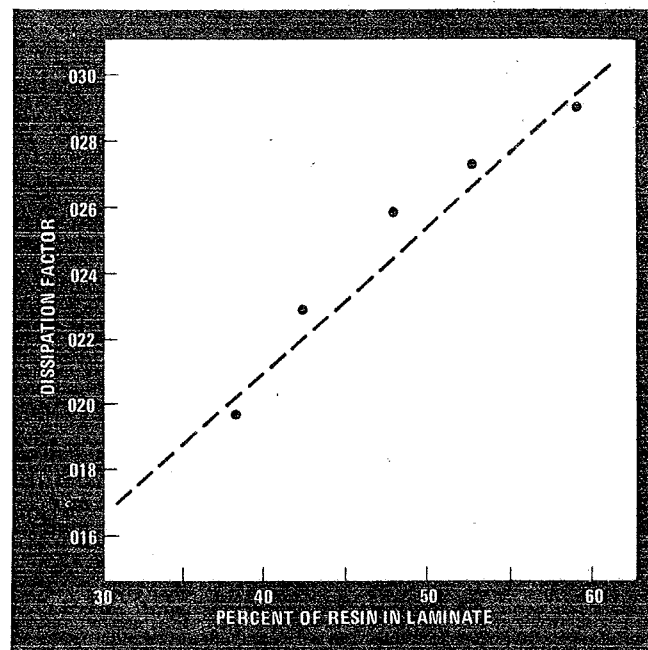
$$\epsilon' = 0.0037 + 0.0435 F_r$$

The constants in these equations apply to Norplex FR-4 laminates produced during 1972-75 and having resin contents varying from about 30% to 65%. For humidity conditioning, each laminate (over 600 samples) was submerged in distilled water for 24 hours at 23°C per MIL SPEC 13949E (D-23/23) before testing at 1 megahertz. The regular variations shown in Figs. 3 and 4 are generally consistent with the equations above.

Measuring hook

Because hook is a change in capacitance with a change in frequency, it is necessary to measure board capacitance at various frequencies. An important aspect of the Tektronix/Norplex investigations was to devise an accurate measurement method. Several techniques were studied, with varying results.

The simplest method of measurement is with a capacitance bridge. It can measure low capacitance values, 1 to 50 picofarads, at frequencies ranging as high as between 100 kHz and 1 MHz and as low as 10 Hz. However, the stray capacitance of the bridge can affect the measurement of low-capacitance samples. Another problem:



4. Inverse relationship. The dissipation factor of boards made of FR-4 goes up with resin content, unlike the dielectric constant. The variation of both the dielectric constant and the dissipation factor are related to the amount of resin in a laminate.

most capacitance bridges are single-frequency devices.

A second measurement method is with a high-impedance attenuator. Such an attenuator (Fig. 5) can be constructed with two capacitances: C_1 being the board capacitance to be tested and C_2 being adjusted to produce an output waveform complying as closely as possible with the input square wave. The deviation, in percentage, of the output waveform from the input square wave indicates the relative amount of hook.

Wide frequency range

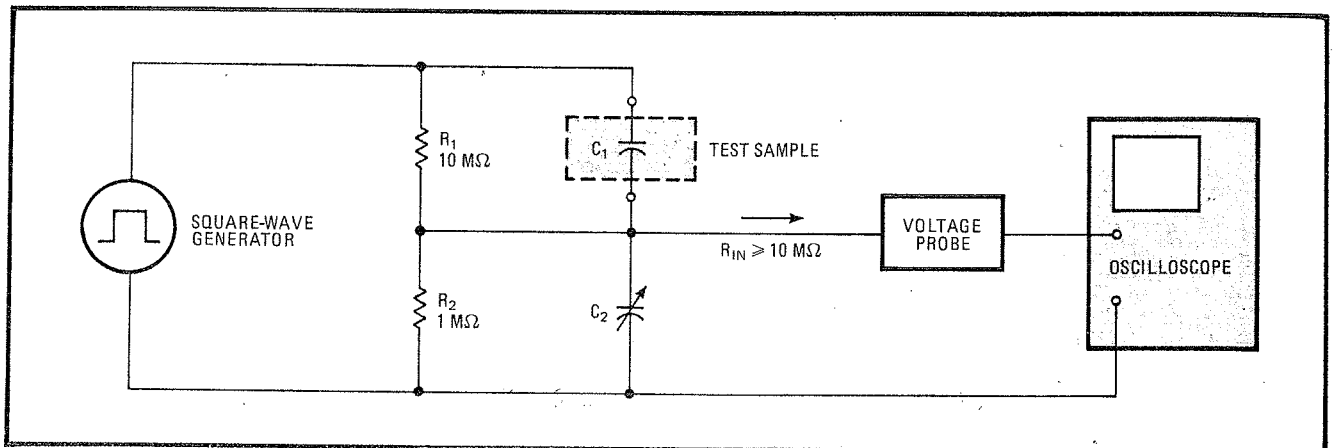
Since the square wave is composed of many frequencies, this measurement approach covers a wide range of frequencies at one time. Moreover, this technique is simple and economical, since it requires only an oscilloscope and a square-wave generator.

However, the attenuator method provides no direct reading of the quantity of hook (the change in capacitance), and stray capacitance in parallel may swamp out hook for low values of C_1 (less than 5 to 25 pF). At low frequencies (just where one most wants to measure hook), the 1-megohm resistors become the dominant elements of the circuit: thus the capacitance effect drops out of the picture.

The most exact way to measure hook is with the charge-amplifier circuit (Fig. 6). This is an operational amplifier with extremely low input bias currents—less than 0.1 picoampere is desirable, and 1 pA is maximum. This precision circuit uses capacitors as both the series-input and feedback impedances for setting the amplifier's closed-loop gain.

The output signal of the charge amplifier is a function of three parameters: the input signal; the fixed capacitance, C_f ; and the sample's capacitance, C_i .

The relationship between these components is:



5. Playing hooky. One of the earlier methods of measuring hook uses a high-impedance attenuator with circuit-board capacitance as an element. However, a drawback is that the circuit is incapable of giving a direct reading of circuit-board capacitance.

TABLE 1: LAMINATE HOOK AT 10 Hz

Type	Resin	Reinforcement	% hook	
			Before humidity conditioning	After humidity conditioning
FR-3	FR - epoxy	paper	14	large
CEM-1	FR - epoxy	paper/glass	5	10
FR-4*	FR - epoxy	glass	4	9
G-11	high-temperature epoxy	glass	3	9
Polyimide	polyimide	glass	4	6
N-3	phenolic	nylon	9	14

* Average of 12 FR-4 laminate variations

$$V_{out} = \frac{C_i}{C_f} (V_{in})$$

If C_f is a known-accurate, high-quality capacitor exhibiting no hook, and if the characteristics and accuracy of V_{in} are known, then the characteristics of V_{out} can only be influenced by C_i .

The signal generator used can be either a sine-wave or a square-wave generator. A sine-wave generator allows capacitance measurement at any given frequency within the bandwidth of the system. A square-wave source allows a dynamic capacitance measurement at all frequencies within the spectrum of the square wave at one time; that is, it shows how the hook capacitance changes with time.

Actual measurements

With an acceptable measurement technique established, the evaluation of materials can start. For testing of laminates, two-sided boards with plated-through holes allow hook to be measured along three orthogonal axes. While X, Y, and Z values of hook often show differences for a given laminate, only the effect of laminate type on the average hook value will be presented here.

When measuring a good capacitor (one with no hook), the output signal can be expected to look exactly like the input from the signal generator. NPO ceramic and poly-

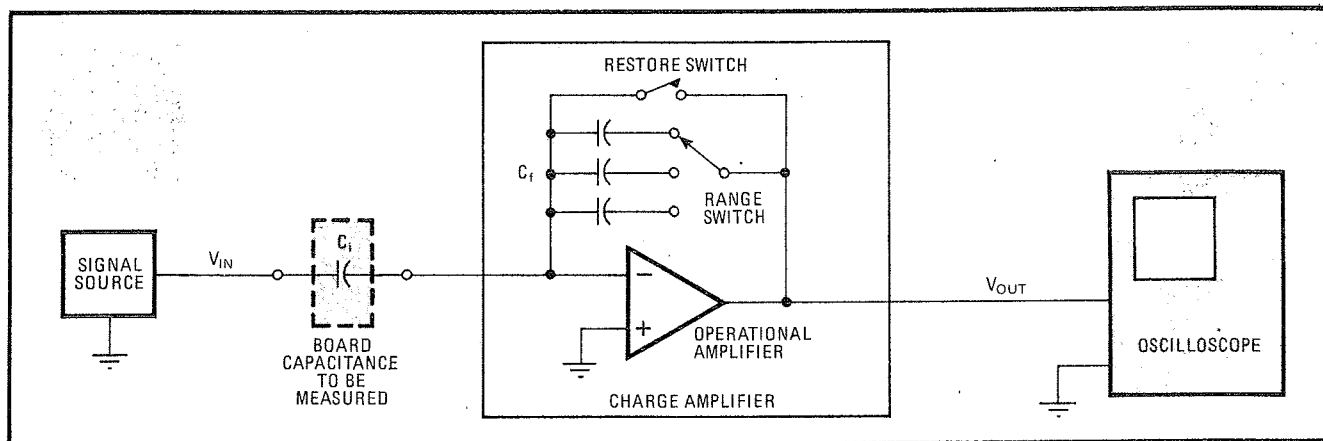
propylene capacitors (units with dielectrics having extremely low dissipation factors) can be inserted as standard C_i s in the circuit of Fig. 6 to develop a reference waveform. Any distortion caused by the signal generator, oscilloscope, or charge amp will be seen in the output waveform associated with the standard C_i , allowing for compensation in any future measurements.

Figure 7 shows capacitance vs time measurements taken on a charge-amp circuit at Tektronix on FR-4 circuit-board materials that have low hook, moderate hook, and a large amount of hook. Hook is measured as a percentage given by the distance the waveform's leading edge has dropped divided by its peak-to-peak amplitude. Circuit-board materials measured are the same materials used in the attenuators that have their responses shown in Fig. 1. However in this case, capacitance is directly displayed.

The waveforms display capacitance vertically. The capacitance in Fig. 7a changes very little after the initial step, compared to the larger changes in Fig. 7b and 7c. In fact, the latter capacitances would continue to increase with a waveform of longer period.

Increase in capacitance

A measurement of board capacitance with a variable sinusoidal generator as the signal source of a charge-amplifier measurement circuit is plotted in Fig. 8.



6. Charge amplifier. An operational amplifier with capacitors as feedback elements can measure board capacitance directly. The wave shape of the signal can be either a sine or a square wave. A square-wave drive results in a display of hook capacitance vs time.

Board capacitance was measured at various frequencies from 1 Hz to 100 kHz. The graph shows that, for frequencies below 1 kHz, the change in capacitance rapidly increases.

Capacitance at still lower frequencies was not measured because of equipment limitations. Presumably it would continue to increase for frequencies somewhat below 1 Hz before reaching a limit.

At Norplex, measurements were made on 12 different types of FR-4 laminate, plus five other printed-circuit laminates. Hook was measured with a 10-Hz square wave before and after humidity conditioning. Results are given in Table 1, along with the composition of the various laminates.

Moisture absorption results in greater hook, and, for a given resin system, paper reinforcement is worse than

glass fiber (see FR-3 and FR-4 in the table). These observations may be related: paper-based laminates absorb more moisture than those with glass-fiber bases.

Table 1 also shows that other resin systems, such as G-11 and polyimide, can be used to produce low-hook laminates. The N-3 nylon-phenolic laminate was an early attempt to study some less traditional systems.

Other factors

The Tektronix/Norplex investigations established that laminate construction and processing may affect hook as much as the materials used, as Table 2 shows. It offers data on the 12 different FR-4 laminate samples, each made somewhat differently. While hook varies substantially from sample to sample, it is possible to produce an FR-4 laminate with low hook, even after moisture

Advice for pc-board users

Current research into hook is beginning to lead to a good economical guarantee of relatively hook-free, FR-4 laminates for printed-circuit boards. But insufficient understanding of the cause of hook still precludes an accurate and reliable formula for the composition of hook-free material.

For instance, hook seems to be a batch- or lot-oriented problem. Years may pass, and several lots of material may be used with hook being low enough not to be objectionable. Then all at once a bad lot of material will be received and cause havoc. All vendors of G-10 or FR-4 laminate material used at Tektronix have supplied both good and bad lots of laminate.

There are, however, several methods that can reduce the effect of hook on circuits.

First, design the circuit and the layout of the printed-circuit board to minimize stray capacitance caused by pc interconnections. It may be necessary to mount all critical components on Teflon standoffs and to do point-to-point wiring to these posts rather than to points directly on the pc board. This keeps the circuit-board capacitance to a minimum, but, of course, drives manufacturing costs up.

Another problem: insufficiently cured laminate material can be noticeably hooky. Baking FR-4 material can be a remedy in some cases.

Another approach is to ask the laminate vendor to agree to a maximum hook specification. A few are now willing to address this requirement. Alternatively, this specification can be in the form of a limit on the change of dielectric constant of the material as measured at 100 kilohertz and at 10 hertz.

The Tektronix approach for FR-4 laminate is a combination of sampling of the incoming material by batch and measuring finished circuit boards for hook before component assembly. A hook test pattern, etched on samples of each batch of material received, checks all three axes. Use of the material in critical applications depends on the results of that test.

For these applications, a 100% check of the finished pc boards before component assembly provides further insurance against scrapping expensive finished boards because they do not meet performance specifications. The cost of a bad board found in an assembled instrument at the calibration stage can be tremendous.

Finally, one important step a laminate user can take is to explain his needs to the vendor. The vendor should realize that today's pc-board requirements go far beyond just supporting and interconnecting components. Today the dielectric properties of a circuit board are decidedly the most important.

absorption (see variation 12, for example).

Again, while high resin content throughout and on the surface of FR-4 laminates generally gave low hook results, the table indicates that other factors also affect laminate hook. It appears that resin-glass interactions are critical.

Hook measurements on laminates also have been made at 1 kHz and 100 kHz. Because of the tentative relation found between resin content and hook, correlations between surface resistance and hook were begun

with new test patterns.

Not all variables have been explored in detail. The data was derived from measurements of hook at 10 Hz and at 1 kHz and surface (insulation) resistance at 500 v dc using a special board pattern in four different modes. Tests included four FR-4 types and two other laminates, each measured before and after moisture conditioning.

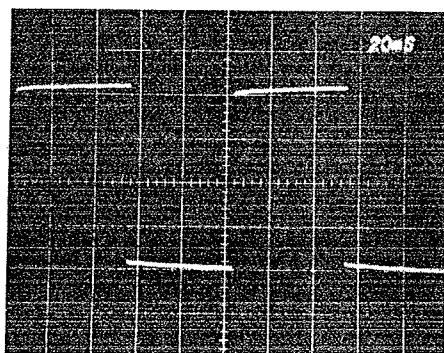
A note of caution: understanding data from experimental sets where many parameters affect the observed results often requires statistical interpretations to separate important from trivial parameters and to identify interactive parameters. The data bank is not complete enough to permit such rigorous interpretation; however, some trends do seem to be fairly apparent by now.

The data indicates that an increasing moisture content in laminates generally increases hook. The CEM (composite epoxy material) and polyolefin samples tested are not generally recognized laminate materials. The former is a variation of a CEM-3 construction (woven plus nonwoven glass fiber with FR-4 resin), and the polyolefin is Norplex's NZ-932 developmental laminate designed for certain specialized applications.

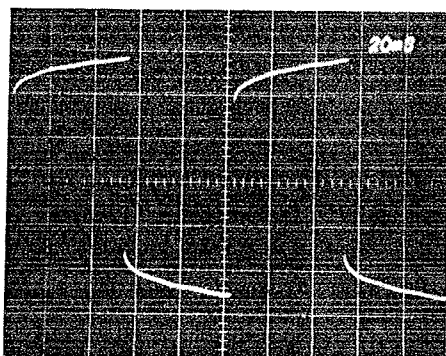
The results for the various FR-4 types reinforce a conclusion stated earlier. While moisture and material type influence hook, variations within a given laminate show that the process of fabrication also strongly influences hook.

While increased moisture content usually raises the hook of a given laminate, it also increases the material's dielectric constant and decreases resistance, even if no more than traces of ionic materials are present. Therefore, hook would be expected to decrease with increasing laminate resistance.

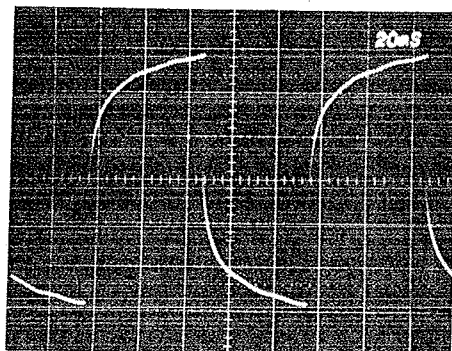
Test results generally confirm this expectation at each of the frequencies used for these surface hook measure-



(a) LOW HOOK (1 pF/div)

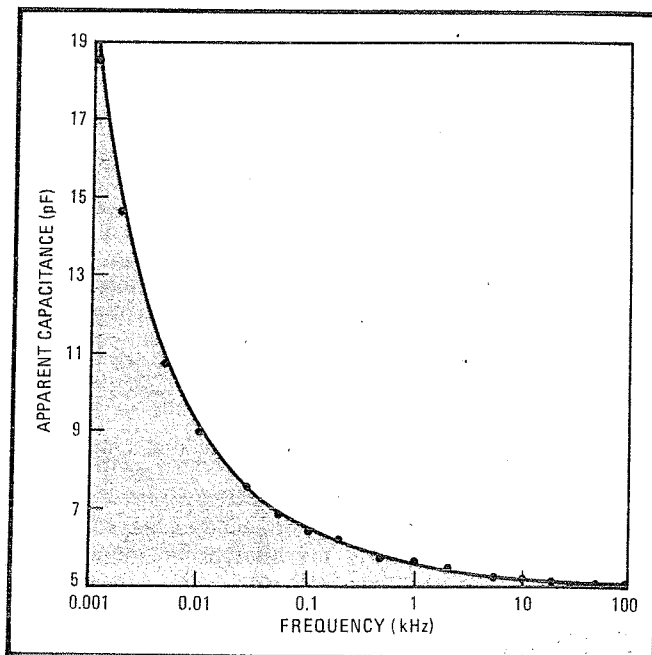


(b) MODERATE HOOK (1 pF/div)



(c) LARGE AMOUNT OF HOOK (2 pF/div)

7. Capacitance vs time. Typical capacitance vs time measurements were taken on FR-4 laminates with a charge amplifier. The hook capacitance associated with moderate and large amounts of hook would continue to increase if a longer period were used.



8. Sinusoidal drive. Driving the charge-amp capacitance-measuring circuit with a sine-wave generator produces a curve of this type for a board with considerable hook. Change in board capacitance is particularly rapid in the dc-to-10-kHz range.

TABLE 2: HOOK IN FR-4 VARIATIONS (10 Hz)

FR-4 variations	Resin content	Resin at surface	% hook	
			Before humidity conditioning	After humidity conditioning
1	low	low	5	12
2	high	low	5	6
3	low	low	5	12
4	low	low	4	11
5	low	high	4	11
6	high	high	4	11
7	high	high	4	8
8	high	high	4	7
9	low	high	3	11
10	high	high	3	7
11	high	high	3	7
12	high	low	2	4

What the laminate vendor can do

The present state of the art permits tests of hook in laminate material, which do in fact relate to end-use performance. However, evaluation of the role of laminate manufacturing techniques in the production of hook should be continued and expanded. This work would develop the necessary theory for the consistent production of laminates that exhibit minimal signal aberration over a wide range of operating conditions.

To assure uniform resin composition, incoming materials should be analyzed in a number of ways with an integral role assigned to chromatography, which separates and analyzes mixtures of chemical substances by differential absorption. This technique determines resin molecular distribution, which must be reproducible in order to maintain a variety of constant laminate electrical properties, including low hook.

Additionally, researchers at laminate manufacturers are using chromatographic processes to separate various fractions from the polymers. This activity will allow a better understanding of the hypothesis that molecular polarizability has a dominant effect on laminate dielectric properties such as hook.

The makers of printed-circuit boards primarily use epoxy-glass-supported laminates for most sophisticated applications, such as wide-band, high-speed, low-drift analog circuitry. Earlier, phenolic products chiefly were used, but the increasing need for electrical stability in the electronics industries is beyond the capabilities of the phenolics. There is some concern that as electronics design becomes more refined, the epoxy-glass system will also become inadequate. This is the main reason for continuing to look at other materials in the polymer world.

ments; however, the picture is not entirely clear. Some discrepancies in the results may be partly due to measuring surface resistance at 500 v dc while measuring hook using a 30-v square wave. It is not expected that surface resistance will depend on frequency or amplitude, but this deserves consideration in future inquiries.

More importantly, the laminate test results reinforce the notion that materials and the methods used for laminate construction are important in determining hook. The surface hook for the two experimental laminates, CEM and polyolefin, is especially sensitive to surface resistance changes.

In other words, moisture conditioning of these laminates caused only small changes in surface resistance (relative to most of the FR-4 laminates), while significant changes in surface hook were measured. It is clear

that no simple mathematical relationship between laminate hook and resistance has yet been identified. While investigations into hook are well launched, there is a long voyage ahead until all the factors that produce hook are pinned down and a mathematical relationship relating these factors is derived. □

Closing the loop

The authors will answer questions on this article. For telephone inquiries until Friday, Oct. 20, the Tektronix authors may be reached from 9 a.m. to 5 p.m. Pacific Standard Time at (503) 644-0160, and the Norplex authors may be reached from 9 a.m. to 5 p.m. Central Standard Time at (608) 784-6070. Direct written inquiries to: Tektronix, P. O. 500, Beaverton, Ore. 97077, or Norplex Division, UOP, 1300 Norplex Drive, LaCrosse, Wis. 54601