PASSIVE PROBES

April 15, 1964

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Chapter 1

PURPOSE OF A PASSIVE PROBE

One important consideration in oscilloscope measurements is that of coupling the oscilloscope to the signal of interest. In some low-frequency applications simple test leads may suffice to couple a signal to the input of an oscilloscope. In the most sophisticated high-speed work, it is necessary to use properly matched coaxial cable terminated in its characteristic impedance at the input connector.

The passive oscilloscope probe provides the greatest convenience and measurement accuracy for general purpose work. The term "passive" is used to distinguish this type of probe from one that provides power gain, such as a cathode-follower or amplifier probe. The passive probe typically consists of a probe body assembly, a ground-lead, and a shielded cable equipped with a suitable connector for the oscilloscope input. Most probes are equipped with interchangeable tips and ground leads for convenient connection to various possible test-points.

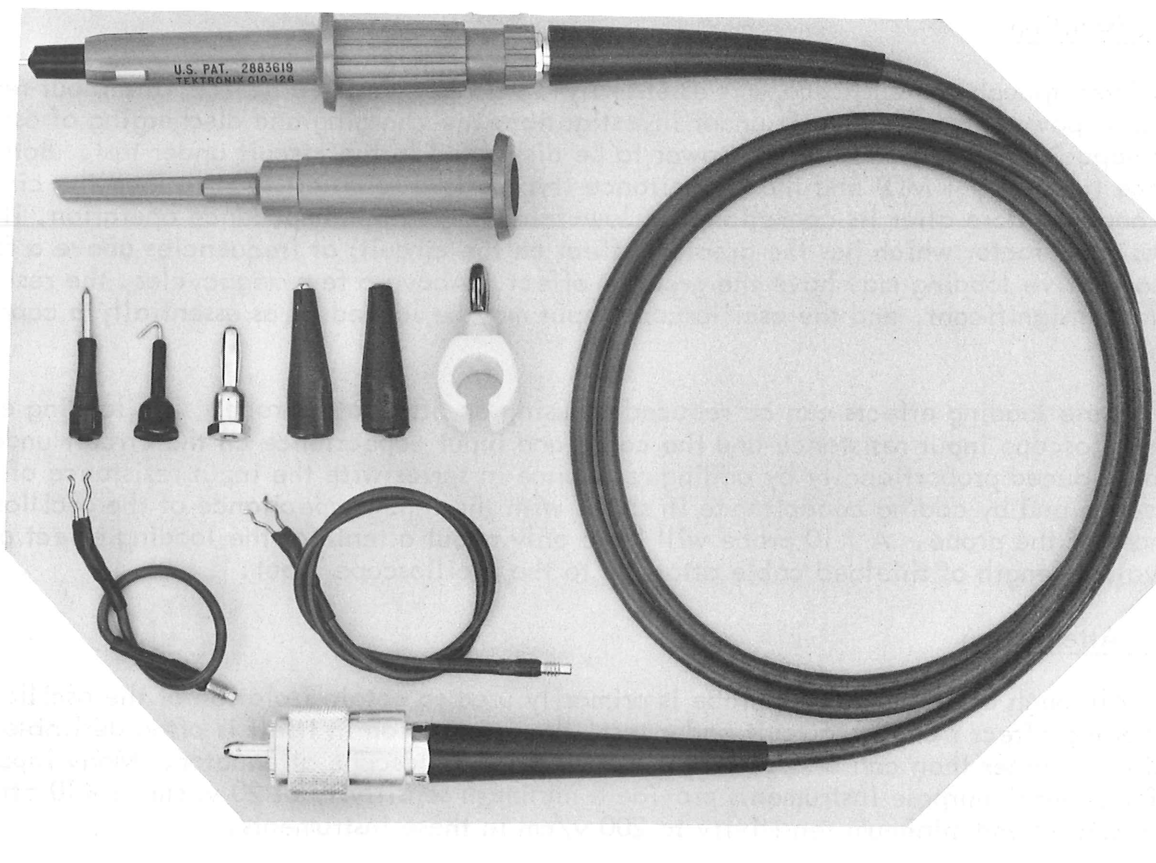


Fig. 1-1. A typical passive probe with several interchangeable tips, ground leads and a holder accessory.

For general-purpose work, the probe serves four important functions: (1) as a convenient test prod for reaching test points and signal sources not otherwise easily accessible; (2) to isolate the oscilloscope input impedance from the circuit under examination; (3) to attenuate large signals; and (4) to extend the low-frequency response of DC-coupled oscilloscopes when AC-coupling at the input is desirable. The second function is usually the most important, and signal-attenuation must be accepted as the price to obtain it.

1-1. Convenience

The oscilloscope is most useful in circuit development and troubleshooting. The oscilloscope probe finds its widest uses in providing a means of input to the oscilloscope. The shielded cable of the probe minimizes pickup of unwanted signals, and the probe body provides a convenient insulated handle for moving the tip from point to point with maximum operator and circuit protection.

The non-attenuating "X1" probe performs only one function -- that of a convenient test prod. Attenuator probes can perform the following additional functions.

1-2. Isolation

Even though an oscilloscope is essentially a voltage-sensitive device, the input resistance will draw power from the circuit under investigation; the charging and discharging of oscilloscope input capacitance will cause extra power to be dissipated in the circuit under test. Both the resistance (typically 1 MΩ) and the capacitance (typically 8 to 50 pf) tend to load the circuit under test, and therefore alter its operation. In low-frequency, high-impedance operation, it may be the resistive factor which has the greatest effect on the circuit; at frequencies above a few Kc, the capacitive loading may have the greatest effect. Above a few megacycles, the resistive load becomes insignificant, and the oscilloscope input may be looked on as essentially a capacitive load.

These loading effects can be reduced by using an attenuator probe. The loading effect of the oscilloscope input resistance and the cable and input capacitance on the circuit under test can be reduced proportionally by adding resistance in series with the input resistance of the oscilloscope and by adding capacitance in series with the input capacitance of the oscilloscope at the nose of the probe. A X10 probe will have only about a tenth of the loading effect of an equivalent length of shielded cable attached to the oscilloscope input.

1-3. Attenuation

Although attenuation in a probe is primarily used to obtain isolation of the oscilloscope input loading effect from the circuit under test, the attenuation in itself is often desirable in observing signals larger than can be accommodated by the oscilloscope attenuator. Many input attenuators for general-purpose instruments provide a minimum sensitivity of 20 v/cm; a X10 attenuator probe will extend minimum sensitivity to 200 v/cm in these instruments.

In low-impedance <u>sampling</u> oscilloscopes, the input sensitivity is usually quite high, and adjustable over a narrow range at best. The passive probe, equipped with interchangeable heads for a wide range of attenuation ratios, provides a convenient means of signal attenuation to the millivolt levels required by instruments, as well as reducing the loading effect of the low-impedance input.

1-4. Extension of Time Constant

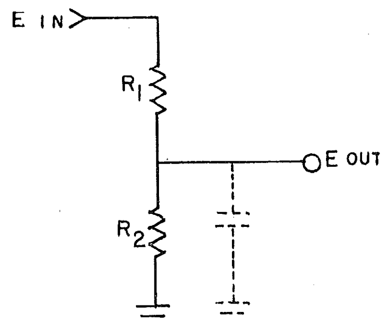
It is often convenient to provide AC-coupling to the oscilloscope input for observation of signals with a DC component. Under these conditions, however, the DC-blocking capacitor will limit the low-frequency response of the oscilloscope. For example, a 0.1-μf blocking capacitor, with a 1-MΩ oscilloscope input resistance provides a time constant of 0.1 seconds; the low-frequency 3-db point will be about 2 cycles. When a longer time constant (or lower-frequency response) is required, an attenuator probe can be used: a 10-times attenuation extends the time constant to 1 second, and extends the low-frequency 3-db point to 0.2 cycles.

Chapter 2

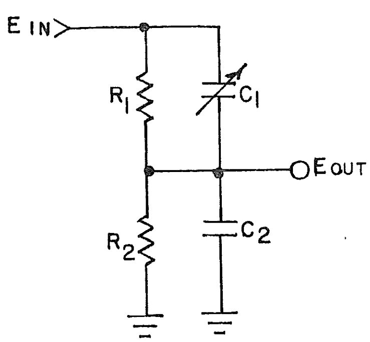
CIRCUITRY AND CONSTRUCTION

2-1. Conventional High-Impedance Passive Probes

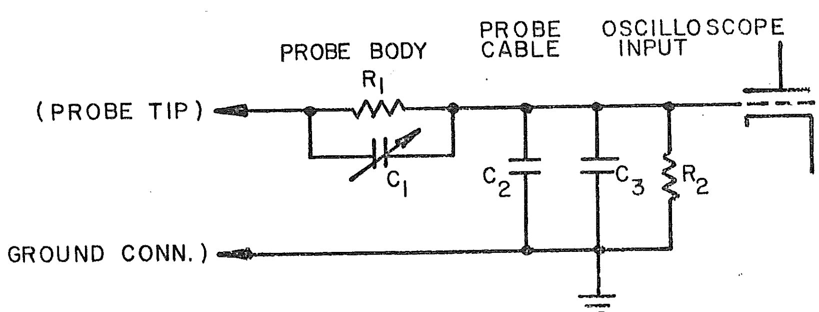
The usual design for passive oscilloscope probes follows approximately the configuration of Fig. 2-1c. The probe itself forms the series element of a compensated resistive divider. If C_1 is adjusted so that $R_1C_1 = R_2(C_2 + C_3)$, the attenuation will be the same for all frequencies.



a. Resistive Divider (uncompensated)
Output voltage is $\frac{R_2}{R_1 + R_2}$ (E_{in}).
Any capacitance across R_2, however, will limit its use at high frequencies.



b. Resistive Divider (compensated)
For AC and RF work, C_2 (shunt capacitance of oscilloscope input) tends to shunt high frequencies to ground. C_1 forms a capacitive divider with C_2 so that voltage division across capacitors is the same as across resistors at all frequencies.

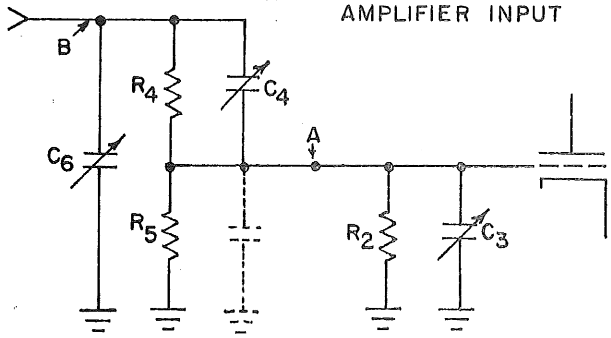


c. Simplified circuit of passive oscilloscope probe.
Basic attenuation ratio (DC) is determined by $\frac{R_1 + R_2}{R_2}$. Capacitor C_1 forms a capacitive divider of the same ratio with the parallel combination of C_2 and C_3, so that high-frequency information is not over-attenuated. Since C_3 may vary between oscilloscopes, C_1 is made adjustable. The product C_3R_2 is maintained constant for all step-attenuator positions, so that attenuation and compensation of the probe need not be recalculated or readjusted when setting of internal attenuator is changed. Typically R_2 = 1 meg, $C_2 + C_3$ may vary from 35 to 85 pf.

Fig. 2-1. Passive Probe Circuitry

Actual input capacitance of the probe will vary, depending on the value of C_3, which will vary between oscilloscope types. The step-attenuator in the oscilloscope itself (Fig. 2-2) is designed for constant input RC (in instruments intended for use with probes) so that switching attenuator positions does not affect the probe attenuation ratio or compensation.

Values of R_4 and R_5 are selected so that input resistance at point B is the same as at point A without attenuator. Capacitor C_4 compensates resistive divider. Capacitor C_6 returns input capacitance at B to same value as that at point A. Attenuator can now be switched in or out of circuit without changing input RC.



Attenuation Ratio:

$$\frac{R_2R_5}{R_2R_4 + R_4R_5 + R_2R_5}$$

Fig. 2-2. Constant-Input RC Attenuator

Fig. 2-3 shows the circuitry for a 100X probe which adds a shunt element for further attenuation and lower input capacitance (smaller value C_1 may be used).

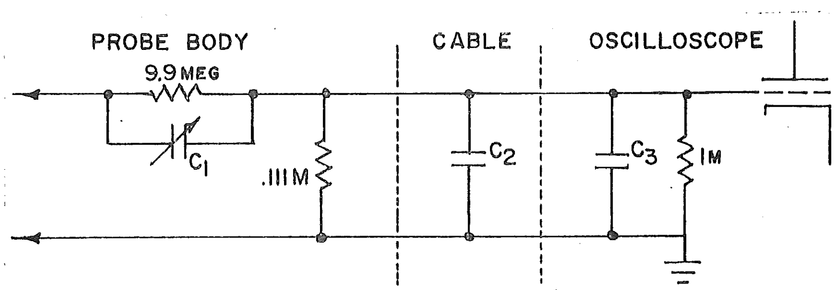


Fig. 2-3. Simplified Circuit for 100X Probe

$$\text{DC Attenuation} = \frac{\frac{1M \times .111M}{1M + .111M}}{9.9M + \frac{1M \times .111M}{1M + .111M}}$$

2-2. Terminally-Compensated Probes

To reduce complexity and weight in the probe body itself, an alternative design is sometimes used, following the circuitry shown in Fig. 2-4. Input capacitance of the probe remains the same regardless of the type of instrument to which it is attached. With short-length (up to 42") cables, performance is slightly inferior to the type where compensation is done in the probe body, because of the higher net input capacitance. In longer lengths (6 to 12') the terminally-compensated probe has slightly better performance.

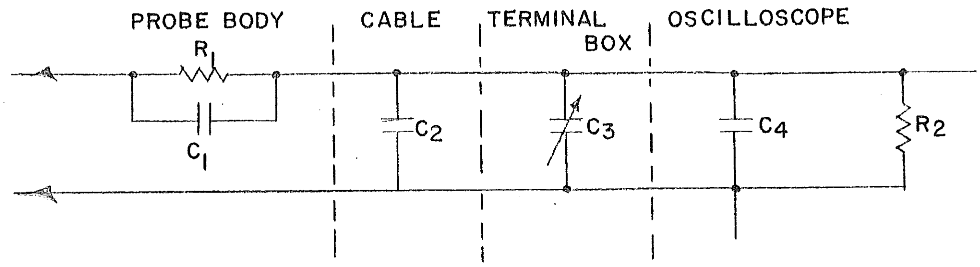


Fig. 2-4. Terminally-Compensated Probe
Compensating capacitor C_1 is fixed value. C_3, located in terminal box at oscilloscope input, is adjusted to make up difference between C_4 and the cable capacitance, so that $R_2(C_2 + C_3 + C_4) = R_1C_1$.
Typical input capacitance for this type of probe (10X atten.) is 12.5 pf for the 42" length.

2-3. Distributed Damping

When signals containing high-frequency information are displayed, the mismatch between the cable and its terminations causes energy reflections which show up primarily as ringing on a fast pulse waveform viewed on a wide-band oscilloscope.

Resistance wire in the probe center-conductor attenuates echoes due to low-impedance cable currents. The value of resistance wire used is critical and depends on cable characteristics and length (Fig. 2-5) to obtain optimum damping without serious loss of high-frequency information. In some cases additional L is needed at the connector to optimize transient response.

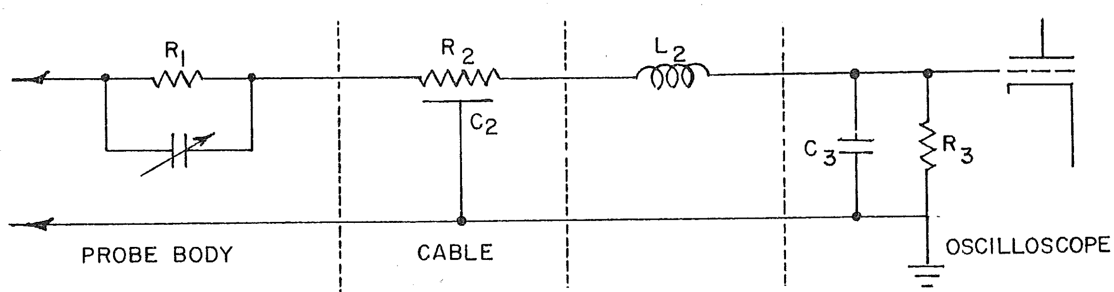


Fig. 2-5. Distributed Damping
Probe cable with resistive center conductor prevents ringing and standing waves due to impedance mismatch. Center-conductor resistance, R_2, may be from 200 to 1000 Ω depending on cable characteristics. Damping method is usable in either input-compensated or terminally-compensated type of probe. L_2 is usually less than 1 μh.

2-4. Passive Probes for Low-Impedance Systems

In sampling oscilloscopes and other high-speed systems operating in the 100-1000 Mc range where signal-handling is done almost entirely at low impedance, a probe following the design shown in Fig. 2-6 is commonly used as a convenient signal attenuator and bridging device for connection into low-impedance systems with minimum loading. Input capacitance of this type of probe is on the order of 0.5 to 0.8 pf. Because the probe operates into the essentially resistive load of a terminated coaxial system, no compensation is required for low attenuation ratios. For attenuation ratios above 20X, shunt capacitance must be inserted across the 50-Ω probe termination.

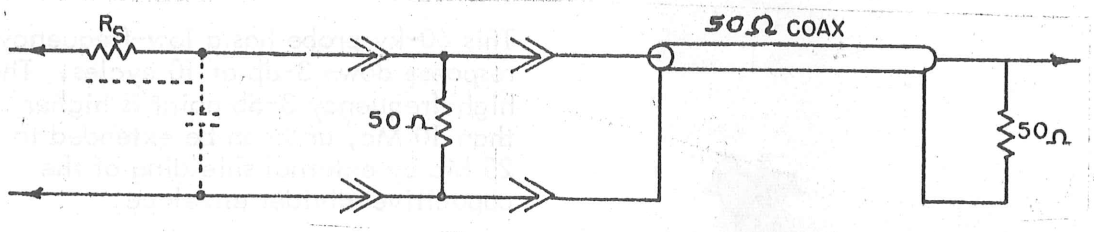
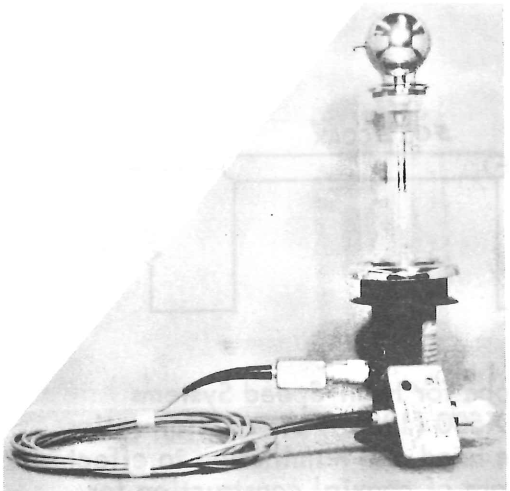


Fig. 2-6. Low-Impedance Probe for High-Speed Systems
R_S in plug-on heads provides X5 (100Ω) to X500 (1225Ω) attenuation ratios. Series-capacitor may be used between probe head and termination to effect AC-coupling. Probe head and termination are of coaxial construction for optimum bandwidth.

2-5. Capacitive Dividers

For high-voltage work in the 50-100 kv area, where the stability and physical size of resistors becomes a serious problem, capacitive dividers of 1000:1 to 20,000:1 ratio are used, employing precision vacuum-capacitors of suitable voltage rating. Fig. 2-7 shows a 60-kv, 10,000:1 attenuator probe with compensating network attached. Chief disadvantage of the capacitive-divider type of probe is its AC-coupling, which makes accurate evaluation of low-frequency sine-waves, long-duration pulses, or pulses with varying duty cycle difficult. Also, physical size and configuration make high-frequency correction more difficult at higher frequencies.



This 60-kv probe has a low-frequency response down 3-db at 10 cycles. The high-frequency 3-db point is higher than 10 Mc, and can be extended to 25 Mc by external shielding of the capacitive-divider envelope.

Fig. 2-7. Jennings Type JP-325 Probe with Tektronix 030-030 Adapter

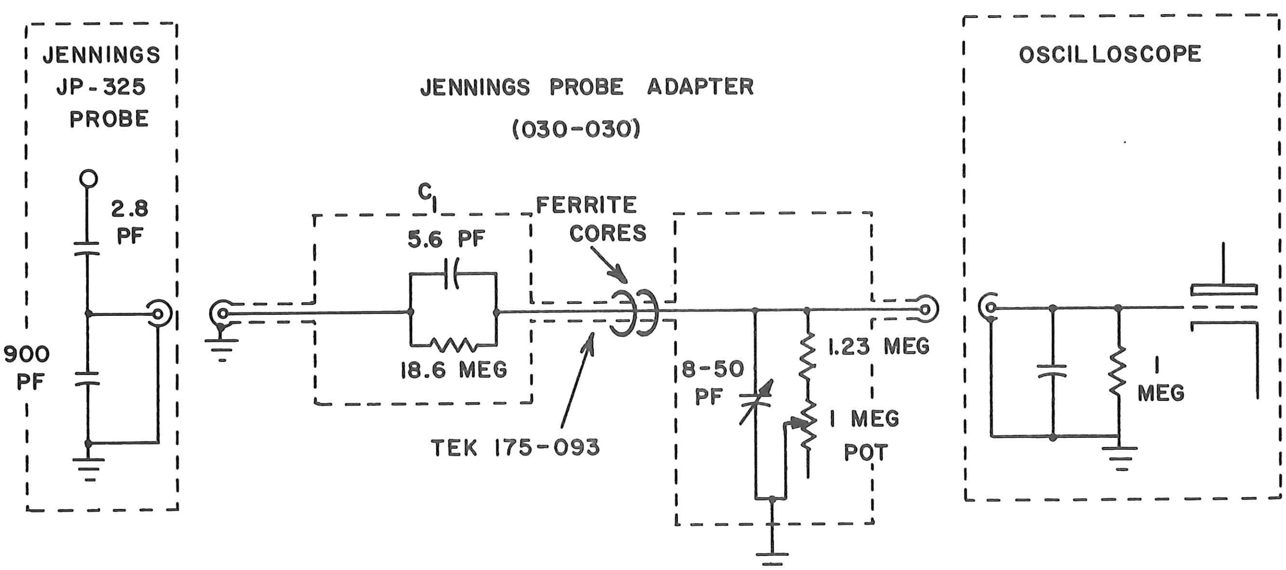


Fig. 2-8. Capacitive High-Voltage Probe Equivalent circuits of the several assemblies.

Chapter 3

BANDWIDTH AND TRANSIENT RESPONSE

3-1. Definitions

Bandwidth (frequency response) as used here indicates the upper sine-wave frequency at which the response of a device or system is -3 db (-30% from its response at some nominal low-frequency value, commonly 1 Kc or 50 Kc).

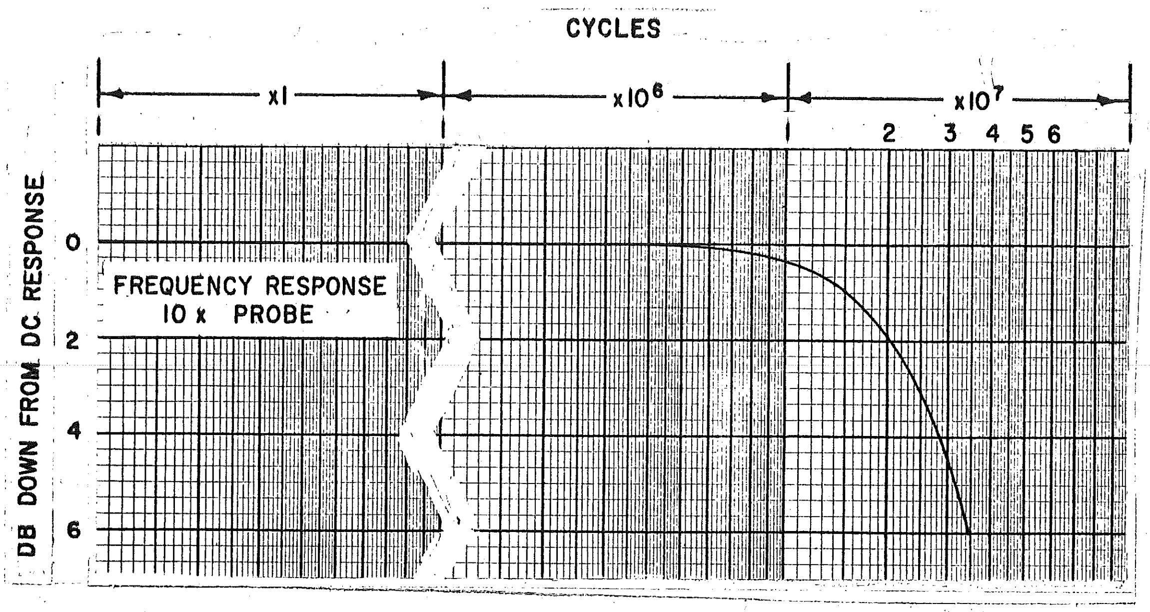
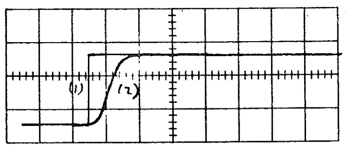
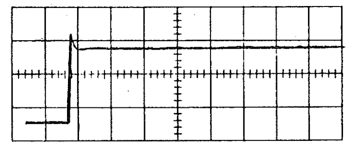


Fig. 3-1. Typical response of 42", 10X attenuator probe

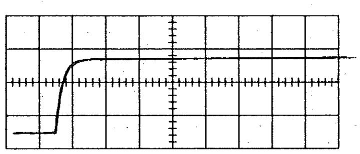
Transient-response, as commonly used, includes both risetime (see below) and the fidelity of waveform reproduction, and is the measure of device or system capability of transmitting complex waveforms without excessive distortion. Transient response is measured by the application of a step-function or pulse waveform of risetime much shorter than that of the system (Fig. 3-2a). The response of the system, for good transient-response, should reproduce the waveform without overshoot (Fig. 3-2b), undershoot (Fig. 3-2c), ringing (Fig. 3-2d), preshoot (Fig. 3-2e) or hook (Fig. 3-2f). The aberrations are measured or specified in terms of percent of the total pulse amplitude. The input pulse must be as free as possible from these defects.



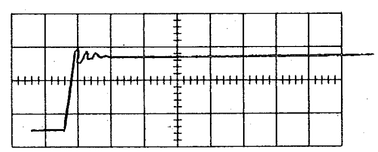
a. Use of fast-rise pulse to evaluate transient response of device. Trace (1) is the input pulse, Trace (2) the output.



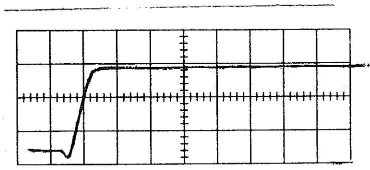
b. Overshoot. Devices should be checked at several sweep speeds for overshoot which may not be apparent at certain sweep rates.



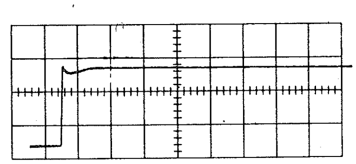
c. Undershoot. Non-symmetrical "corners" on leading edge indicate over-damped response.



d. Ringing. Excess undamped inductance in probe circuit.



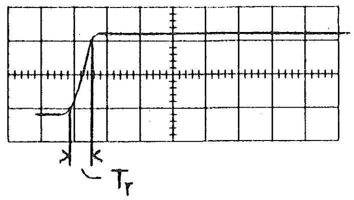
e. Pre-shoot. Not commonly found in probes; usually results from "transitional" inductive peaking in pulse generators or amplifiers.



f. Dielectric hook. Time about 10 μsec/cm.

Fig. 3-2. Transient Response

Risetime of a device or system is the time required for the output to rise from 10 to 90% of its final value in response to a step-function input of risetime considerably less than the system risetime.



If input step-function risetime and oscilloscope risetime are less than displayed risetime by a factor of 3 or more, displayed risetime accurately represents risetime of devices under test.

Fig. 3-3. 10-90% Risetime

If overshoot and other aberrations do not exceed about 2%, risetime (T_r) is related to bandwidth (BW) by the formula $(BW)(T_r) \approx 0.35$. When two devices of specified risetime are connected in cascade (such as a probe and an oscilloscope) the composite system risetime (T_r) may be calculated from the formula $T_r \approx \sqrt{{T_{r1}}^2 + {T_{r2}}^2}$

The limiting effect of the probe on the bandwidth and transient response (and hence on the accuracy of oscilloscope measurements) occurs in two ways:

1. In the effect of the probe input RC on the circuit under test,

2. In the internal losses in the probe itself.

3-2. Effect on Signal Source

The input RC of an oscilloscope probe will always have some effect on any circuit to which it is connected.

In the case of signals containing only low-frequency information at medium or low impedance, the effect is negligible. For high-frequency information, represented in complex waveforms by rapid changes and by a sharp leading edge of the waveform, the input RC of the probe (see Chapters 2 and 6) may have a significant loading effect, altering the performance of the signal source. Assuming a purely resistive signal source impedance R, the input capacitance of the probe C will limit the risetime of the signal source to approximately 2.2 RC seconds, and its bandwidth to $\frac{1}{2\pi RC}$ cycles.

When probe risetime and bandwidth specifications are defined, the effect of probe input capacitance is partly taken into account by connecting the probe across a 25-Ω signal source (a terminated 50-Ω system). A probe having 10-pf input capacitance will limit the risetime and bandwidth of a system to which it is connected, approximately as shown in Fig. 3-4.

Source Impedance (non-reactive)	Bandwidth Limit (-3 db)	Risetime Limit (10-90%)
10 Ω	1600 Mc*	0.22 nsec*
100 Ω	160 Mc*	2.2 nsec*
1000 Ω	16 Mc*	22 nsec*
10 K	1.6 Mc	220 nsec
100 K	160 Kc	2.2 μsec
1 M	16 Kc	22 μsec

Fig. 3-4. Limiting effect of 10 pf shunt capacitance on signal sources of various impedances. Actual bandwidths of the circuits will depend on other reactances present. For input capacitance limitations in terms of (5%) measurement accuracy, see Fig. 6-4.

*NOTE: Depending on probe type, the probe-loading effect will be greater than indicated, especially above 100 Mc, because of dielectric losses. Bandwidth and risetime may be more severely limited than shown. See Appendix for results on an actual system.

3-3. Ringing

In addition to the limiting effect on the circuit under test, the probe and cable will degrade the signal internally to some extent. If ordinary coaxial cable is used, internal losses will be low, but excessive ringing will be introduced. The ringing will be particularly objectionable when the oscilloscope response approaches the frequency for which the probe cable is a quarter wavelength.

To eliminate ringing due to reflections in the probe cable, resistance wire of the proper value may be used (see Fig. 2-5) to damp any ringing due to the lack of impedance-matching. Notice, however, that the resistance of the center-conductor forms a part of the resistance-capacitance divider which is not compensated.

Inductive peaking may be used to extend high-frequency response, so that the input waveform is reproduced as accurately as possible (Fig. 3-5).

a. Non-symmetrical leading edge indicates lack of inductive correction.

b. Same waveform; probe inductively corrected for proper transient response.

Fig. 3-5.

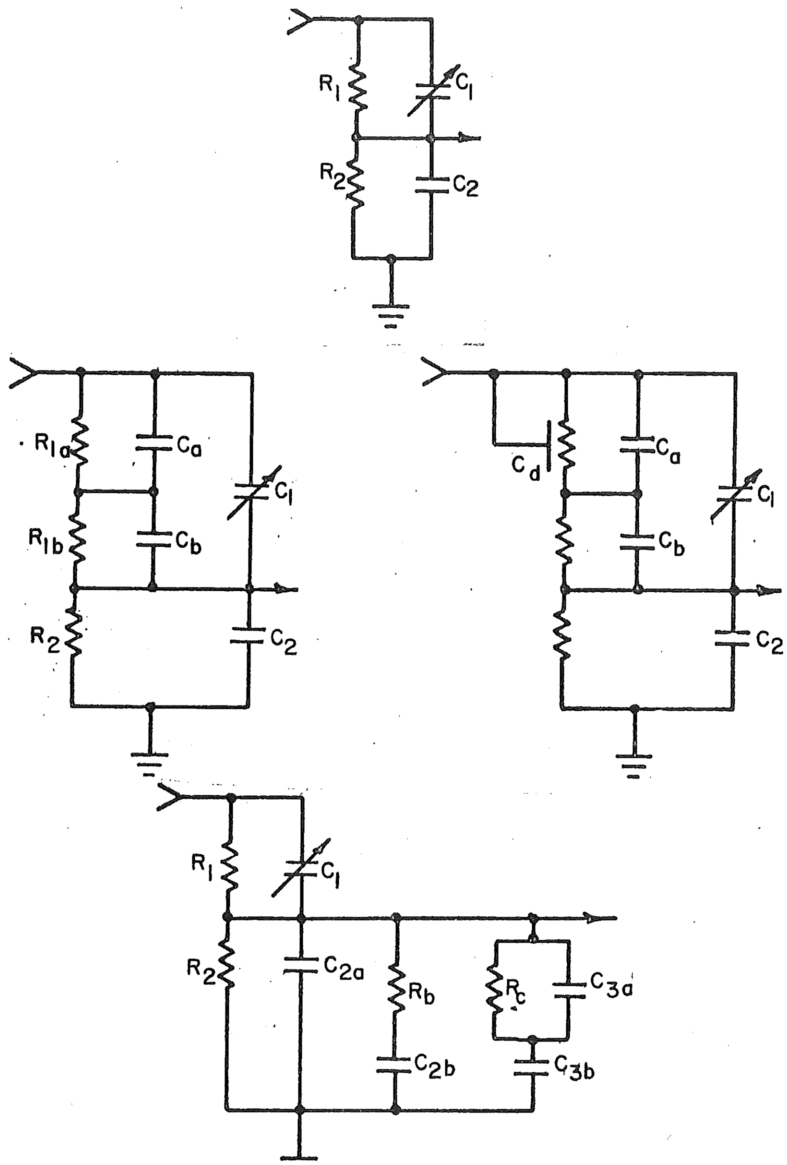
3-4. Hook Effect

Hook, named for the shape of the response of some voltage dividers to a step function (Fig. 3-2f), is displayed as a time-constant in a compensated voltage divider not related to the nominal values of the divider components. In practical terms, it's a dip following the leading edge in the transient response of an attenuator, which can't be eliminated by adjustment of the compensating capacitor(s).

Environmental hook is due to uneven capacitance distribution in relation to a resistor (Fig. 3-6b). Dielectric hook refers to frequency-related dielectric losses in insulating materials which appears as a resistance component in series with the capacitance of the dielectric (often arising within a capacitor) Fig. 3-6c. Environmental hook may be caused by poor attenuator construction techniques, use of resistors with unevenly distributed internal capacitance, or use of resistors with lossy dielectric coatings. Hook of this type usually has a time constant on the order of 0.2 msec in high-impedance (1MΩ) dividers.

Dielectric hook occurs most often as a result of stray capacitance involving lossy dielectrics, particularly phenolics, bakelite, vinyl, and most colored or glass-filled plastics, rather than being due to losses in physical capacitors used. Vacuum-tubes also commonly exhibit some degrees of hook. Time-constants involved are on the order of 10 μsec and less in 1 MΩ dividers.

With properly designed probes and attenuators, aberrations due to hook are usually quite small, (less than 1%). In critical applications and slide-back measurements, where hook amounting to 0.1% may be objectionable, special probes and the use of carefully selected scope input circuitry may be necessary. These techniques are too expensive for general-purpose application.



a. Ideally compensated divider. All time constants are related to R_1, R_2, C_1 and C_2. Adjustment of C_1 so that $R_1C_1 = R_2C_2$ provides perfect compensation.

b. Hook caused by unequal distribution of capacitance across resistor ($R_{1a}C_a \neq R_{1b}C_b$). Effect is minimized by adding environmental capacitance C_d (usually a sleeve), equalizing distributed capacitance.

c. Hook caused by dielectric losses. Effect is complicated by variation in effective R and C values with frequency, and differences in loss characteristics of various dielectrics composing C_2. Proper dielectric selection and control is the only remedy.

Fig. 3-6. Hook Effect
Equivalent circuits of compensated voltage dividers exhibiting hook.

3-5. Inductance Effects

For high-frequency information, the probe is essentially a capacitance-divider; the resistive portions of the divider having no significant effect on the input impedance or the attenuation ratio. Any inductance inserted in series with this capacitance will form a series-resonant circuit (Fig. 3-7) and will ring if driven by a signal having significant frequency components at or above its resonant frequency. Whether these aberrations appear on the oscilloscope display will depend on the oscilloscope bandwidth, and particularly on the "zero-response" frequency* of the instrument. For low-frequency work, a common-ground connection between the circuit under investigation and the oscilloscope can consist of a simple test-lead connected between chassis. Fig. 3-8, however, shows how the inductance of a two-foot test lead used as a common ground connection rings when viewing a pulse of .02 µsec risetime.

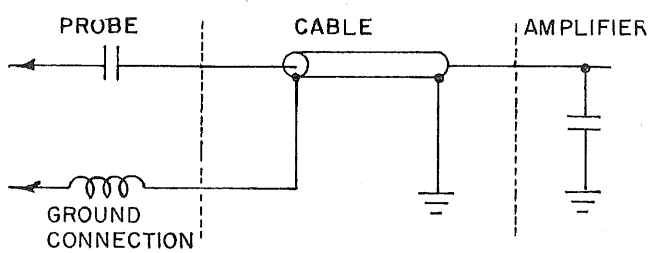


Fig. 3-7. Series-resonant circuit formed by excessive lead-length in probe ground return.

For oscilloscopes of 10-15 Mc bandwidth and less, ringing can be avoided in most cases by using the ground strap furnished with the probe, connected from the probe ground terminal to a ground point closely associated with the circuit under test. Fig. 3-9 shows the improvement using a 12" ground-strap, over the case where the only common connection was via the test lead between chasses.

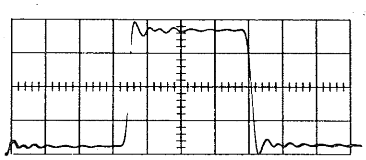


Fig. 3-8. Ringing introduced by inductance of 24" ground return lead connected to oscilloscope chassis; 0.1 µsec/cm. (Oscilloscope bandwidth 15 Mc, signal risetime about 20 nsec.) Slower-rise waveforms would not be affected as seriously.

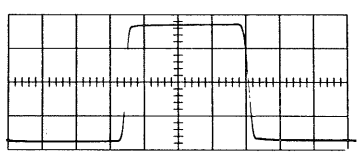


Fig. 3-9. Response to Fig. 3-8 with 12" ground return, connected between probe ground terminal and circuit under test.

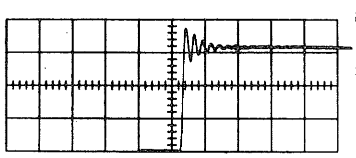


Fig. 3-10. Ringing of 12" ground return with 80 Mc oscilloscope; .05 µsec/cm.

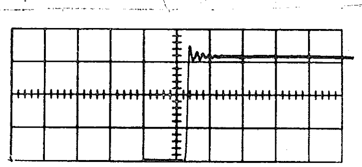


Fig. 3-11. Ringing of 5" ground return with 80 Mc oscilloscope; .05 µsec/cm.

*Usually about 3 to 4 times the -3db frequency, for instruments having properly-corrected transient response.

For instruments of greater than 15 Mc bandwidth used for very fast-rise waveforms, even greater precautions are necessary. Figs. 3-10 and 3-11 show the effect of 12" and 5" ground straps when used in viewing a pulse of less than 1 nsec risetime, on an oscilloscope of 4.5 nsec risetime (80 Mc bandwidth). A practical method for obtaining displays free of ringing in this range is the use of a coaxial adapter, such as that shown in Fig. 3-12. The adapter provides a short ground-return path, and consequently a low series inductance. Resonances formed with the probe input capacitance and the inductance of such an adapter are well beyond the zero-response frequency of most oscilloscopes using high-impedance probes.

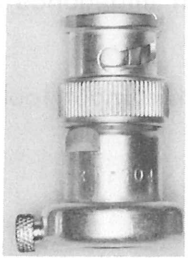


Fig. 3-12. Coaxial (BNC) adapter for use with probe.

Note that precautions against inductances on the ground side of the circuit apply equally to inductances in series with the probe input. Even short lengths of wire ahead of the probe tip may be enough to cause noticeable ringing in fast pulse work.

Chapter 4

INPUT IMPEDANCE

Although the term <u>input impedance</u> introduces this section, R and C terms were used in evaluating the loading effect on the signal to be measured. Actual impedance may not reveal information as useful as the effective R and C.

The effective input R and C do not remain constant because the input looks into a complex network (Fig. 4-1).

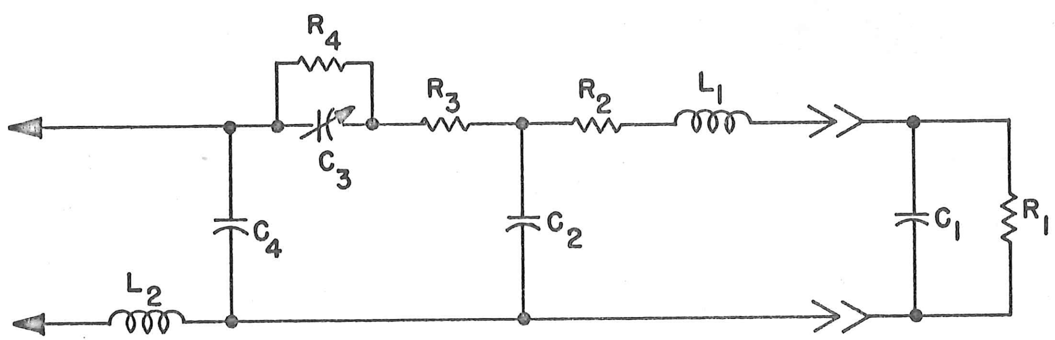


Fig. 4-1. Equivalent Circuit of Passive Probe

Approximations are noted in the text.

The schematic shows an approximation of the probe circuitry at frequencies from 1 Mc to 50 Mc. The scope input is represented by C_1 and R_1. The resistance of R_1 is so much larger than the reactance of C_1 that it can be neglected at these frequencies for practical calculations. Note that the capacitance of C_1 varies with frequency (and sometimes environmental factors); C_1 includes capacitances of wiring, switch wafers, and vacuum tube input; these capacitances vary measurably with frequency, because of dielectric changes, resistance changes and transit time.

The resistance R_2 is that of the inner conductor of the probe cable, designed to damp out resonances at the electrical length of the cable. L_1 is the distributed inductance of the cable, and C_2 is the distributed capacitance. For rough calculations at these frequencies they can be considered as lumped constants, but the distributed nature of the constants should be kept in mind. R_3 is a physically lumped component used for auxiliary damping. The series resistor R_4, can be neglected at the higher frequencies. C_3 is the input leg of the capacitive voltage divider and is made adjustable in order to compensate for the network at the desired attenuation ratio. C_4 represents the capacitance of the probe body and tip.

L_2 is the inductance of the ground wire attached to the probe itself. At low frequencies it is of no concern, but must be considered at higher frequencies, when it is often advisable to use a short ground prod to limit this inductance.

Fig. 4-2 shows how input characteristics of a general-purpose passive probe (P6006) change with frequency. A sample calculation of probe characteristics is presented in the Appendix. The change in apparent input capacitance, C_p, results primarily as the reactance of the input capacitance of the scope changes with frequency; however, the input capacitance of the scope also changes at the higher frequencies.

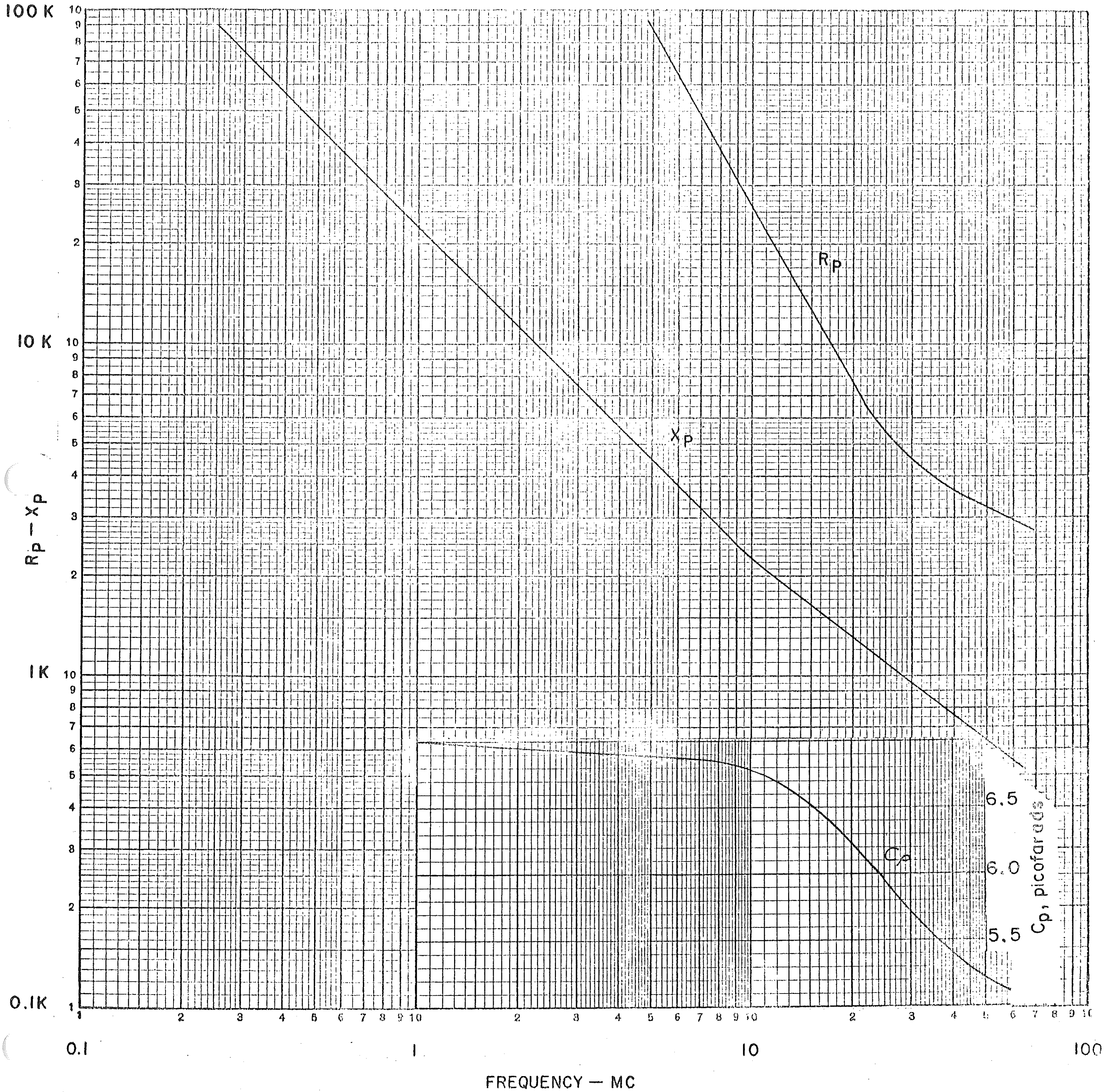


Fig. 4-2. Input characteristics of a general purpose probe as a function of frequency.

Chapter 5

VOLTAGE RATINGS

Probe voltage ratings are derived empirically and may be specified in different forms depending on the service required.

The DC rating depends primarily on the voltage rating of the compensating capacitor and the insulation in the nose.

The RMS rating may be specified below a particular frequency as equal to the DC rating. The RMS performance must be derated as frequency increases because the various portions of the circuit become subject to higher temperatures as the distribution of current changes with frequency. The equivalent circuit diagram, Fig. 5-1, shows the damping resistor R_3 and the cable resistor R_2 carrying more current as frequency increases; the operating voltage is limited by the heat-dissipating characteristics of resistor and cable. The input resistance in Fig. 5-1 is approximately 21 KΩ at 10 Mc; if 100 volts RMS is imposed on the probe, 1/2 watt must be dissipated in the probe and cable. This is almost as much as can be applied continuously without damaging the probe.

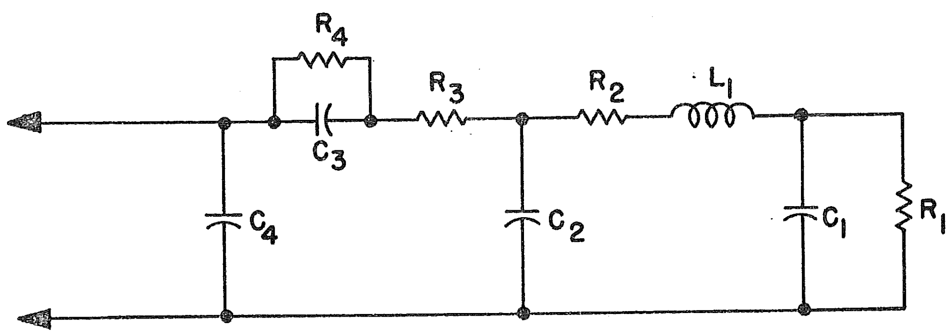


Fig. 5-1. Approximate probe circuitry at frequencies between 1 Mc and 50 Mc.

The peak rating, or peak pulse rating applied depends on the geometry of the probe head as well as the characteristics of R_3. A fast-rising pulse sees C_3 and C_2 as very low impedance, so that momentarily, E^2/R_3 watts is dumped into R_3. The body of R_4 is capacitively related to other conducting elements, and this circumstance momentarily imposes a high dissipation burden on some portion of R_4.

In consequence of these considerations a limited rate-of-rise of voltage in volts per unit time is sometimes applied, in addition to the peak pulse limitation. The allowable peak pulse is determined by the rate at which the several components can dissipate the energy, and is usually specified at a low duty factor (such as 10%) at a maximum pulse width. An example of these voltage ratings is shown in Fig. 5-2.

All probe voltage ratings are based on an ambient temperature of 77°F (25°C). At higher temperatures the operating voltages should be further derated.

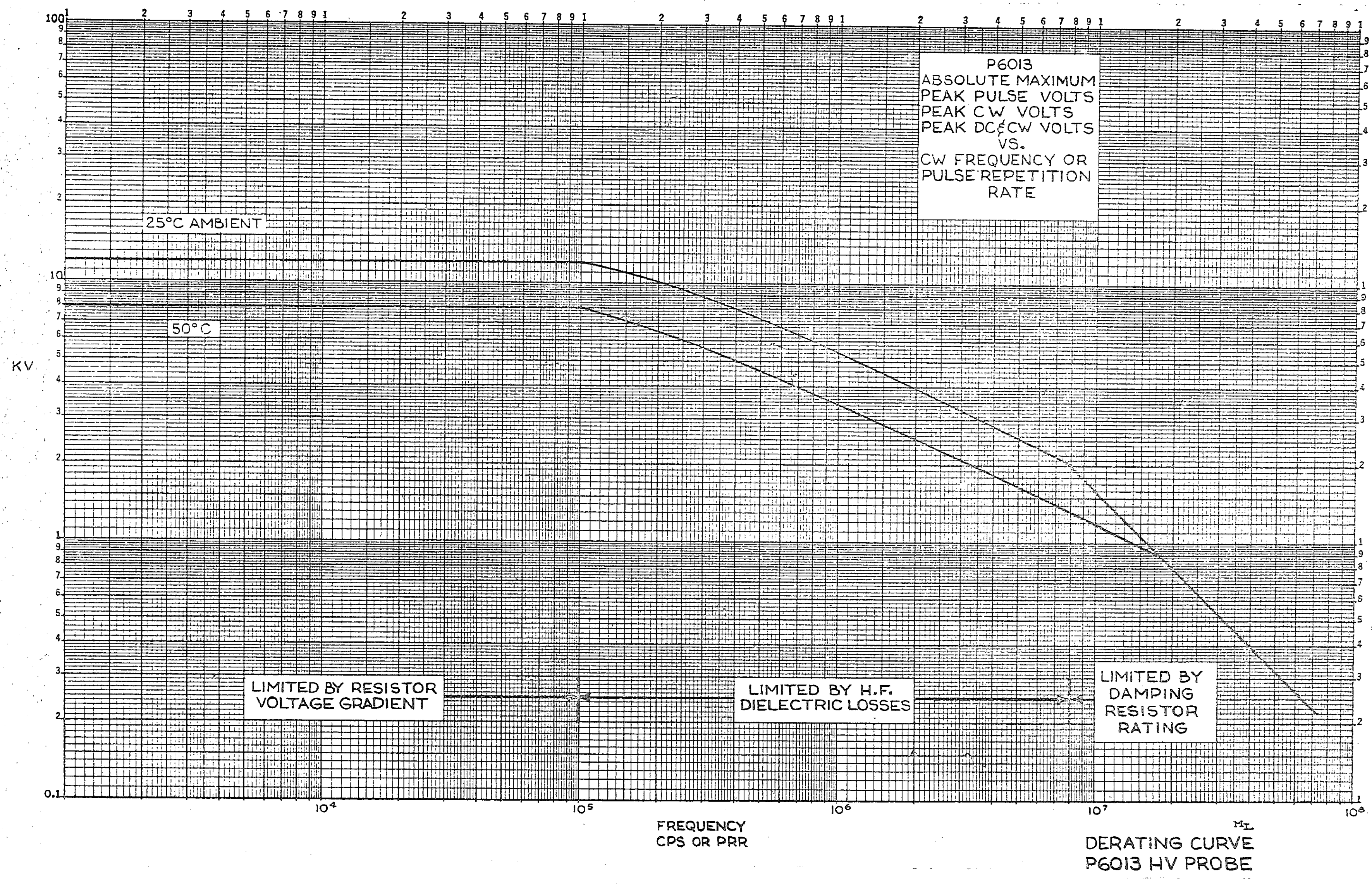


Fig. 5-2. Example of Probe Derating Curve

Chapter 6

USE OF PROBES

6-1. Selecting the Right Probe

For any application, a variety of probes may be available. Principles of selection for general purpose probes are as follows:

A. Select a probe which can be adjusted to match the input resistance and capacitance of the oscilloscope.

B. Select a probe having a suitable high-voltage rating. The choice should be modified by the intended application -- measurements of DC, low-frequencies, or high-frequencies. Note that voltage derating of most probes is required for radio-frequency work.

C. If the application requires a high input impedance, select a probe having the shortest cable length and the highest attenuation ratio compatible with the sensitivity desired. For high-frequency measurements and pulse applications, select a probe having the lowest input capacitance.

D. Special-purpose probes are normally required for the following applications:

1. Differential or Slide-Back Measurements

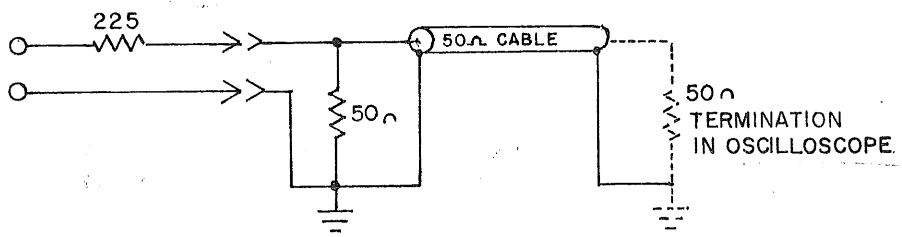
An ordinary RC probe contains one-half of a compensated voltage divider, and the division ratio of the whole divider may be in error by as much as ±3%. If these ordinary probes are used ahead of a differential amplifier, which is able to read out tiny differences between two input voltages, the common-mode rejection ratio of the system is rather poor. A typical figure might be 10:1 or 20:1.

Much higher common-mode rejection ratios (50,000:1 or greater) can be obtained if a pair of special, adjustable-ratio probes are used ahead of the differential amplifier. The adjustment range of these special probes is usually great enough to compensate for errors in the probes themselves and for the usually ±2% errors in the division ratios of the vertical attenuators used within the oscilloscope. Each time the vertical attenuator is turned to a new range, adjustable-ratio probes must be re-corrected to maintain a high common-mode rejection ratio.

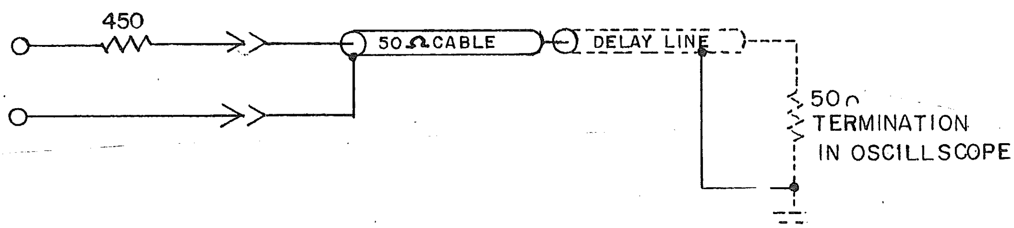
2. Sampling System

Passive probes for use with sampling oscilloscopes and plug-in preamplifiers must match the low-impedance signal input of the oscilloscope. Some sampling systems require a 50-Ω termination in the probe (Fig. 6-1a); other systems can be used with only a series attenuation element (Fig. 6-1b). The advantage of the latter is in obtaining higher probe input impedance with less attenuation. A probe with a 50-Ω termination may be used with either sampling system. The unterminated type of probe may be used only with a system having a built-in or accessory delay-line between the probe and the point where the sampling actually takes place, so that the interrogation circuit looks into 50 Ω during the period of interrogation.

Sampling systems incorporating the sampling bridge or interrogation circuit in the tip of the furnished probe may also be used with accessory probes or with attenuator heads which fit directly on the furnished probe. Only probes designed expressly for use with the particular sampling system should be employed, so that an optimized match to the input reactance of the furnished probe may be obtained.



a. Terminated type probe with 10X head. Input impedance for 10X attenuation is 250 Ω.



b. Unterminated type probe with 10X head. Input impedance for 10X attenuation is 500 Ω. A delay line may be used between probe and termination. See Fig. 7-2.

Fig. 6-1. Two types of passive probes for low-impedance sampling system inputs (50 Ω).

6-2. Proper Compensation

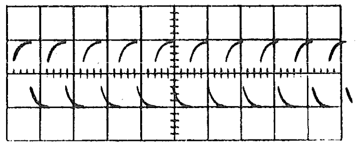
Adjustment of the probe compensation is usually necessary whenever a probe is transferred from one oscilloscope or plug-in to another. This procedure is not necessary for probes used for low-impedance sampling inputs and X1 probes. It is good practice to check probe compensation before starting any series of measurements, especially where a co-worker may have borrowed the probe since its last compensation check.

Compensation instructions for various probe types are generally furnished with the probe. General-purpose probes normally require only a single adjustment; high voltage and other special-purpose probe types may require two or more compensating adjustments.

The importance of proper probe compensation is illustrated in the waveforms of Fig. 6-2.

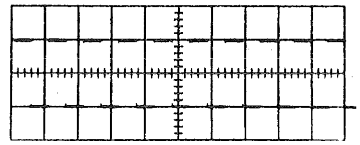
Note that what appears only as waveform distortion in viewing a 1-KC square wave results in serious amplitude errors for high-frequency sinewaves or short-duration pulses. The normal range of probe compensation adjustment allows measurement errors of -50%, +100% and greater, so a compensation-check is always worthwhile.

Undercompensated



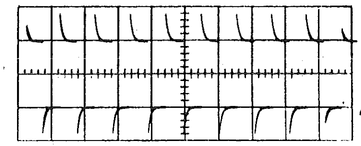
Round Corners

Correctly Compensated



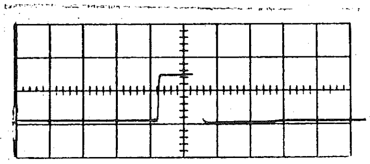
Square Corners

Overcompensated

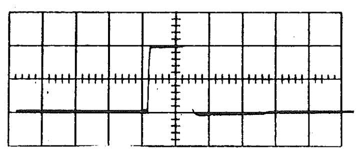


Overshoot

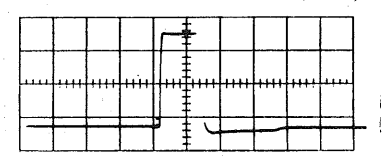
Calibrator Waveform, 1 Msec/cm
30 Mc oscilloscope with 10X probe



Indicated Amplitude 1.4 v

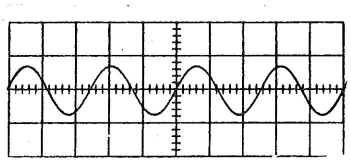


True Amplitude 2 v

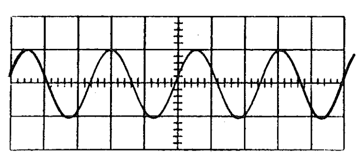


Indicated Amplitude 2.6 v

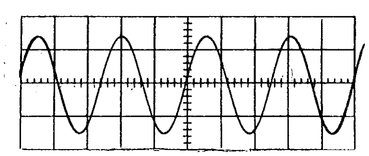
Short Pulse, 2 Msec/cm
30 Mc oscilloscope with 10X probe



Indicated Amplitude 1-1/2 v



True Amplitude 2 v



Indicated Amplitude 3 v

20-Kc Sinewave, 20 μsec/cm
30 Mc oscilloscope with 10X probe

Fig. 6-2. Effects of Improper Probe Compensation

6-3. "Standardization" of Inputs and Attenuators

If proper probe compensation is to be maintained as the oscilloscope input attenuator (volts/cm switch) is operated, the attenuator must have the same input RC time constant (and, of course, resistance) in each position. Otherwise, it would be necessary to re-compensate the probe each time the attenuator setting is changed.

Oscilloscopes intended for use with probes are factory-adjusted to provide the same input time constant at all attenuator positions. In many instruments this value is standardized to a specific capacitance (typically 20, 22, 24, 47 or 50 pf) for all instruments of a type. In other instruments, the input capacitance specification may be only approximate.

In either case, as components age and tubes or transistors are replaced, the input capacitance for the various attenuator positions may be affected differently, producing miscompensation at some sensitivities. Therefore, for best accuracy, attenuator compensation and input time constant standardization should be a regular part of periodic instrument calibration.

6-4. Selection of Test Points

For the most accurate and meaningful measurements, select the lowest impedance test point which will provide a useful waveform. Even though the input impedance of a probe is made as high as possible, it will still have some finite effect on the circuit under test.

The effects of the probe are minimized by selecting low-impedance test points. Usually, cathodes or emitters should be chosen in preference to plates or collectors; inputs to high-impedance voltage dividers in preference to mid-points; circuits with low resistive loads in preference to those working into high resistance. However, a circuit with low shunt capacitance to ground is usually a better test point than one with high stray or load capacitance. Circuits with inductive peaking or compensation produce displays which are difficult to evaluate properly in high-speed (pulse) work. It's often preferable to make indirect measurements than to try to make accurate evaluation of inductive-circuit waveforms affected by probe input capacitance.

The formula below yields the percentage difference in output of two low- pass filters. It can be used to determine the effects of probes and source conditions on measurement accuracy.

$$\text{Percent Error} = 100\left[1 - \sqrt{\frac{(fRC_1)^2 + .0253}{(fRC_2)^2 + .0253}}\right]$$

where:

- R = Test-point source resistance
- C_1 = Test-point source capacitance plus stray capacitance
- C_2 = C_1 plus probe input capacitance
- f = Frequency

Note that the formula may be used for risetime measurements where risetime in seconds, $T_r \approx \frac{0.35}{f}$.

Because the equation is cumbersome to use, graphs have been provided for convenience. Fig. 6-3 shows a family of curves plotting percent amplitude error against frequency or risetime, for several probe input capacitances, where source resistance is 1000 Ω and source capacitance plus stray capacitance is 20 pf. The frequency response of the 100-Ω, 20-pf RC without the probe is shown on the dotted line.

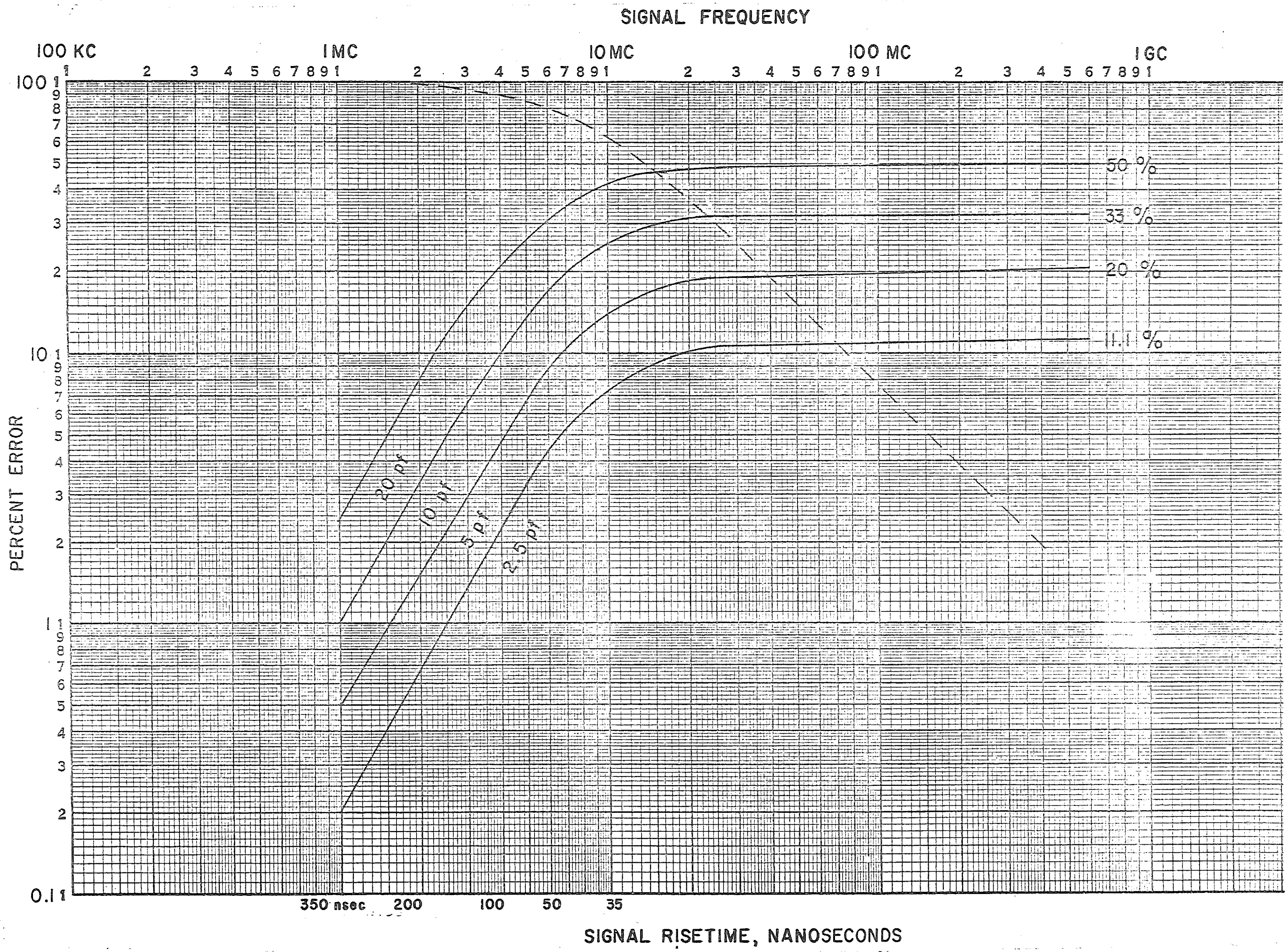


Fig. 6-3. Percent error vs frequency for source conditions of 1000 Ω and 20 pf

Fig. 6-4 shows the limiting cases for probes of various input capacitances, plotted against various test-point source resistances. In each case, the limit is taken to be the point where insertion of the probe into the circuit changes sine-wave amplitude or pulse risetime in the circuit by 5%. The oscilloscope and probe bandwidth may have additional effects on the display. The probe input capacitance is chosen approximately to equal the source capacitance plus stray capacitance.

Fig. 6-4 assumes a source and stray capacitance equal to the probe input capacitance. If the source plus stray capacitance is less than the probe capacitance the curves may be shifted to the right, allowing either a higher source impedance or a higher frequency.

To use Fig. 6-4 for probe selection, estimate the signal frequency or risetime, the source resistance, and the shunt capacitance. Then select a probe whose input capacitance is equal to, or less than, the estimated shunt capacitance, and whose 5%-error curve falls to the right of the point defining the frequency and source resistance.

To select a test-point, follow the frequency or risetime line across to the probe curve, then read up to find the maximum test-point resistance.

Fig. 6-5 presents the same data as Fig. 6-4 but assumes that source and stray capacitances are negligible.

In high-speed work, where test points are at low impedance but passive probes of conventional design (input C = 6 to 14 pf) present a capacitance too high for normal circuit operation, passive probes designed to work into 50-Ω sampling systems may be used to good advantage. The type shown in Fig. 6-1b, terminated only at the oscilloscope, should be used for highest input resistance for a given attenuation ratio. Input capacitance of these probes is usually about 0.5 to 0.8 pf; input resistances at frequencies below a few hundred Mc are 500 Ω for 10X attenuation, or 5000 Ω for 100X.

The effective input resistance of these probes is much more constant with frequency than that of conventional probes and if the test-point impedance is known, the measurement error can be easily calculated, even for complex waveshapes.

6-5. Effect of High-Frequency Fields

When a probe is used in a high-frequency field, voltages may be induced in the ground-loop (ground-lead for example) from the oscilloscope to the device under test. This voltage will be displayed on the oscilloscope in addition to the signal being observed.

A high-impedance path in the outer conductor of the cable (braid) can be provided by putting a ferrite core over the cable. The core and cable then behaves as a transformer and the voltage induced by the high frequency across this core will result in a voltage drop in the braid and also in the center-conductor of the cable. This way a common-mode isolation between the device under test and the oscilloscope is provided, and only the signal of interest will be presented on the CRT.

6-6. Time Delay

In time or phase measurements that use separate probes for each signal, the delay introduced by the probes should be considered. A standard 42-inch probe delays the signal about 5 nsec (10^{-9} seconds).

At 1 Mc, a properly-compensated, 42-inch probe will introduce a phase shift of about 1.8°.

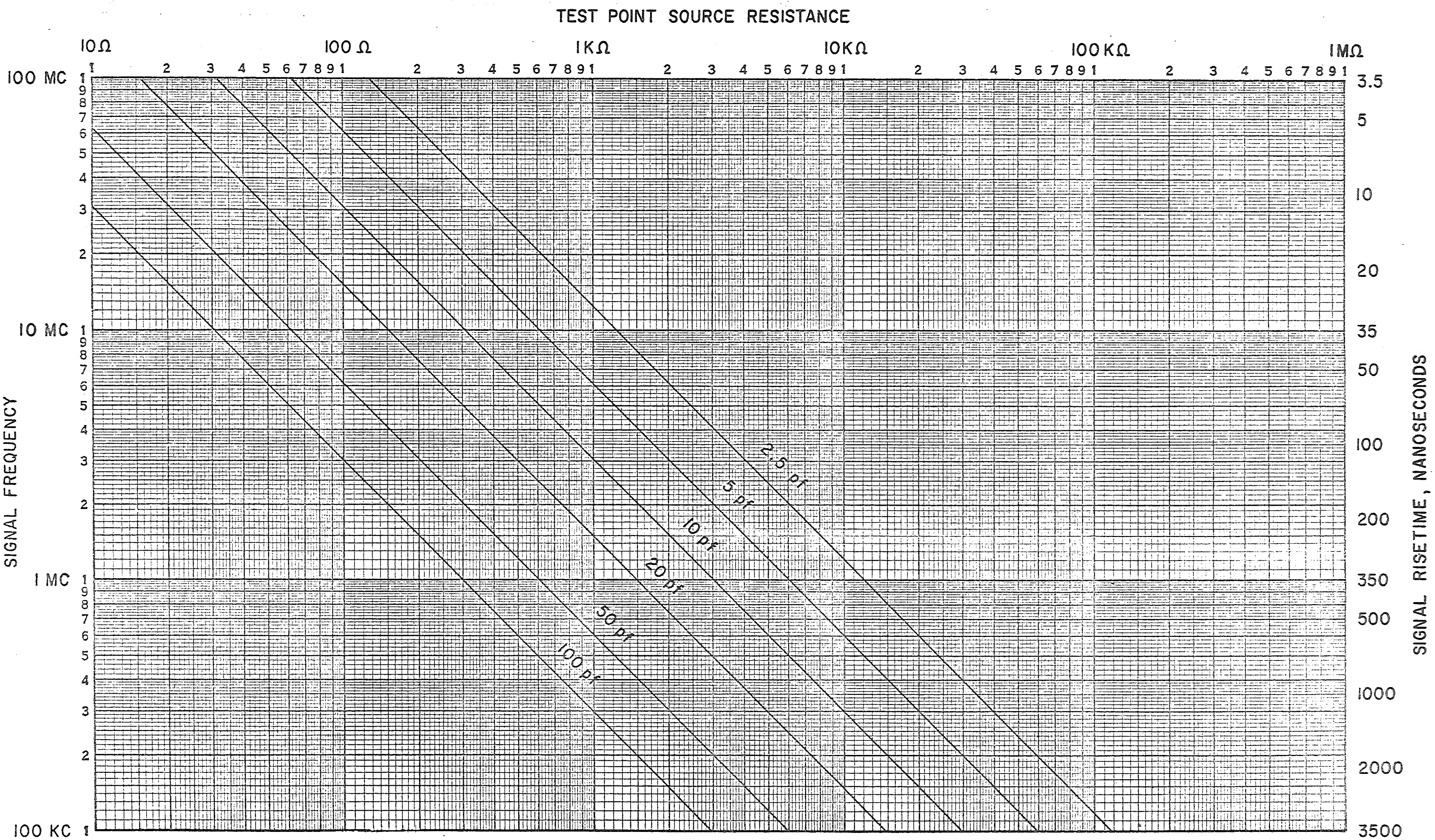


Fig. 6-4. Signal frequency (or risetime) plotted against source resistance for 5% maximum error. Capacitance figures are Probe C ≈ Source C plus Stray C.

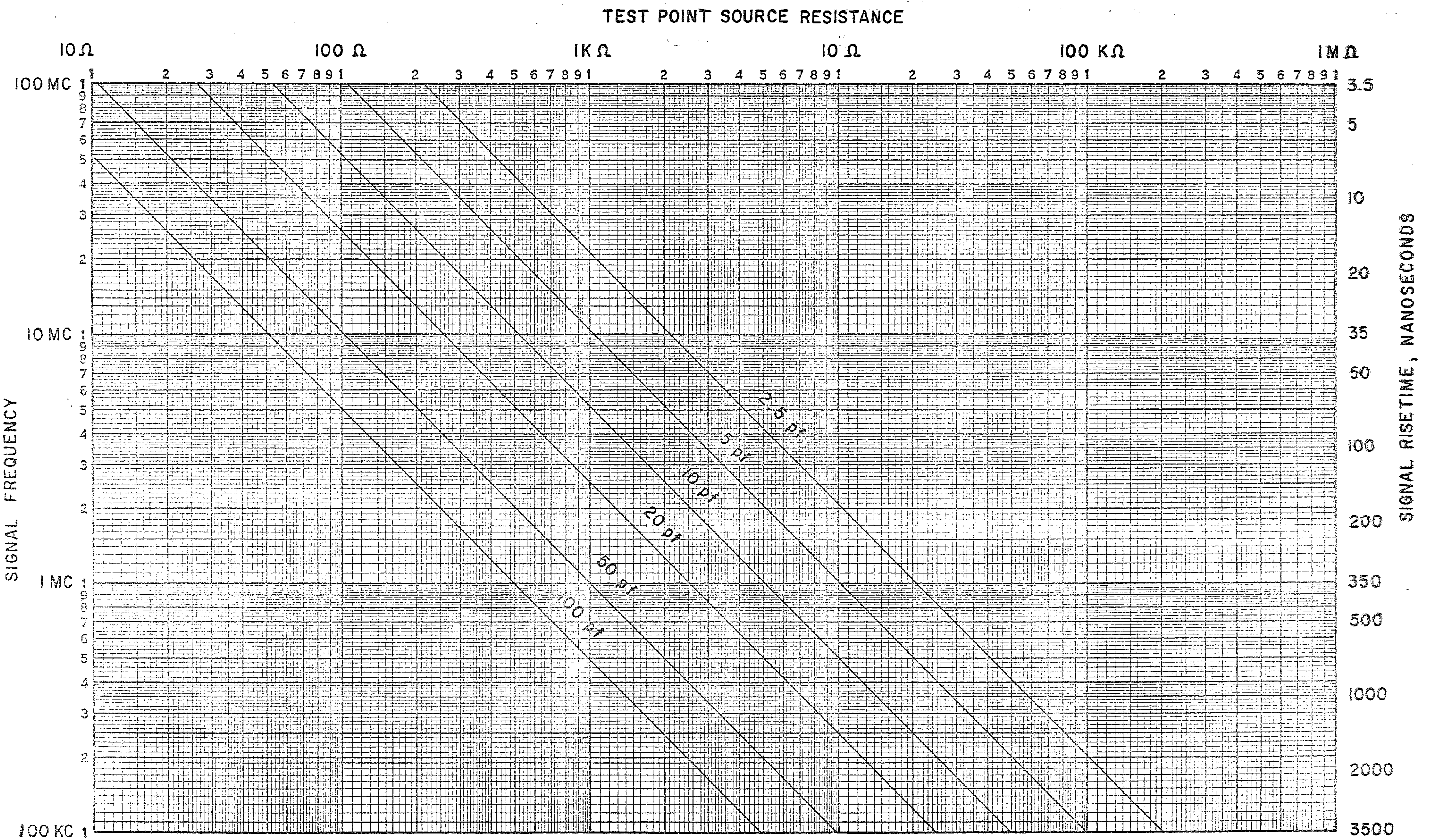


Fig. 6-5. Signal frequency (or risetime) plotted against source resistance for 5% maximum error. Capacitance figures are probe-input capacitance. Source and stray capacitance assumed negligible.

6-7. Care of the Probe

Oscilloscope probes -- particularly those designed for wide-band applications -- are susceptible to damage if treated carelessly. Avoid kinking or straining the cable, or subjecting the probe to excessive heat. Probes not in use may be stored in drawers, or hung from wall racks. Plastic probe-hangers, equipped with banana plugs, are available for mounting probes on the oscilloscope or peg board (with 1/8" holes). If probes are damaged, replacement parts and subassemblies (where simple part replacement is not practical) are usually available from the manufacturer. Substitution of non-standard parts is not advisable if original electrical performance is to be restored. In wide-band probes, even shortening the cable by more than a few percent may have noticeable adverse effects on performance.

APPENDIX

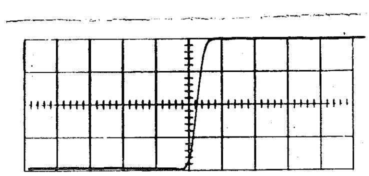
1. Characteristics of Probes Used with Type 82 Plug-in Unit

Tektronix Type 82 plug-in, with a Type 585 oscilloscope, provides a risetime of less than 4.5 nsec with an input resistance of 1 MΩ and an input capacitance of approximately 15 pf.

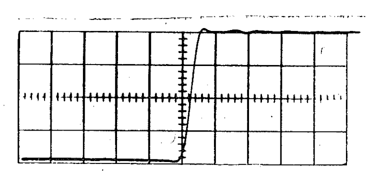
Several specialized probes are available to use with Type 82 for particular measurement requirements.

P6008 is a 10X attenuation, passive probe used with Type 82 where high input resistance and low input capacitance are important. P6008 reduces plug-in input capacitance to about 7 pf and increases input resistance to 10 MΩ. The probe is compensated for best response with the Type 82, but compensation should be examined each time the probe is used with a different Type 82.

For high-frequency or fast-response measurement it is necessary to minimize inductance from probe to source to avoid ringing. For this reason, the bayonet ground assembly, Tek 013-052, is provided. When a longer ground lead is imperative, the 3-inch ground strap may be used with the bayonet ground. Fig. 7-1 shows the response to be expected under these conditions. Note that the risetime appears shorter than the true value because the ringing contributed by the 3-inch ground lead distorts the rise. A more accurate measurement can be made by passing the ground lead through two or three ferrite beads (Ferroxcube 101, for example); the risetime increases to about 5 nsec, which is closer to the expected value of 5.5 nsec risetime. Another important factor is the risetime of the instrument with probe when observing fast-rising pulses from impedance levels higher than 25 Ω.



a. P6008 using bayonet ground assembly and grounding pin.
Time base: 10 nsec/cm
Sensitivity: 1 v/cm



b. P6008 using bayonet ground assembly and 3-inch ground strap.
Time base: 10 nsec/cm
Sensitivity: 1 v/cm

Fig. 7-1

All Tektronix instrument and probe risetimes are checked with a source impedance of 25 Ω. Whenever a P6008 is connected to a circuitry with impedance higher than 25 Ω, degrading of the risetime will occur, due to the time constant of the source impedance and the input capacitance of the probe.

For example:

$$\begin{aligned} \text{Source } R &= 500\ \Omega,\ C_{in} \text{ probe} = 7 \text{ pf} \\ \text{then, } T_r &= 2.2\ RC \\ &= 2.2 \times 500 \times 7 \times 10^{-12} \\ &= 7.7 \text{ nsec} \end{aligned}$$

Risetime observed on CRT (assuming pulse of zero risetime) = $\sqrt{7.7^2 + 5^2}$ which is approximately 9.1 nsec, in which 5 nsec is the risetime of the P6008 probe with instrument. This example shows that, for measuring fast-rising pulses, the source impedance and the input capacitance of the probe or instrument have to be as low as possible.

For the best performance, a probe with the lowest input capacitance should be used. When the source impedance is made larger, amplitude nonlinearity increases. For example, with a 1 KΩ source resistance, nonlinearity is only $\frac{1\ K}{10\ M}$ = 0.01%. With a 1 MΩ source resistance, nonlinearity will be $\frac{1M}{10\ M}$ = 10%. The increase in risetime with increasing source resistance is shown below:

Source Resistance	Total Risetime*
25 Ω	<5 nsec
50 Ω	5 nsec
75 Ω	5.15 nsec
100 Ω	5.22 nsec
200 Ω	5.8 nsec
500 Ω	9.1 nsec
1 KΩ	16 nsec

* Instrument and P6008

P6009 is a 100X attenuation passive probe used with Type 82 where minimum input capacitance is required in addition to high input resistance. Input resistance is 10 MΩ and input capacitance is reduced to about 2.5 pf, compared to 7 pf for P6008. This reduction of input capacitance may be imperative for some high-frequency measurements.

If the 3-inch ground lead is used, some ringing can be expected from fast-rising pulses. Although ringing will not be as obvious as that with P6008, caution should be exercised in interpreting the display. It may be necessary to use the bayonet ground assembly to prevent ringing.

System response to signals from a high source resistance will not be impaired as much with P6009 as with P6008 because of the lower input capacitance of P6009. For example:

With a source resistance of 500 Ω, the risetime of source resistance and probe input capacitance,

$$T_{ra} = 2.2 \times 500 \times 2.5 \times 10^{-12} = 2.7 \text{ nsec.}$$

Combining this with the overall 4.5 nsec risetime of P6009 with 82 plug-in:

$$T_{ra} = \sqrt{2.7^2 + 4.5^2} = 5.3 \text{ nsec.}$$

For higher source resistances, system response with P6009 becomes much faster than with P6008.

P6034 and P6035

In some high-frequency applications or pulse work the 7 pf capacitive loading of the P6008 or the 2.5 pf capacitive loading of the P6009 may be an important factor which has to be considered in measurements. In those cases where the input capacitance might be too high, the 10X P6034 or the 100X P6035 can be used. The input capacitance of these probes is 0.6 pf ±0.1 pf, while the input resistance is, respectively, 500 Ω and 5 KΩ. In some cases, a resistive loading may be preferred to capacitive loading, since the parallel resistance loading at some frequencies can be calculated more easily than the effect caused by capacitive loading.

Fig. 7-7 shows the typical input impedance vs frequency of the P6034, P6035, P6008, and P6009. When using the P6034 or P6035 probe, the end of the probe has to be properly terminated with 50 Ω. This can be done with a type 874QBP-A GR-to-male BNC adapter (Tek 017-064) and a 50 Ω BNC termination (Tek 011-049).

A higher-performance cable, such as RG8A/U can be used to extend the overall length of the probe. The additional cable must be provided with a GR fitting and connected to the cable end of the P6034 or P6035. Note that the oscilloscope end of the cable must be terminated. By choosing the correct length of cable, the reflection can be moved out of the area of interest. The results are illustrated in Figs. 7-2 through 7-6.

50-Ω Terminated P6034 Straight into 82

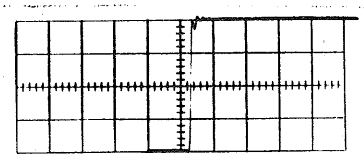


Fig. 7-2. 50 nsec/cm

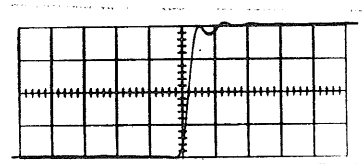


Fig. 7-3. 10 nsec/cm

P6034 with 5 nsec (approx. 40") RG8A/U Cable between Probe and Termination

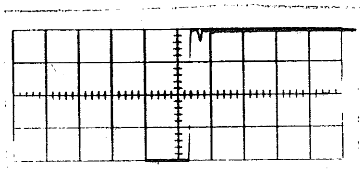


Fig. 7-4. 50 nsec/cm

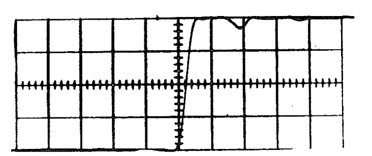


Fig. 7-5. 10 nsec/cm

Response with 20 nsec (13ft.) between P6034 and 50 Ω Termination

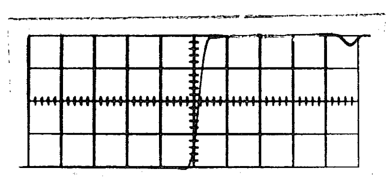


Fig. 7-6. 10 nsec/cm
Dip is reflection due to termination

The reflection, which appears as an 8% dip in the waveform, is caused by the input capacitance of the Type 82 connected in shunt with the 50 Ω termination. The reflection travels down the cable and reflects back when it reaches the resistor in the probe body. The down and back time of this reflection is twice the delay time of the cable between the termination and the resistor in the probe body.

As an alternate method of controlling the reflection, a 50 Ω GR 2X attenuator (Tek 017-046) can be connected between the probe and the 50 Ω termination. The attenuator will decrease the reflection amplitude by a factor of four. Although the probe attenuation is doubled, the voltage rating remains the same, which is 16 volts for the P6034 and 50 volts for the P6035.

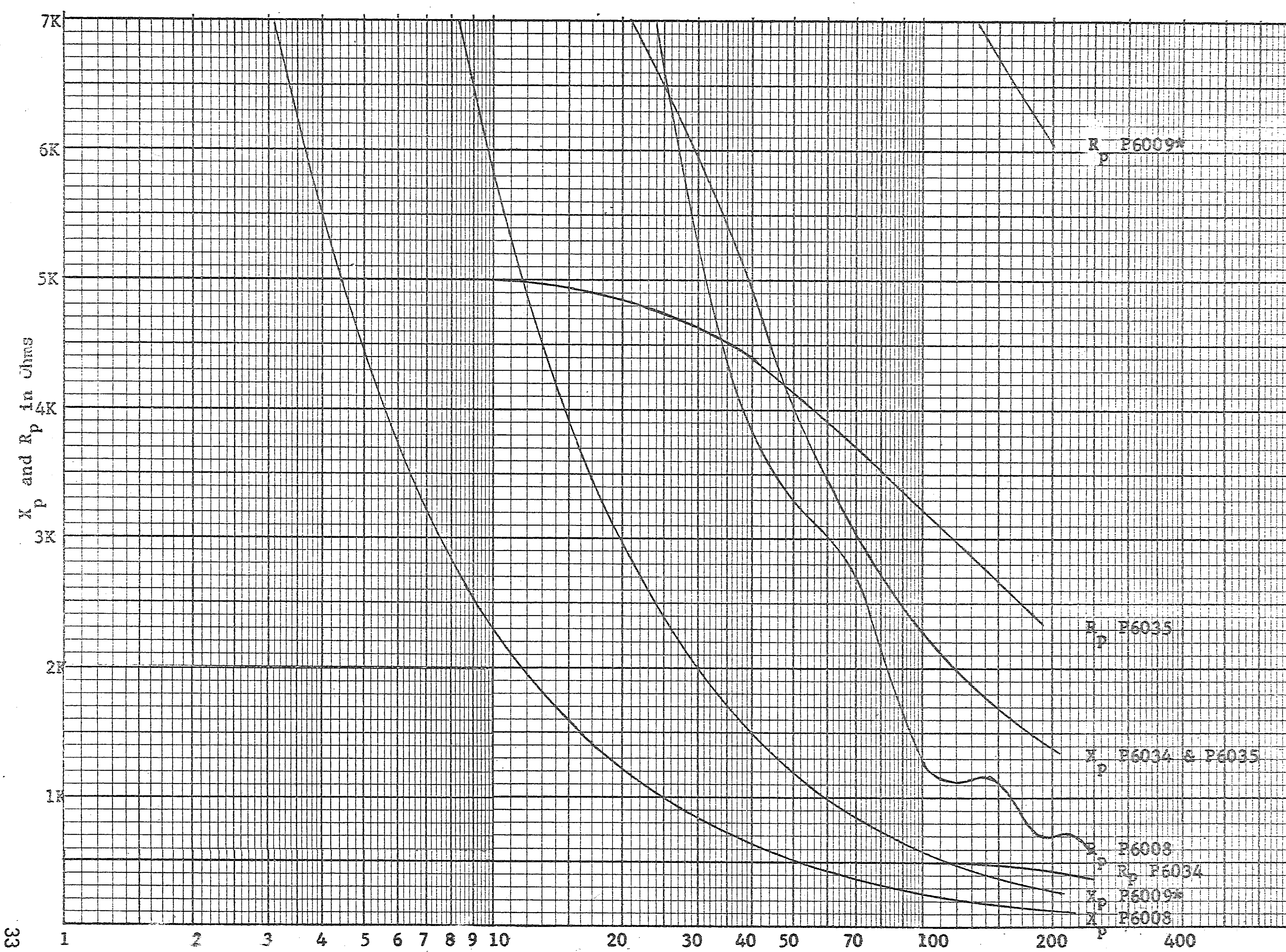
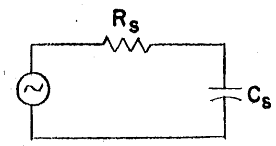


Fig. 7-7. Input Impedance vs Frequency

Conditions of high source impedance impose the same limitations on P6034 and P6035 that were noted above for P6008. Characteristics of P6034 and P6035 are defined using a 25-Ω source impedance. The risetime will be changed from:

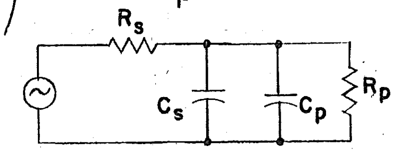
$T_r = 2.2\,R_sC_s$



where R_s is source Resistance

C_s is source Capacitance

to $T_r = 2.2\left(\dfrac{R_sR_p}{R_s + R_p}\right)(C_s + C_p)$



where R_p is probe Resistance

C_p is probe Capacitance

and the amplitude will be reduced by the factor $\left(\dfrac{R_p}{R_s + R_p}\right)$ times the rated attenuation ratio of the probe.

For example, if R_s = 1 K and C_s = 2 pf, the actual T_r = 4.5 nsec; using a P6034 (R_p = 500 Ω; C_p = 0.6 pf), T_r = 2 nsec.

When the source impedance is 1 KΩ, total attenuation for

$$\text{P6034} = \frac{1\text{ K} + 500\ \Omega}{50\ \Omega} = 30\text{X (instead of 10X)}$$

$$\text{P6035} = \frac{1\text{ K} + 5\text{ K}}{50\ \Omega} = 120\text{X (instead of 100X)}$$

When the P6034 or P6035 is used on signals with a DC-component higher than that for which the probe is rated, an AC-coupling capacitor can be used to block the DC and low frequency components up to 500 volts maximum; the response of the probe will not be affected at high frequencies. AC coupling is accomplished by inserting a 4700-pf GR type 874 K coupling capacitor (Tek 017-028) between the cable connector end of the probe and the 50-Ω termination. Decay time-constant is then 0.235 μsec. When using the 2X GR attenuator the coupling capacitor should be placed between the probe connector and the attenuator (Fig. 7-8). The low-frequency cut-off with the P6034 will be approximately 70 Kc. With the Type P6035, f_{co} is approximately equal to 7 Kc.

No ringing will be visible when using the 2-1/2" ground strap with these probes, because of the low input capacitance.

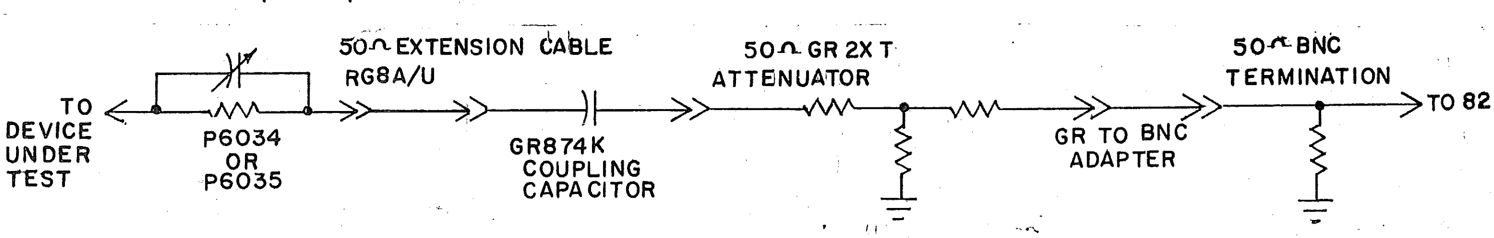


Fig. 7-8. Connections for P6034 or P6035 to Type 82 Plug-in

P6015

When signals greater than 1.5 Kv have to be observed with a Type 82 plug-in unit, a P6015 1000X high-voltage probe can be used. This probe increases the input R to 100 MΩ and decreases the input capacitance to approximately 2.8 pf. The risetime of the P6015 in combination with a Type 82 plug-in and a Type 580 series scope is approximately 5.5 nsec at an overall sensitivity of 100 volts per centimeter. At an overall sensitivity of 10 volts per centimeter, the combination risetime is approximately 6 nsec.

The P6015 should be compensated for the input capacitance of the Type 82 plug-in unit. On fast-rising pulses, the inductance of the ground strap will introduce ringing, as it does when used with the P6008 and P6009. This ringing can be reduced by putting ferrite cores (as many as needed) over the cable.

CT-1 and P6040

The CT-1 is a current transformer designed to measure fast current transients. The conductor carrying the current to be measured must be passed through the core of CT-1; for this reason the CT-1 is often permanently attached to the circuit. P6040 conducts the output of CT-1 to the scope.

The transresistance of CT-1 is 5 mv/ma into 50 Ω. The CT-1 introduces 1 Ω shunted by approximately 5 μh into the source, when the P6040 is properly terminated in 50 Ω. The risetime of CT-1 alone is about 350 ps; with the Type 82 in the 100 mv position the total risetime is about 4 nsec; the overall sensitivity is 20 ma/cm. With the 82 in the 10X gain position and the attenuator in the 0.1 v/cm, the total sensitivity is 2 ma/cm with a total risetime of approximately 4.3 nsec. The low frequency 3-db point is at 35 Kc with a time constant of 5 μsec.

2. Sample Probe Calculations

Following is a sample calculation at 10 Mc to show how the several parameters affect the characteristics of P6006 probe as frequency changes. The special coaxial cable used is 42" long, and is represented by the lumped constants, 33 pf, 290 Ω, and 0.8 μh. Within the useful frequency range of the probe, the errors arising from the lumped-constant assumption are not significant to the discussion.

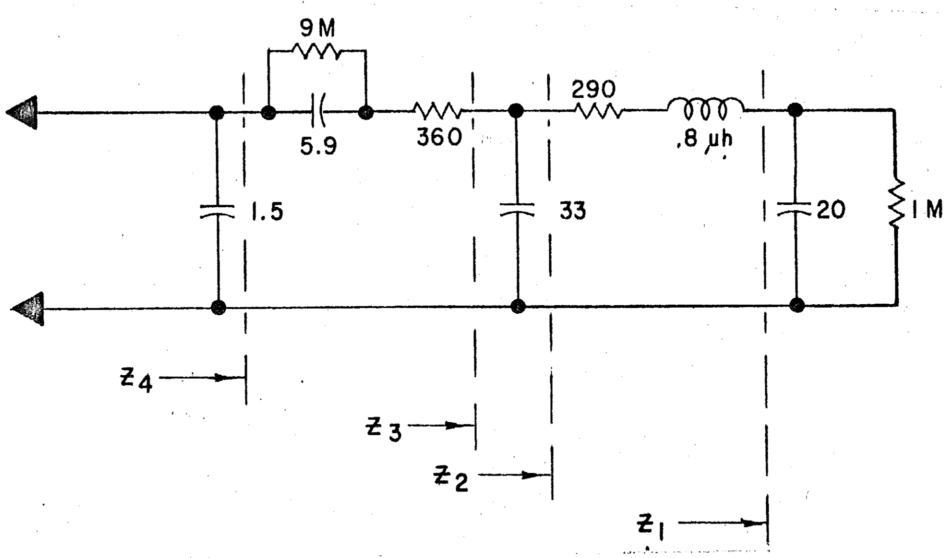


Fig. 7-9. The equivalent circuit of a P6006 probe

Convenient expressions are found on page 121 of Reference Data for Radio Engineers (Federal Telephone, 4th Edition) for transforming impedance between series and parallel configurations:

$$Z^2 = R_s^2 + X_s^2 = \frac{R_p^2 X_p^2}{R_p^2 + X_p^2} = R_s R_p = X_s X_p \qquad \text{(Equation 1)}$$

Beginning at the right side of the diagram (Fig. 7-9) with Z_1, the resistance and capacitance of the scope input are 1 MΩ and 20 pf. At 10 Mc the reactance of 20 pf is 800 Ω, and the 1 MΩ may be neglected. The 800 Ω is added in series with the 0.8 μh and the 290 Ω for Z_2:

$$Z_2 = 290 + j50 - j800 = 290 - j750 \ \Omega$$

To convert the R and X of Z_2 to parallel form, convert from Equation 1 above:

$$Z^2 = R_s^2 + X_s^2 \qquad \text{(Equation 2)}$$

$$Z^2 = (290)^2 + (750)^2 = 645 \times 10^3$$

and

$$R_p = \frac{Z^2}{R_s} \qquad \text{(Equation 3)}$$

$$R_p = \frac{645 \times 10^3}{290} \qquad = 2220\ \Omega$$

and

$$X_p = \frac{Z^2}{X_s} \qquad \text{(Equation 4)}$$

$$X_p = \frac{645 \times 10^3}{750} \qquad = -j860\ \Omega$$

then $C_p = 18.5$ pf

Add 33 pf in parallel:

$$C_{p+} = 18.5 + 33 \qquad = 51.5 \text{ pf}$$

and

$$X_{p+} = -j308\ \Omega$$

Now it is necessary to transfer these parallel components of Z_3 into series form. First find the value for Z_3^2 by using equation 1 above:

$$Z^2 = \frac{R_p^2 X_p^2}{R_p^2 + X_p^2} \qquad \text{(Equation 5)}$$

$$Z_3^2 = \frac{(2220)^2\ (308)^2}{(2220)^2 + (308)^2} \qquad = 93.4 \times 10^3 \Omega$$

and

$$R_s = \frac{Z^2}{R_p} \qquad \text{(Equation 6)}$$

$$R_s = \frac{93 \times 10^3}{2.22 \times 10^3} \qquad = 44\ \Omega$$

and

$$X_s = \frac{Z^2}{X_p}$$

$$X_s = \frac{93 \times 10^3}{308} \qquad = -j303\ \Omega$$

then

$$Z_3 = 44 - j303\ \Omega$$

To find Z_4, determine the reactance of 5.9 pf at 10 Mc and add it to the 303 Ω reactance of Z_3, and add the 360 Ω to the 44 Ω end of Z_3. The 9 MΩ is neglected because it is not significant compared to the reactance of 5.9 pf at 10 Mc.

$$Z_4 = 44 + 360 - j303 - j2700$$

$$Z_4 = 404 - j3000 \, \Omega$$

To convert Z_4 to the parallel form, use equation 2:

$$Z^2 = R_s^2 + X_s^2$$

$$Z^2 = (404)^2 + (3000)^2 = 9.16 \times 10^6$$

and equation 3:

$$R_p = \frac{Z^2}{R_s}$$

$$R_p = \frac{9.16 \times 10^6}{404} = 22.7 \text{ K}\Omega$$

and equation 4:

$$X_p = \frac{Z^2}{X_s}$$

$$X_p = \frac{9.160 \times 10^3}{3 \times 10^3} = -j3050 \, \Omega$$

The capacitance represented by a reactance of 3050 Ω at 10 Mc is 5.2 pf; the 1.5 pf capacitance contributed by the hardware at the nose of the probe is added in:

$$C_{pt} = 5.2 + 1.5 = 6.7 \text{ pf}$$

At 10 Mc, the circuit being examined will look into a resistance of 22.5 KΩ and a capacitance of 6.7 pf.

Values calculated by this procedure can be compared to the curves of Fig. 4-2.