Measurement Concepts

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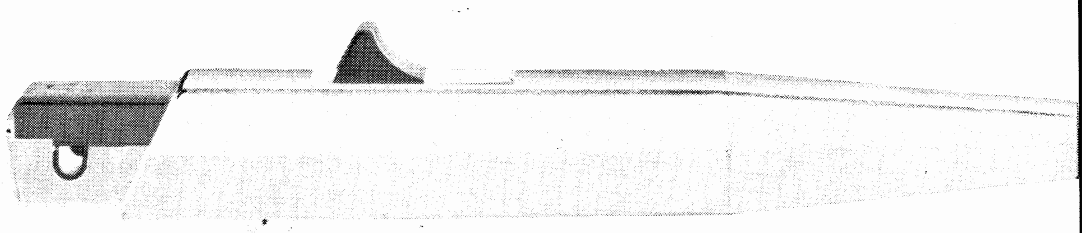
PROBE MEASUREMENTS



PROBE MEASUREMENTS

BY

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TEKTRONIX®

MEASUREMENT CONCEPTS

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CONTENTS

INTRODUCTION

The intent of this book is to develop an understanding of the usefulness and limitations of a cathode-ray oscilloscope input coupling device, "The Probe." The following chapters will deal with understanding specifications, considerations in use and signal measurement evaluation of Tektronix, Inc. probes. The area of probe circuitry and construction will be covered only to a depth necessary in conveying a specification or measurement concept. An in-depth discussion of the mechanical and electrical make-up of probes is contained in a companion volume, *Oscilloscope Probe Circuits*.

Ideal Function

The probe's function is to provide a medium for the transfer of signal energy from a source to the input of the oscilloscope without disturbing the source and without changing the structure of the transferred energy. At the present state-of-the-art no probing device achieves the *ideal* case and all probes load a signal source to some extent. No matter how non-ideal a probe may be, it will still serve several useful purposes:

1. The probe is a handy, movable, probing device which greatly extends the "usability" of our oscilloscope vertical amplifiers.

2. The probe's shielded cable will reduce external fields from causing distortion of a signal.

3. The probe will reduce the loading effects which would have been present if the oscilloscope input were connected directly to the signal source. (Passive nonattenuating probes are an exception to this statement.)

4. The attenuator probe will change the sensitivity range of the oscilloscope to which it is connected.

Probes may be divided into several classifications. Among these are Passive, Active and Current.

Passive Probes

These contain only passive elements, i.e., resistors, capacitors, inductors. Their main advantage is lowest cost of all probes providing reduced loading. At present this type has the fastest risetime, 0.1 ns (P6034). Their main disadvantage is, although reduced loading results from $\geq$ 10X attenuation factor, it requires an increased oscilloscope sensitivity to maintain a given signal amplitude.

Active Probes

These contain small tubes, FET's, transistors or combinations of devices which provide signal gain. Their main advantage is providing the reduced loading effect of attenuator passive probes without signal attenuation thus maintaining the oscilloscope's original sensitivity range. Their main disadvantage is higher cost. They also have limited dynamic range and are less rugged than passive probes.

Current Probes

These convert current flux fields to voltage signals by transformer action. They may contain other semiconductor devices such as a Hall Generator. The main advantage is that they provide minimum load on the circuit under test. The main disadvantage is they reflect Z into the circuit under test. It is difficult to evaluate current waveforms in a reactive circuit.

VOLTAGE PROBES				
Recommended Use Area	**Probe Only Risetime**	**Probe Input R,C**	**Attenuation**	**Type**
DC to 3.5 GHz	0.1 ns	0.7 pF, 500 Ω	10X	P6034 Miniature
DC to 1.7 GHz	0.2 ns	0.6 pF, 5 kΩ	100X	P6035 Miniature
DC to 1 GHz	0.35 ns	2 pF, 100 kΩ	1X	P6038 Sampling
DC to 850 MHz	0.4 ns	3.6 pF, 10 MΩ	10X	P6032
DC to 230 MHz	1.5 ns	5.5 pF, 10 MΩ	1X	P6045 FET
DC to 150 MHz	1.2 ns	10 pF, 10 MΩ	10X	P6047 Miniature
	2 ns	2.5 pF, 10 MΩ	100X	P6009
DC to 100 MHz	3 ns	7.5 pF, 10 MΩ	10X	P6008
	3.5 ns	10 pF, 1 MΩ	0.1X	P6046 Differential Probe & Amplifier
	2.6 ns	1 pF, 1 kΩ	10X	P6048 Miniature
DC to 50 MHz	4 ns	2.7 pF, 100 MΩ	1000X	P6015 High Voltage Up to 40 kV
	2 ns	10 pF, 10 MΩ	10X	P6010 Miniature
DC to 33 MHz	7 ns	3 pF, 100 MΩ	1000X	P6013A High Voltage Up to 12 kV
	5 ns	7 pF, 10 MΩ	10X	P6006
	7 ns	2 pF, 10 MΩ	100X	P6007
	12 ns	50 pF, 1 MΩ	1X	P6011 Miniature
	5 ns	11.5 pF, 10 MΩ	10X	P6012 Miniature
	7 ns	12 pF, 8 MΩ	10X	P6023
	10 ns	50 pF, 1 MΩ	1X	P6027
	10 ns	50 pF, 1 MΩ	1X	P6028
DC to 21 MHz	17 ns	13.5 pF, 10 MΩ	10X	P6049 Miniature

CURRENT PROBES			
Recommended Use Area	**Probe Risetime**	**Minimum Defl. Factor**	**Type**
35 kHz to 1 GHz	0.35 ns	5 mV/mA	P6040/CT 1
1.2 kHz to 150 MHz	0.5 ns	1 mV/mA	P6041/CT 2
8.5 kHz to 150 MHz	2.2 ns	1 mA/mV	P6022/Passive Termination
100 Hz to 70 MHz	5 ns	1 mA/div	P6022/134 Amplifier
450 Hz to 60 MHz	5.8 ns	2 mA/mV	P6021/Passive Termination
DC to 50 MHz	7 ns	1 mA/div	P6042/Amplifier
12 Hz to 40 MHz	9 ns	1 mA/div	P6021/134 Amplifier

Fig. 1-1. List of all current Tektronix probes (passive highlighted).

1

UNDERSTANDING SPECIFICATIONS

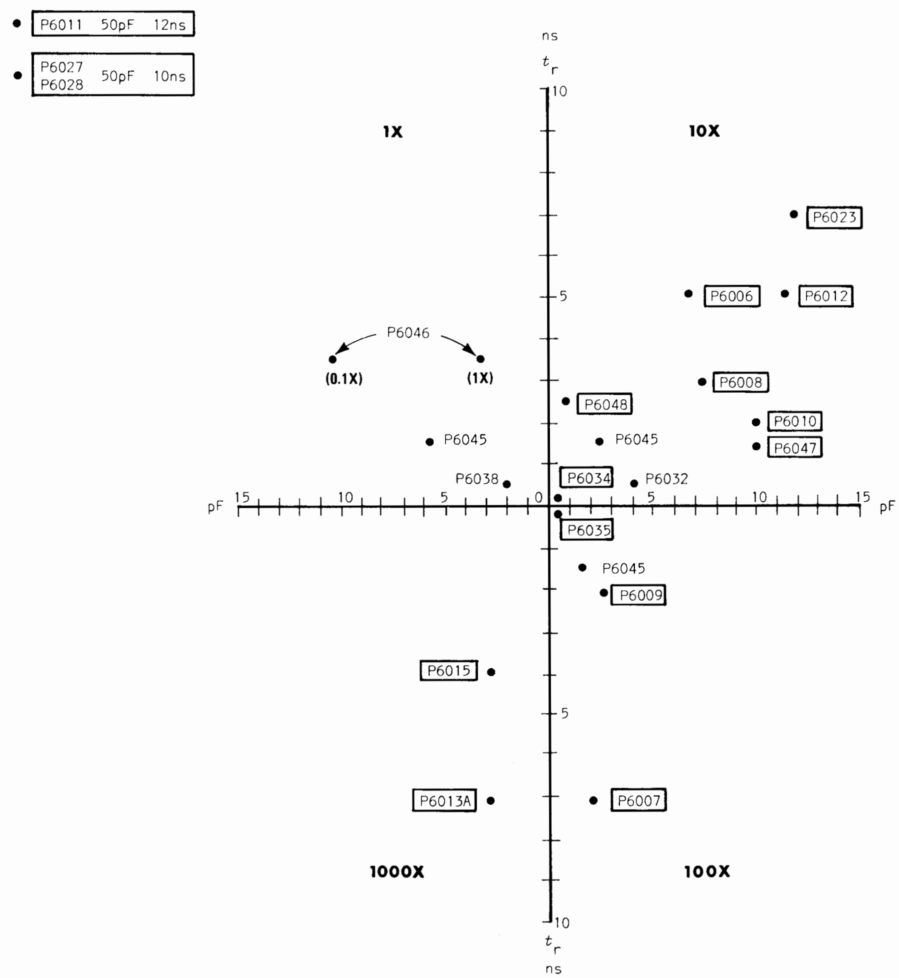


Fig. 1-2. Identical information to Fig. 1-1 showing faster probes toward the center.

need for basic under-standing

The passive probe is presently used from DC to frequencies in excess of 3.5 GHz. Fig. 1-1 lists all probes currently available from Tektronix with the passive probes highlighted. Fig. 1-2 displays this same group of probes in a different manner: showing the individual probes effective capacity versus risetime (t_r) and separated into attenuation quadrants of 1X, 10X, 100X and 1000X. These charts graphically display a very large number of probe types, any one of which may be able to accomplish a specific measurement requirement. To effectively select one from this grouping, a basic understanding of the probe's specifications is necessary.

P6006

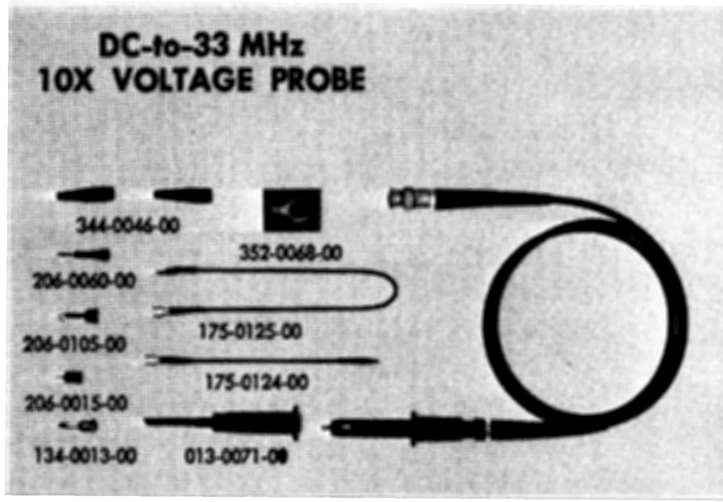
Consider the specifications of the Tektronix P6006 probe as shown in Fig. 1-3. As the specification indicates, the P6006 is a general purpose probe designed for use with oscilloscopes having a frequency or bandwidth capability of DC to 33 MHz. This statement, while very general in nature, does place the intended use area of the P6006 at ≤33 MHz. Using the probe within this frequency range will insure a *minimum loading effect* (Chapter 3).

The next portions of the specifications interrelate and should be considered at one time.

Compensation range capability is stated by: "The probe can be compensated to match plug-ins and oscilloscopes with input capacitance of 15 pF to 47 pF and input resistance of 1 MΩ.

Attenuation is 10X.

Input Resistance is 10 megohms.



The P6006 is a general-purpose probe designed for use with Tektronix DC-to-33 MHz Oscilloscopes. The probe can be compensated to match all Tektronix Plug-Ins and Oscilloscopes with input capacitances of 15 pF to 47 pF and input resistance of 1 MΩ.

ATTENUATION is 10X.

INPUT RESISTANCE is 10 megohms.

INPUT CAPACITANCE for standard length probe is approximately 7 pF when used with an instrument having a 20-pF input capacitance; 8.5 pF for the 6-ft version, 11 pF for the 9-ft version, 13 pF for the 12-ft version.

PROBE RISETIME is approximately 5 ns.

TYPICAL RISETIME of probe, Type 1A2 Plug-In Unit, and Type 545B Oscilloscope is 12 ns.

VOLTAGE RATING is 600 V DC, AC peak, or DC and AC peak combined.*

P6006 3.5-FT PROBE, order 010-0127-00 BNC or 010-0125-00 UHF

P6006 6-FT PROBE, order 010-0160-00 BNC or 010-0158-00 UHF

P6006 9-FT PROBE, order 010-0146-00 BNC or 010-0142-00 UHF

P6006 12-FT PROBE, order 010-0148-00 BNC or 010-0144-00 UHF

Includes: straight tip (206-0015-00); hook tip (206-0105-00); retractable hook tip (013-0071-00); spring tip (206-0060-00); banana plug (134-0013-00); two minigator clips (344-0046-00); probe holder (352-0068-00); 5-inch ground lead (175-0124-00); 12-inch ground lead (175-0125-00); instruction manual (070-0381-00).

*Peak-to-peak voltage derating is necessary for CW frequencies higher than 5.7 MHz when working into a 20-pF input, or higher than 3.6 MHz when working into a 47-pF input.

Fig. 1-3. P6006 specifications.

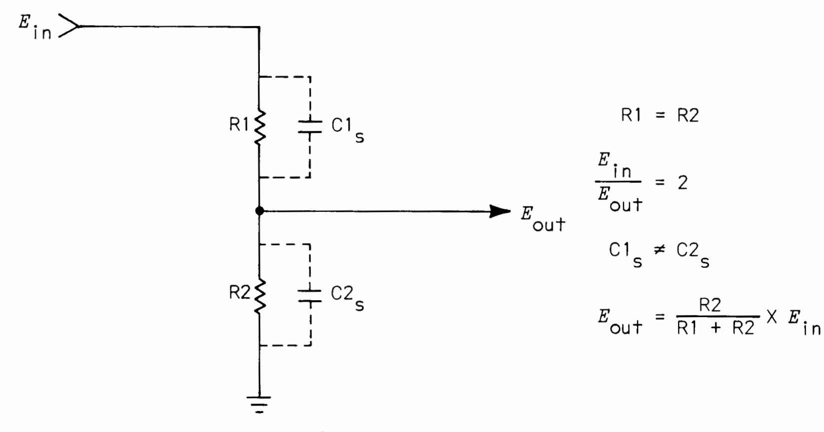


Fig. 1-4. Simple attenuator.

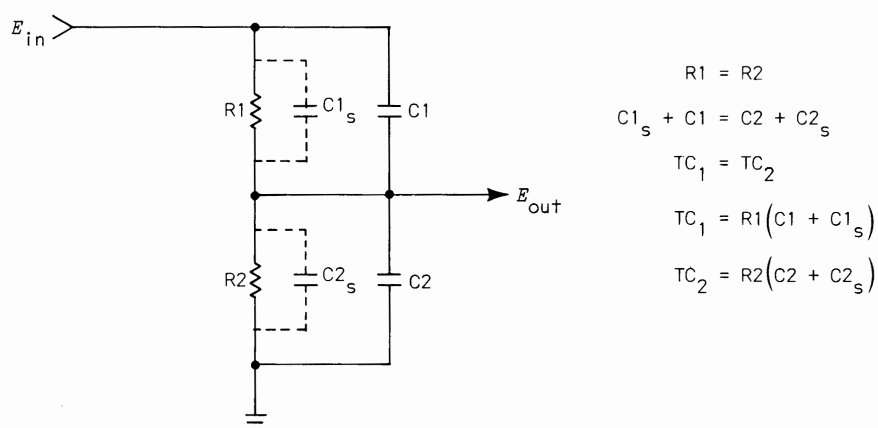


Fig. 1-5. Compensated 2X attenuator.

passive attenuation and compensation

A passive probe is an extension of an oscilloscope vertical amplifier's passive input attenuator. To gain a basic understanding of passive attenuation and compensation, consider the simple attenuator in Fig. 1-4. If R1 = R2, then this divider will have an attenuation factor of 2 times. (E_{in} to E_{out} = 2.) The division will be 2X for DC only. In addition to the resistance values R1 and R2, each has additional physical and environmental capacities. If the frequency of the voltage applied to this simple attenuator were increased from some low value, the attenuation factor would change due to these "stray" capacities. The change in the attenuation factor with frequency results from this "uncompensated" voltage divider. To properly compensate this divider, additional capacity is added in shunt with each resistor and has the same reactance ratio as the intended division ratio. Fig. 1-5 shows a properly compensated 2X voltage attenuator.

constant impedance

Assume that R2 and C2 were the input of an oscilloscope having values of 1 MΩ and 20 pF respectively. If a 2X attenuator were to be selected by an oscilloscope vertical sensitivity switch, one other design restriction would exist which adds complexity to a simple frequency compensated attenuator. The restriction requires the input impedance (shunt R and C) to appear the same in all attenuator positions. Fig. 1-6 shows a 2X attenuator which maintains the original input R and C values.

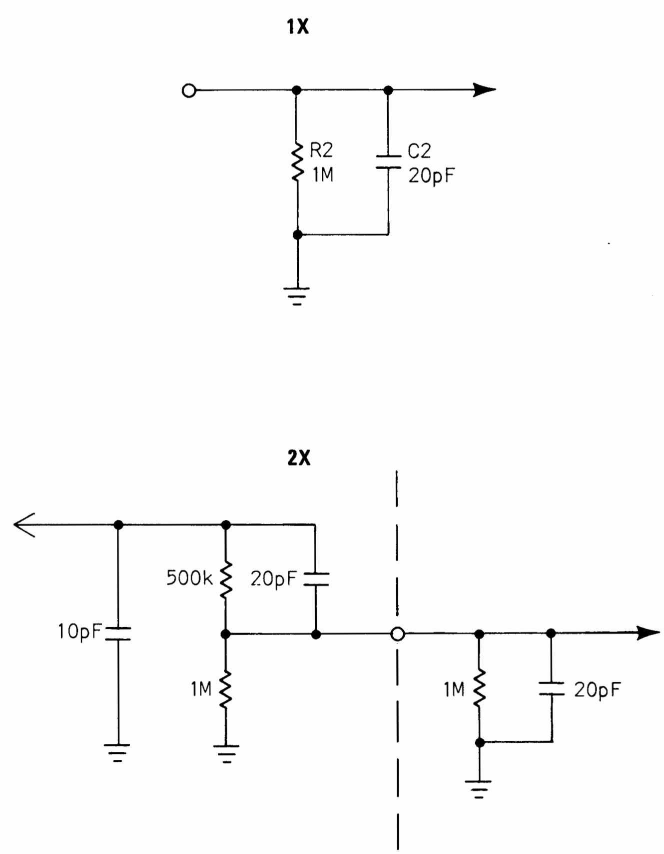


Fig. 1-6. Circuits 1X and 2X have the same input impedance (1 MΩ, 20 pF).

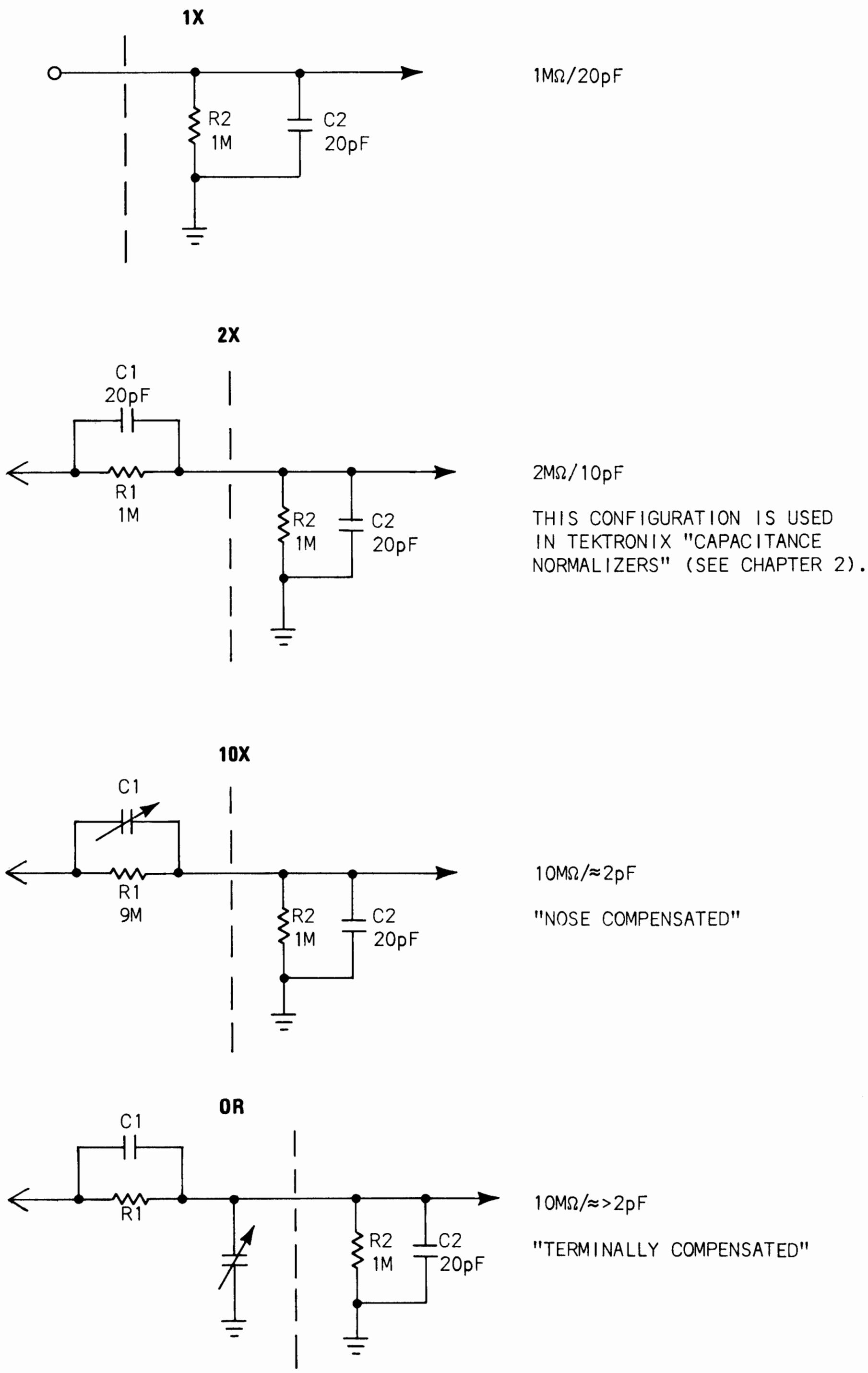


Fig. 1-7. Input impedance increases with passive attenuator.

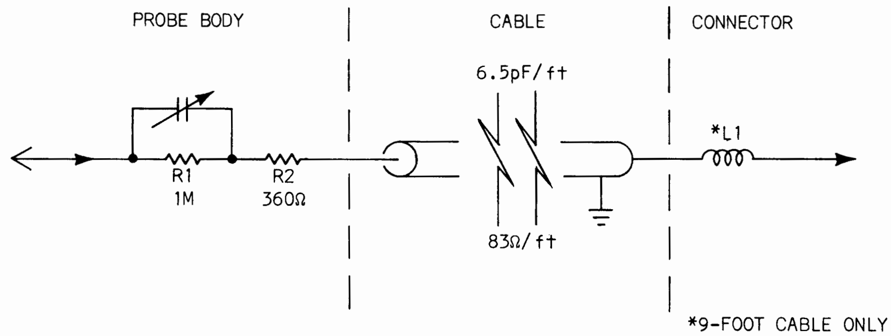


Fig. 1-8. P6006 probe schematic.

The passive probe maintains the same attenuation concept but takes advantage of the increased input impedance (increased R, decreased C) inherent in the design. Fig. 1-7 shows this advantage. Compensation may be accomplished by making C1 variable or by adding a variable across C2. In the case of the P6006, C1 is variable with sufficient range to allow proper compensation of the probe if C2 has values of 15 pF to 47 pF.

Attenuation of 10X is established by the value of R1 and R2.

Input resistance of 10 megohm is the sum of R1 + R2.

Input capacitance for a standard length (3.5 ft) probe is approximately 7 pF when used with an instrument having 20 pF input capacitance.

Difficulty arises when trying to relate the 7 pF specification to the simple attenuator probes of Fig. 1-7. Fig. 1-7 failed to include the distributed capacitance of the probe cable which is in shunt with C2. The passive attenuator probe is generally an unterminated coaxial system where an impulse would tend to have reflections and undesirable signal distortion. To damp these reflections, a cable of special resistance center wire is used. Because of the very small center wire, the capacity/foot is also quite small, ≈6.5 pF/ft.

resistance wire

Fig. 1-8 shows the P6006 schematic which evolved from the simple compensated passive probe of Fig. 1-7. Even with this schematic, it is still difficult to determine the input capacity. In addition to physical components, environmental capacitance exists at internal connections, around the probe nose resistor, and several other not so obvious locations. Input capacity values may be approximated by using Fig. 1-9. Tektronix chooses to measure this capacity with their Type 130 L-C Meter at a frequency of 140 kHz.

input capacity

Probes with longer cables will have additional capacity across C2 which requires C1 to be adjusted to a larger value for proper compensation. This change in C1 raises the input capacity of the probe. Specifications stating input resistance and input capacity are measured at some low frequency or DC. For information concerning effective input R and C at high frequency, refer to Chapter 3.

Probe Risetime (t_r) is approximately 5 ns. This is a *probe only* risetime specification. All Tektronix probes are specified for t_r under the same conditions that are used to specify our oscilloscope's t_r. The signal source is a terminated 50 Ω generator. (25 Ω source resistance) Fig. 1-10 shows a typical arrangement in determining this specification. The terminated 50 Ω generator establishes a 25 Ω source resistance and the following relationships are used.

probe t_r

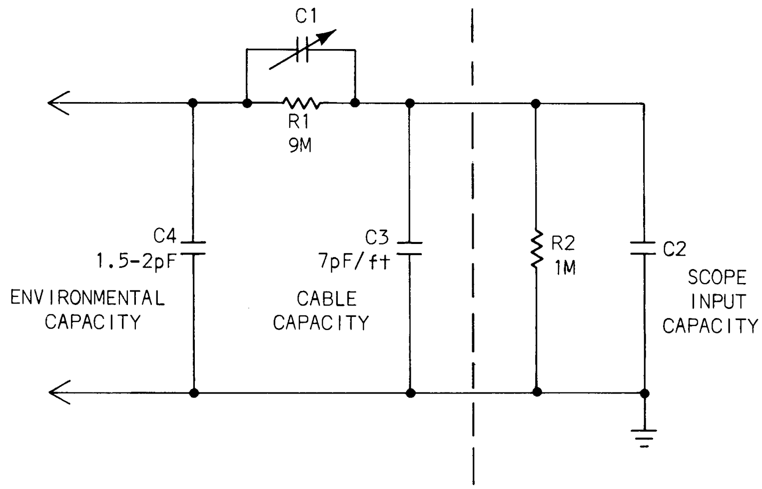
$$\text{System } t_r^2 = t_r^2 \text{ probe} + t_r^2 \text{ scope}$$

or

$$\text{Probe } t_r = \sqrt{t_r^2 \text{ system} - t_r^2 \text{ scope}}$$

To determine the system risetime capability of an oscilloscope and probe combination when driven from a 25 Ω source, use the above equations. For detailed analysis of t_r from other than a 25 Ω source, see Chapter 3.

Voltage Rating is 600 V DC, AC peak, or DC and AC peak combined. The specification also includes a footnote which states: "Peak to peak voltage derating is necessary for CW frequencies higher than 5.7 MHz when working into a 20 pF input or higher than 3.6 MHz when working into 47 pF input."



ASSUME C2 = 20pF

ASSUME 3.5ft CABLE = C3 = 7pF · 3.5 = 24.5pF

FOR PROPER COMPENSATION $R1C1 = R2(C2 + C3)$

$$C1 \approx \frac{R2(C2 + C3)}{R1} \text{ OR } 4.9\text{pF}$$

$$\text{EFFECTIVE INPUT } C \approx C4 + \frac{C1(C2 + C3)}{C1 + C2 + C3} \approx 6.4\text{ pF}$$

Fig. 1-9. P6006 input capacitance approximation.

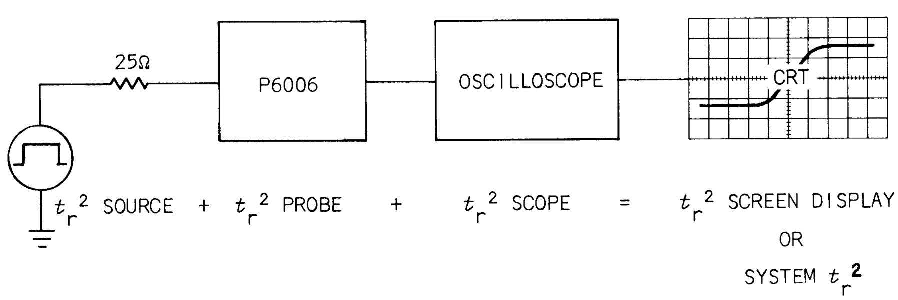


Fig. 1-10. Typical method of determining t_r.

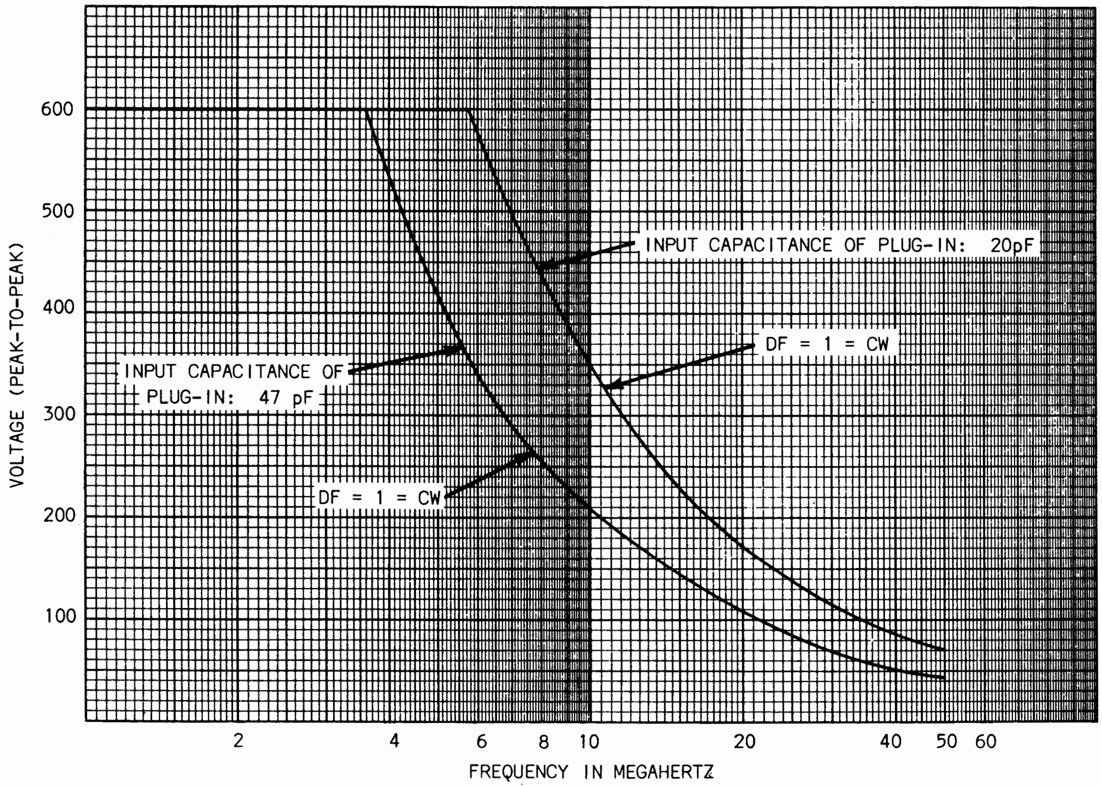


Fig. 1-11. P6006 derating curves (3.5 ft cable)

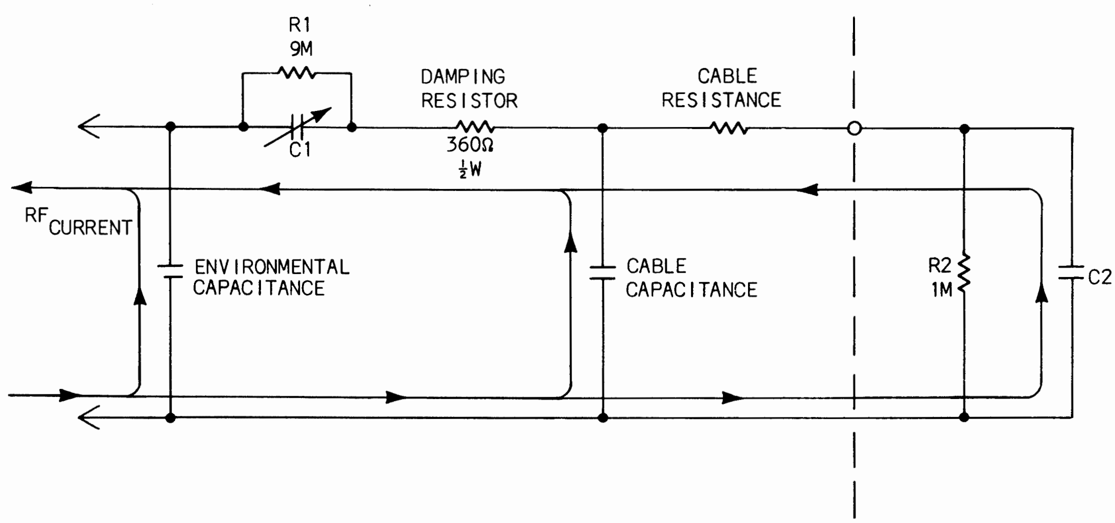


Fig. 1-12. P6006 equivalent circuit and RF current paths.

rating and derating

Fig. 1-11 shows the voltage derating curves for the 3.5 ft P6006 probe. DC voltage ratings and voltage derating with frequency are common to all probing devices. The 600 V DC, AC peak, or DC and AC peak rating is established by the voltage breakdown point of the physical components used in the probe's front end or tip assembly. The component usually referred to is the capacitor in shunt with the probe input resistor. See Fig. 1-12, C1. As frequency is increased, the curve remains flat until the capacitive reactance of C1, the cable capacity and C2 decrease in value sufficiently to allow more of the applied voltage to be developed across an unbypassed element. The derating will then follow the power dissipation limit curve of that element until most of the applied voltage is being developed across the element. The power dissipation limit of this element determines the final maximum applied RMS voltage.

limiting element

The 3.5 ft P6006 power limiting element is a 360 Ω 1/2 watt unbypassed resistor which is used to complete the "damping" requirements. The two derating curves, 20 pF and 47 pF plug-in input, show the effect of changing the value of C1 for proper compensation. This changes the capacitive reactance and allows additional voltage to be developed across the "damping" resistor when using a 47 pF input capacity plug-in or oscilloscope.

While all probes are not designed or manufactured exactly the same, the various portions of the voltage derating curve will relate to a power dissipation factor in the environment of the nose assembly, a physical unbypassed resistance, the probe cable itself or the effective resistance of the probe. For effective resistance discussions see Chapter 3.

temperature and probes

Temperature Range is a specification not generally stated unless, due to a state-of-the-art condition, temperature range restrictions are required. The P6006, as are most of our passive probes, is intended for general laboratory instrument use. At Tektronix, this is defined as 0°C to 50°C (ambient temperature). If the P6006 were taken to a very low temperature, it would still transfer a signal. The nose time constant (R1C1) would change and the cable and plastic parts would become extremely stiff and brittle. (No Flexing Allowed.)

The upper temperature limit is sometimes specified in the probe's instruction manual. The P6006 will operate normally up to +75°C. At temperatures above +75°C, the plastic assemblies will become soft and distortion of these parts will be permanent. Recent investigations into the development of an environmentally satisfactory probe has shown promise. At this point in time, -40°C to +150°C appears to be an achievable objective.

2

CONSIDERATIONS IN USE

Probe Selection

1. Be sure to select a probe which will match input resistance and capacitance of the oscilloscope you intend to use and that it is equipped with the correct mating connector.

2. Select a probe with adequate risetime and bandwidth for the required measurements and for the oscilloscope that you intend to use. Recall that the probe will degrade the bandwidth of the oscilloscope in almost all cases and that the system t_r may be found by:

   $$t_r^2 \text{ system} = t_r^2 \text{ probe} + t_r^2 \text{ oscilloscope.}$$

   Recall that these t_r specifications were determined using a 25 Ω source impedance generator.

3. Consider the possible loading effect the probe may have on the circuit under test. Recall that the probe with the highest input resistance and the lowest input capacitance will generally provide the most accurate measurements. For additional information on loading effects, see Chapter 3.

4. When considering high voltage applications, always select a probe having a voltage specification greater than the highest voltage measurement requirement. Recall that the voltages given in specifications are DC values and that derating of these values will be necessary for high frequency CW work.

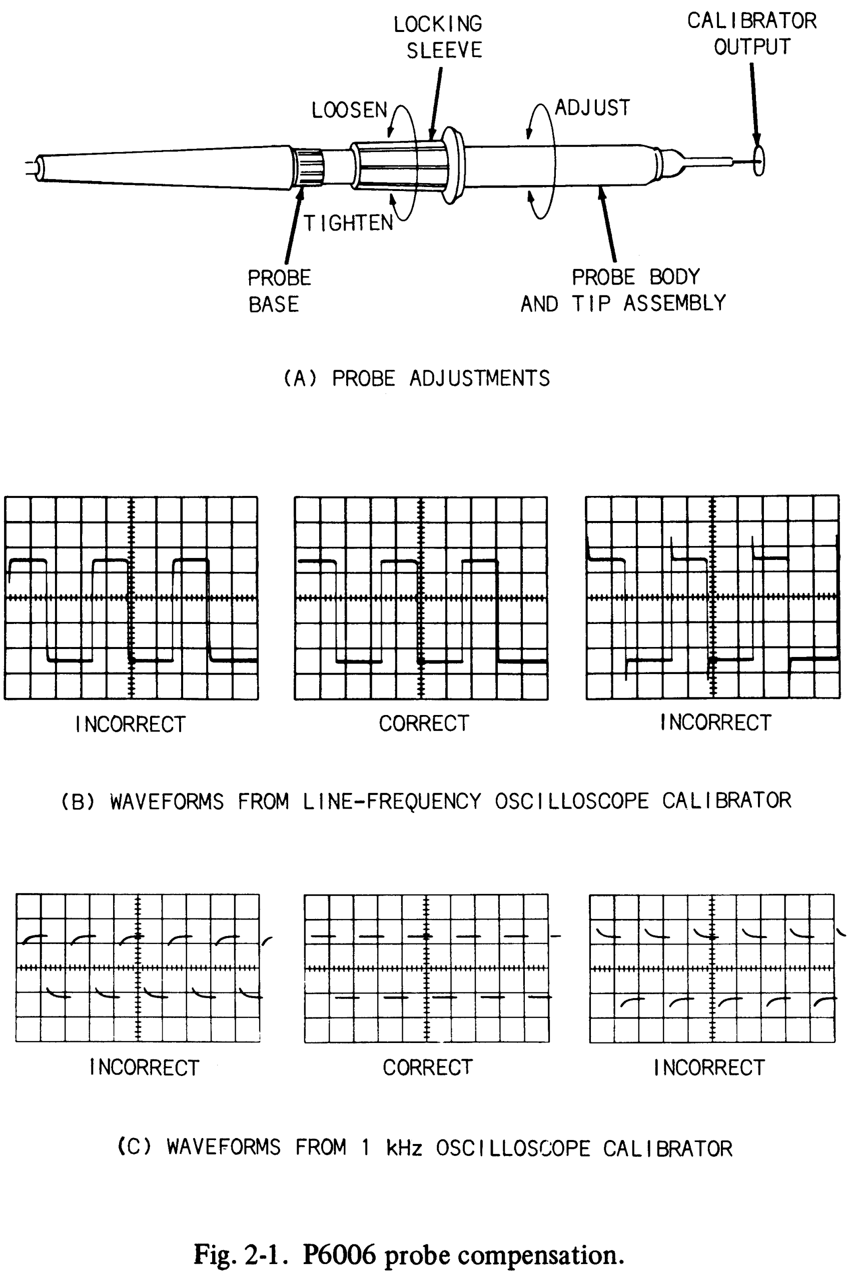


Fig. 2-1. P6006 probe compensation.

Proper Compensation

The adjustment of the probe compensation is usually necessary whenever a probe is transferred from one oscilloscope to another or from one channel to another of a multitrace plug-in. It is a good practice to always check the compensation before starting a series of measurements, especially where a co-worker may have borrowed the probe since its last compensation check.

adjusting compensation

Compensation is simply a matter of adjusting the value of a capacitor so the attenuation ratio remains the same for all frequencies.* This is usually accomplished by touching the probe tip to a source of low frequency square waves, typically 1 kHz, and then adjusting the resultant waveform to have a flat top. Fig. 2-1 shows this adjustment.

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*Some probes contain very high frequency adjustments which must be set using a specific procedure contained in the probe instruction manual.

Interestingly enough, what appears as a gross waveform distortion, when viewing the compensation of an attenuator probe with a 1 kHz square wave, will show something entirely different with various other wave shapes or pulse widths. As Fig. 2-2 points out, amplitude error is the result of a miscompensated probe.

amplitude vs shape

Normalized Input Attenuators

If proper probe compensation is to be maintained as an oscilloscope's volts/div switch positions are selected, the input attenuators must present a constant resistance and capacitance value to the probe. These attenuators were originally factory adjusted. However, as components age and tubes or transistors are replaced, the input capacitance of the various attenuator positions may be affected differently. These changes could produce miscompensation on some ranges.

Attenuator compensation and input time constant "normalization" should be a part of the regular periodic instrument calibration and maintenance procedure. This assures that once the probe is compensated on one attenuator range, it will remain properly compensated on all other ranges.

Selection of Test Point

Select the lowest inpedance point which will provide a useful waveform. Although the input impedance (R and C) of a probe is made as high as possible, it still will always have some finite effect on the circuit under test. For additional information see Chapter 3.

low impedance test point

Probe loading effects can be minimized by selecting low impedance test points. Usually cathodes, emitters and sources should be chosen in preference to plates, collectors or drains. Circuits with inductive peaking or compensation often produce displays which are difficult to evaluate properly. In high speed pulse work, it is often preferable to make current measurements than to attempt an accurate evaluation of inductive circuit voltage waveforms because of the effects of the voltage probe's input capacity. See Chapter 9.

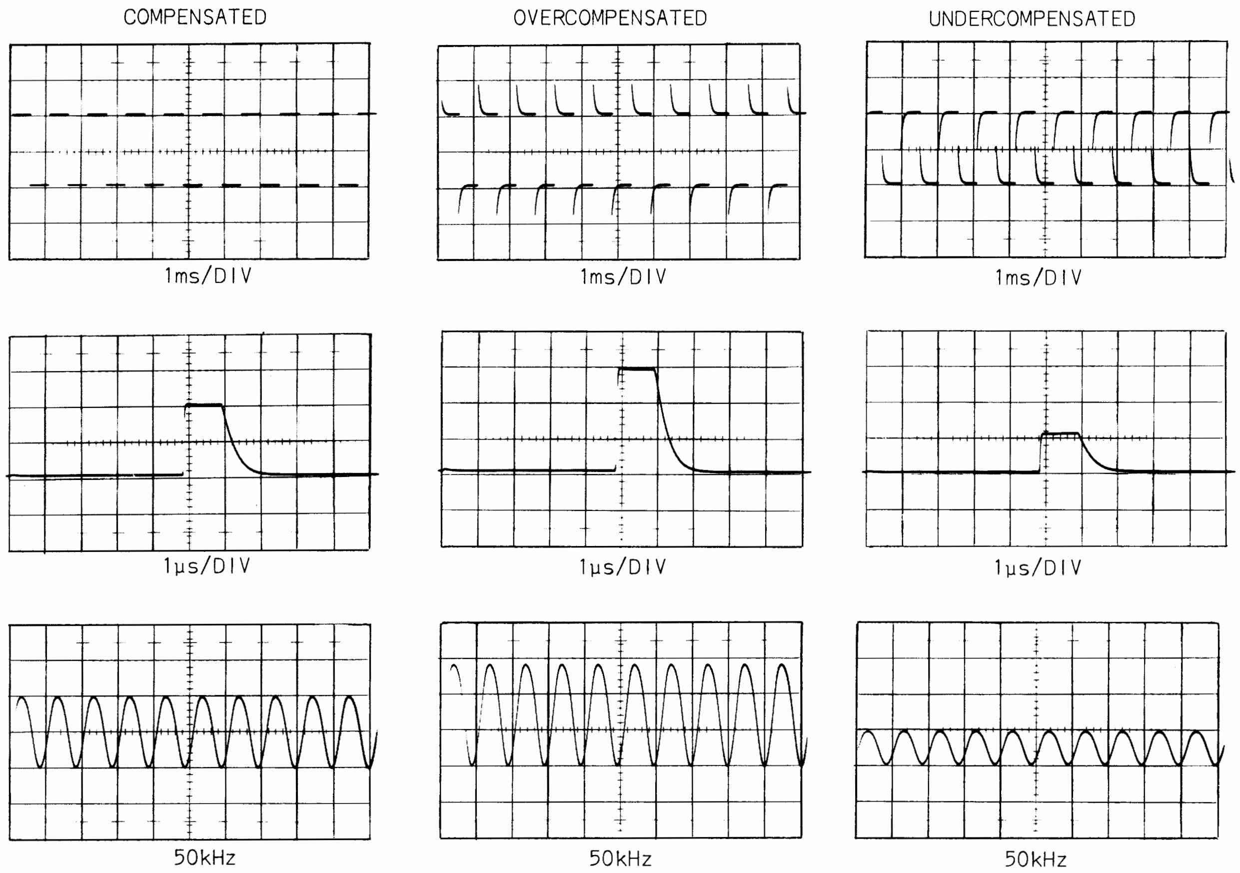


Fig. 2-2. Effects of probe compensation.

Where the circuit complexities do not allow quick estimation of the probe's effect on a high impedance point, a useful technique is to use a dual beam or dual trace instrument. Use the second trace to monitor from a low impedance test point the overall performance of the circuit under test when the first probe is connected to that circuit.

Effect of High Frequency Fields or "Ground Loops"

When a passive probe is used in a high frequency field or in areas where extremely fast transients exist, currents may be induced in the ground paths between the oscilloscope and the circuit under test (Fig. 2-3). These induced signals will be displayed on the oscilloscope in addition to the signal of interest. Ferrite cores placed over the probe cable will introduce additional losses in the ground path and greatly reduce the effects of these induced currents. This technique has been used successfully in the design of passive attenuator probes such as the P6008. See Fig. 2-4.

ferrite cores

Delay Time

Every probe device has some amount of time delay or phase shift with frequency. The standard 42 inch probe cable has a signal delay of approximately 5 ns. This means at a frequency of 1 MHz, the cable will introduce approximately 1.8° of phase shift.

$$\frac{\text{Period at 1 MHz}}{\text{5 ns delay}} = \frac{360^\circ}{X} \quad \text{Therefore } X = 1.8^\circ.$$

Probe delay rises to a place of importance when attempting to make time delay or phase difference measurements with dual channel or multiple probe usage. Additional difficulty arises in attempting to verify this very short interval of time because of the variations in risetime of the signals.

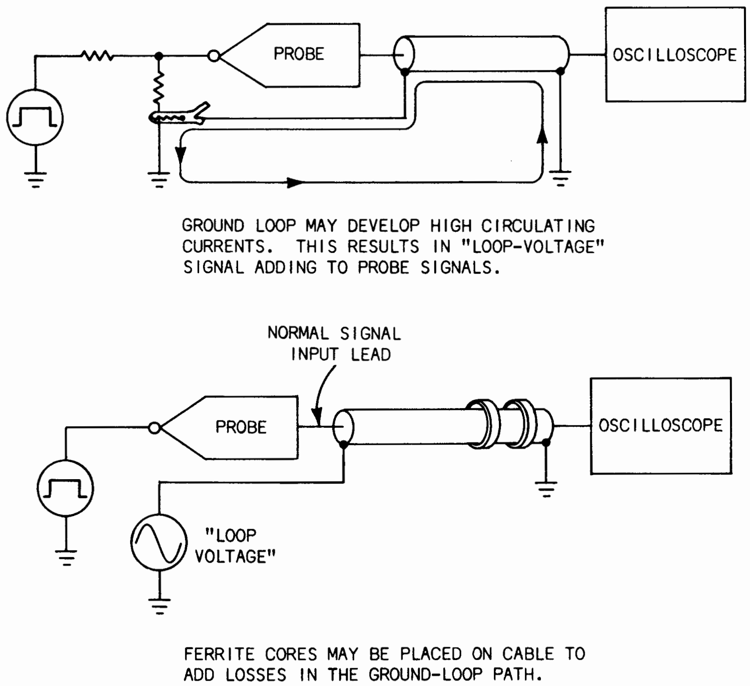


Fig. 2-3. "Ground loops."

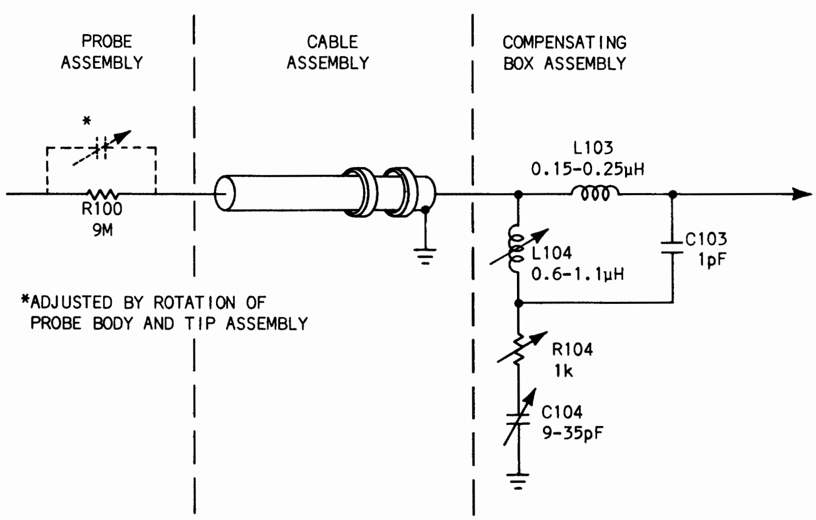


Fig. 2-4. P6008 probe schematic.

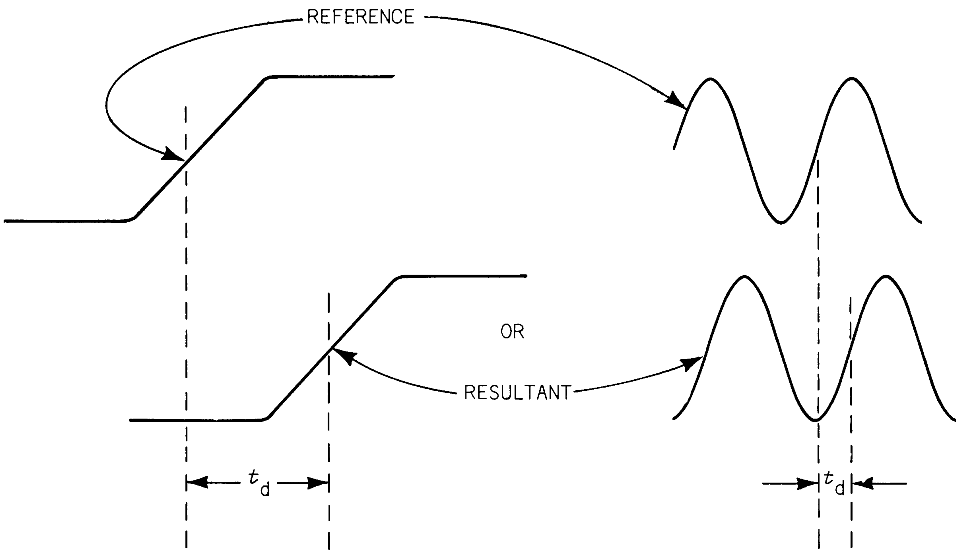


Fig. 2-5A. Reference and resultant waveforms have equal t_r. t_d = delay time or phase difference.

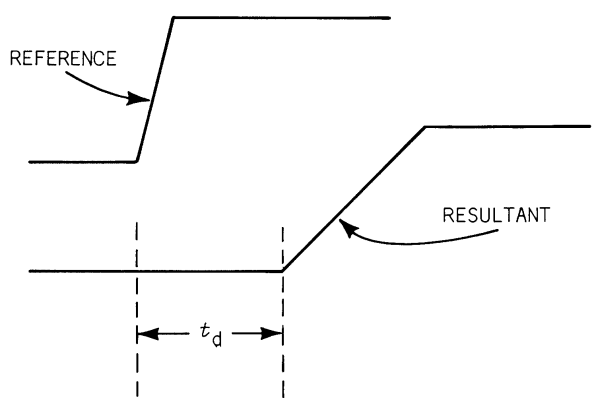


Fig. 2-5B. Reference and resultant t_r not equal. t_d correlates with velocity of propagation of probe cable.

Fig. 2-5.

reference and resultant waveforms

If the reference waveform has exactly the same t_r as the resultant waveform after the delay interval, the delay difference can be measured at any point of equal amplitude on each waveform. See Fig. 2-5A. If there is a difference in t_r between the reference and resultant waveforms, then arbitrary measurement points must be chosen. It has been found that the velocity of propagation of Tektronix probe cables can be verified by choosing a point at the very start of any observable resultant waveform. See Fig. 2-5B.

best technique

Significant measurement errors can result if the difference in delay between multiple channel measurement capability is not taken into consideration. For instance, the delay time difference between a 3.5 foot 10X passive probe and a 6 foot 100X passive probe will be ≈3.5 ns. The best technique for determining the exact time or phase shift difference between multi channel capability is to attach all probes to a single reference signal and observe any time displacement. This technique accounts for all probe differences as well as any amplifier differences.

Voltage Derating Curves and Pulses

RMS and peak

Chapter 1 pointed out the reasons for derating the voltage capability of the passive probe. Recall that in the case of the P6006 (Fig. 1-11), the 600 V limit resulted from the maximum voltage capability of the shunt nose compensating capacitor. The curves from 600 V followed a power dissipation limit of an unbypassed resistor. These power curves are developed by considering only RMS voltages. If pulses were applied to the probe, the RMS values should remain the same but the peak voltage would be higher.

Two formulas are used to determine what pulse voltage may safely be applied to the probe. *In no case can the peak pulse voltage exceed the DC voltage limit.*

$$\text{Pulse voltage } E = \frac{\text{Voltage from curve at CW frequency}}{\sqrt{\text{Duty Factor}}}$$

$$\text{Duty Factor} = \frac{\text{Pulse duration}}{\text{Pulse period}}$$

CW signal's Duty Factor = 1

Ground Lead Inductance Effects

The passive probe is essentially a capacitance divider for high frequency information. Fig. 2-2 showed the fact that amplitude changes with probe miscompensation. An inductance inserted in series with this input capacitance will form a series-resonate circuit, Fig. 2-6, and will "ring" if driven by a signal containing significant frequency components at or above the circuit resonance

aberrations frequency. Whether these aberrations (ring) appear on the oscilloscope display will depend on the oscilloscope's bandwidth. If the oscilloscope's bandwidth is low compared to the resonate frequency, very little signal distortion will be detectable. As the instrument's bandwidth approaches the resonate point, some pulse front corner changes would be observable with a possible "decrease" in the signal's apparent risetime. Bandwidths above the resonant point show the "ringing" distortion, Fig. 2-7.

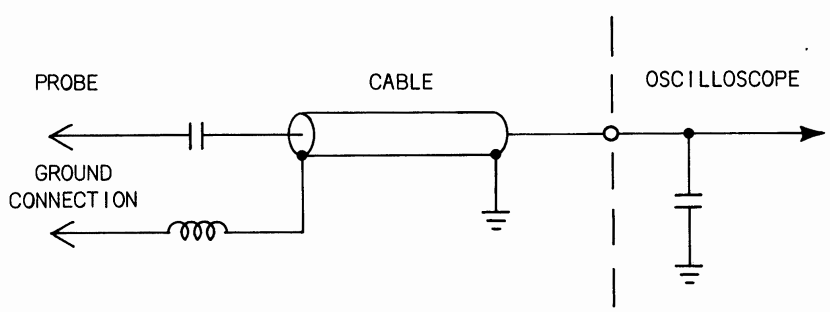
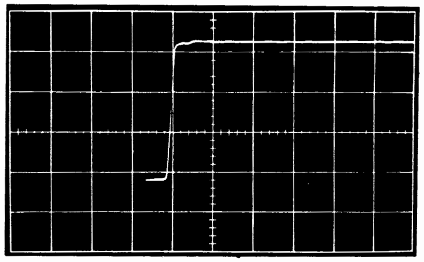


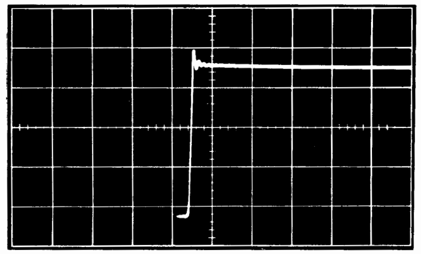
Fig. 2-6. Series-resonant circuit formed by excessive lead length in probe ground return.



.1μ/DIV

(A)

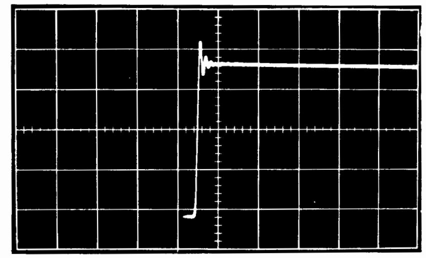
SCOPE BANDWIDTH = 15MHZ
GROUND LEAD 12 INCHES LONG
PROBE = P6010



.1μ/DIV

(B)

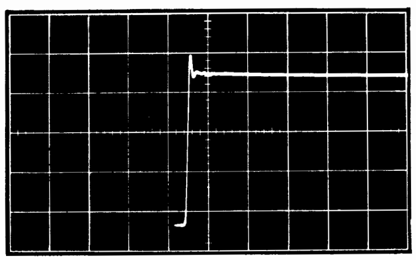
SCOPE BANDWIDTH = 50MHZ
GROUND LEAD 12 INCHES LONG
PROBE = P6010



.1μ/DIV

(C)

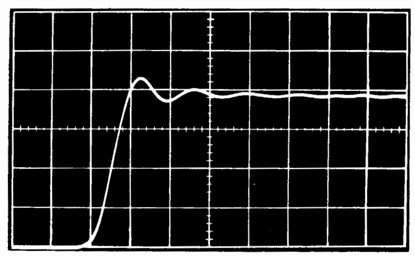
SCOPE BANDWIDTH = 100MHz
GROUND LEAD 12 INCHES LONG
PROBE = P6010



.1μs/DIV

(D)

SCOPE BANDWIDTH = 100MHz
GROUND LEAD 12 INCHES LONG WITH **FERRITE**
PROBE = P6010

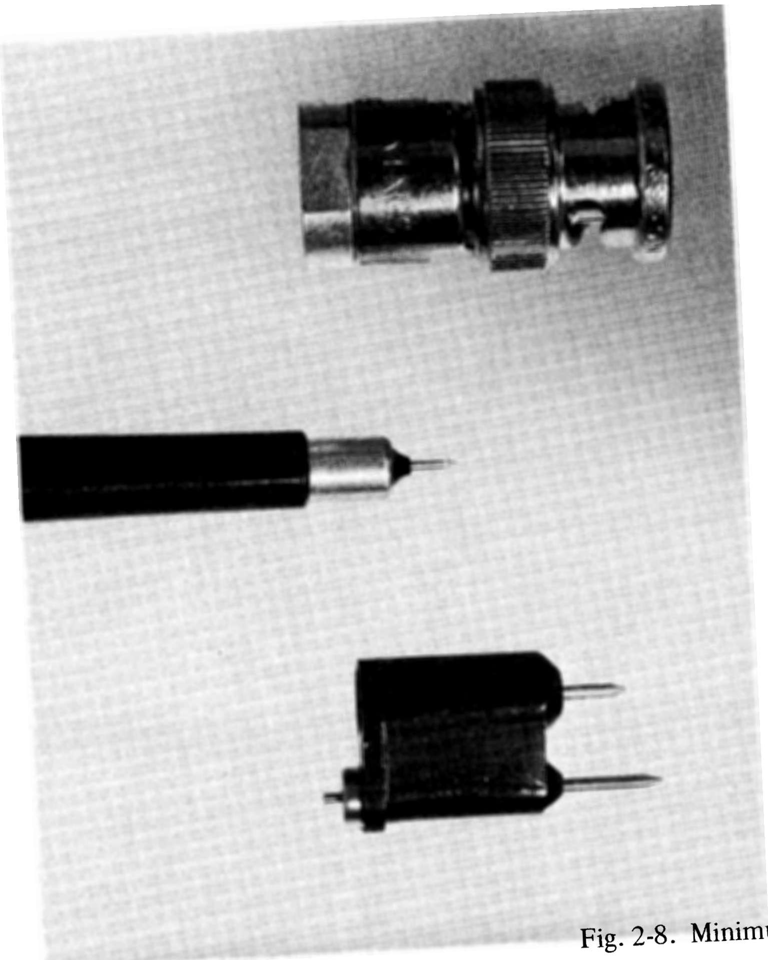


10ns/DIV

(E)

EXPANDED TIME SCALE OF P6010 AND
12-INCH LONG GROUND LEAD "RING"
"RING" FREQUENCY ≈ 70MHz

Fig. 2-7. Inductive effects of ground leads.



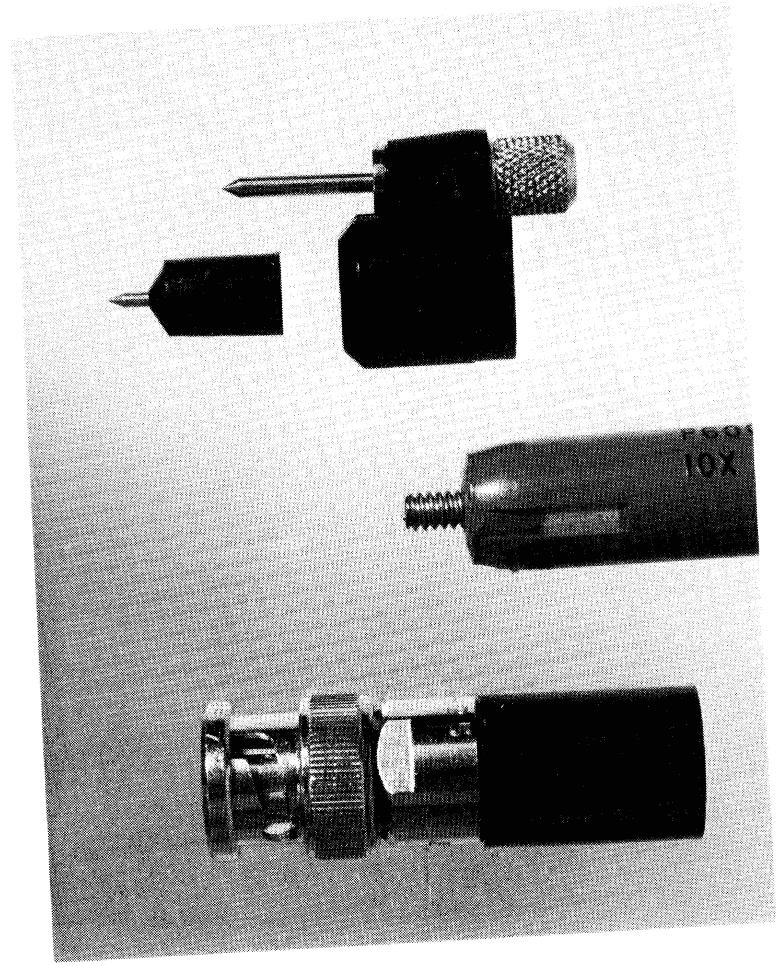


Fig. 2-8. Minimum inductance grounding adapter.

ground lead inductance

To verify "ground lead inductance" problems, change the ground return path and look for signal shape changes. If the ground return lead must remain excessively long, loop the lead through a small ferrite core. This will introduce losses in the resonate circuit and reduce the tendency to ring. The effect of long ground leads tends to drop out as the probe input capacity decreases. With the decrease in input capacity, the resonate point usually increases beyond the practical limit of the oscilloscope. The spring-loaded bayonet ground or a chassis mounted connector and probe to connector adapter are practical methods of obtaining a minimum inductance ground path. See Fig. 2-8.

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

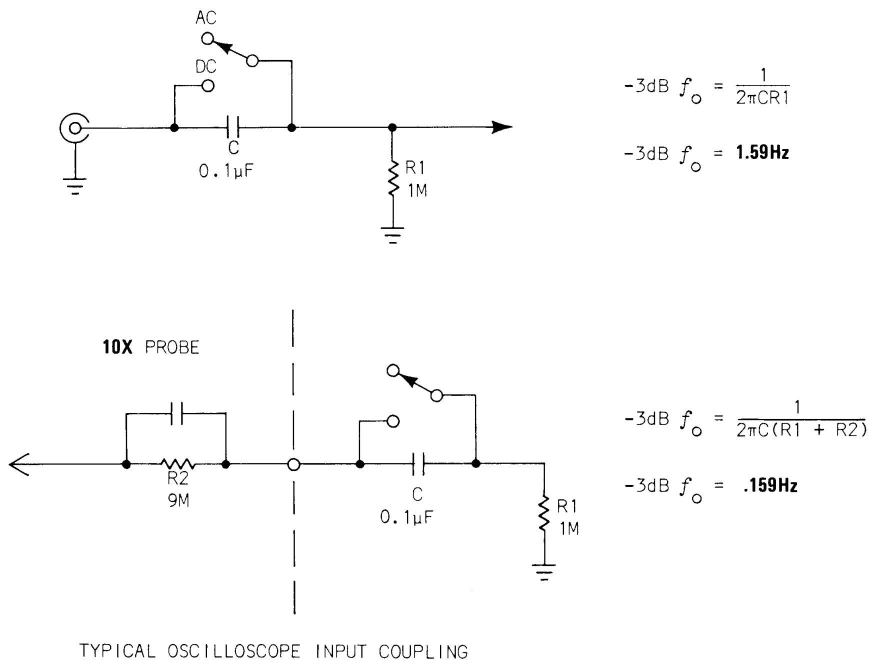


Fig. 2-9. AC coupled low frequency -3 dB points.

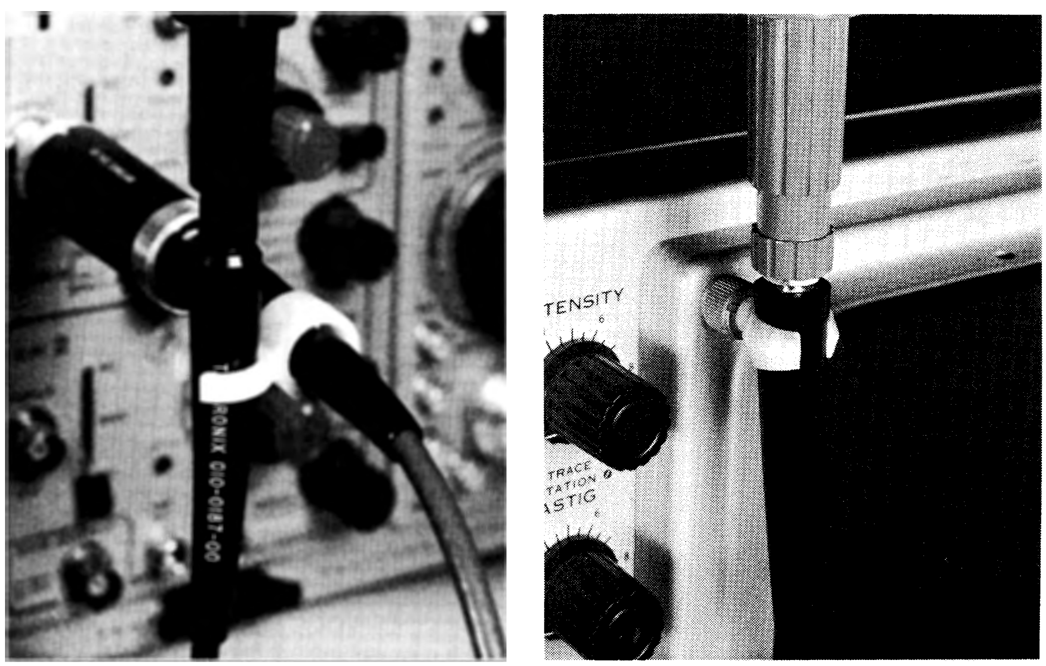


Fig. 2-10. Probe hangers.

Extension of Input AC Coupled Low Frequency Response

Most oscilloscopes provide an AC input coupling capability which allows the observation of small AC signals riding on a large DC level. The series DC blocking capacitor, together with the input resistor to ground, forms a high pass filter with a -3 dB point of $f_o = \frac{1}{2\pi RC}$. By use of a 10X passive attenuator probe, the low frequency -3 dB point may be extended 10X. See Fig. 2-9.

Care of the Passive Probe

The oscilloscope passive probe is an extremely rugged device but is susceptible to damage if treated carelessly. Avoid kinking or straining the cable or subjecting the probe to excessive environmental conditions. When not in use, probes should be stored in drawers or supported by the plastic probe hangers supplied with the probe. See Fig. 2-10.

repairing

If probes are damaged, replacement parts or subassemblies are available from Tektronix. Substitution of *non-standard* parts is *not* advisable if the original performance is to be restored. Even shortening the cable by more than a few percent will have a noticeable effect on the probe's transient response. Recall that the resistance center conductor has been specifically selected to damp and eliminate the reflections that would exist in an unterminated system. If this resistive element is reduced, the reflections will not be properly damped and may cause noticeable signal distortions.

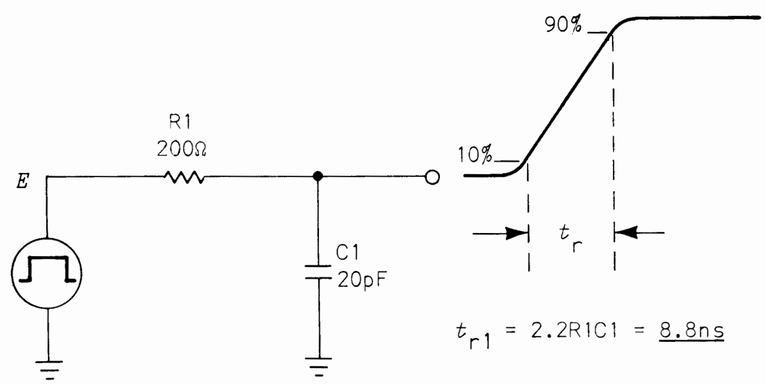


Fig. 3-1. Typical signal source.

3

SIGNAL MEASUREMENT EVALUATION

The Introduction of this book described the *ideal* probe as being one that would be capable of transferring signal energy from a source to the oscilloscope without "loading the source" and without distorting that signal information. Unfortunately, the *ideal* probe does not exist. All probes will load the circuit under test to some extent. But what changes occur when a probe is attached? How will these changes affect the signal and can the desired information be determined from the oscilloscope display?

two signal types

Two types of signal sources should be considered when dealing with probe loading effects. Pulse or step-function sources dealing with amplitude, risetime (t_r), transient response and time distortions; and sinewave sources concerned with amplitude and phase relationship distortion.

signal source impedance

Most discussions of probe loading usually deal with a "purely resistive" source and thus set about to calculate the degradation associated with probe input capacity. In reality, a signal source will have some output capacity of its own and the signal source impedance may be reduced to a simple series R and a shunt C. Fig. 3-1 represents a typical signal source. Source capacity generally found in modern circuits ranges in value from 1 pF to something less than 100 pF and source resistance varies from a fraction of an ohm to several hundred ohms. These values seem to exist in the medium to high speed area and will vary with a particular circuit.

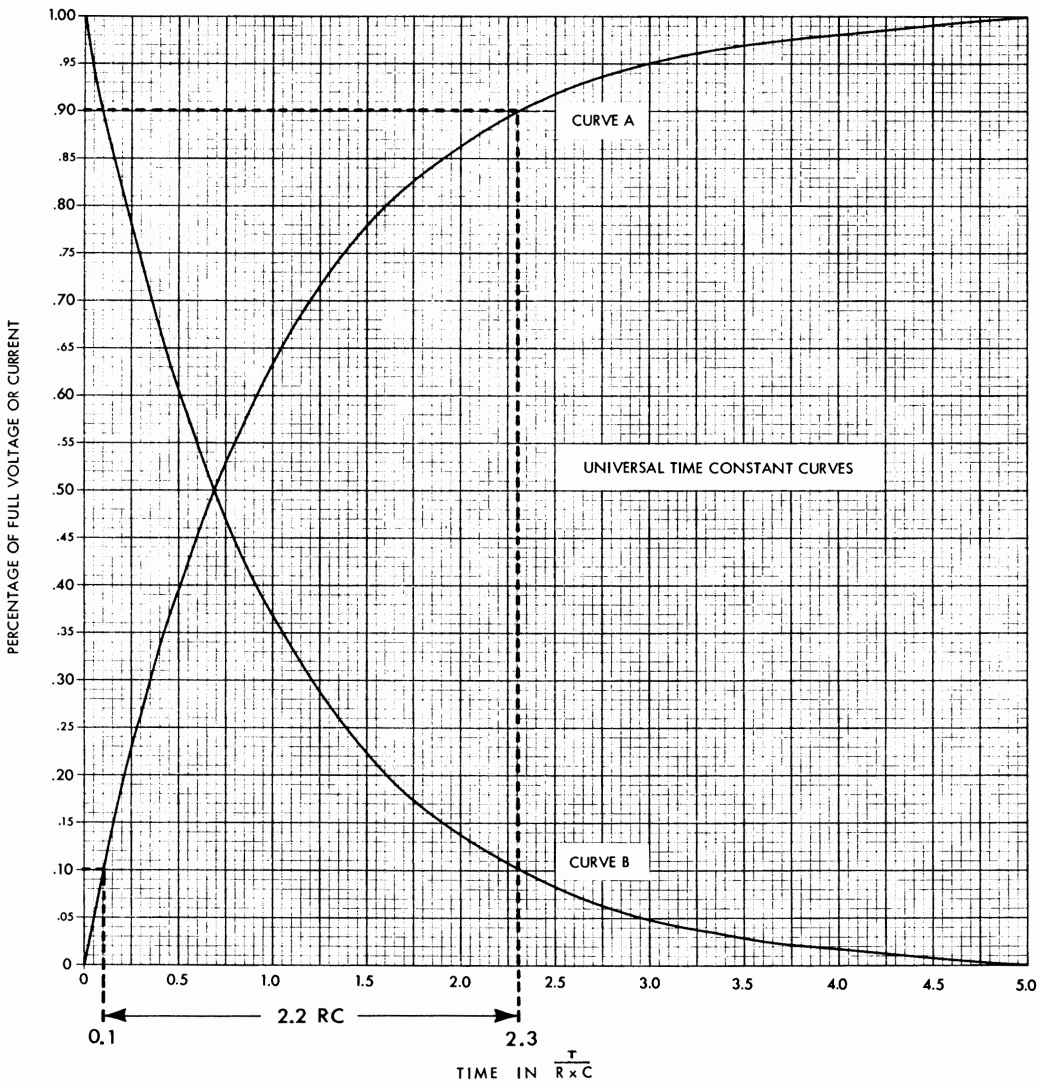


Fig. 3-2. Universal time constant curves.

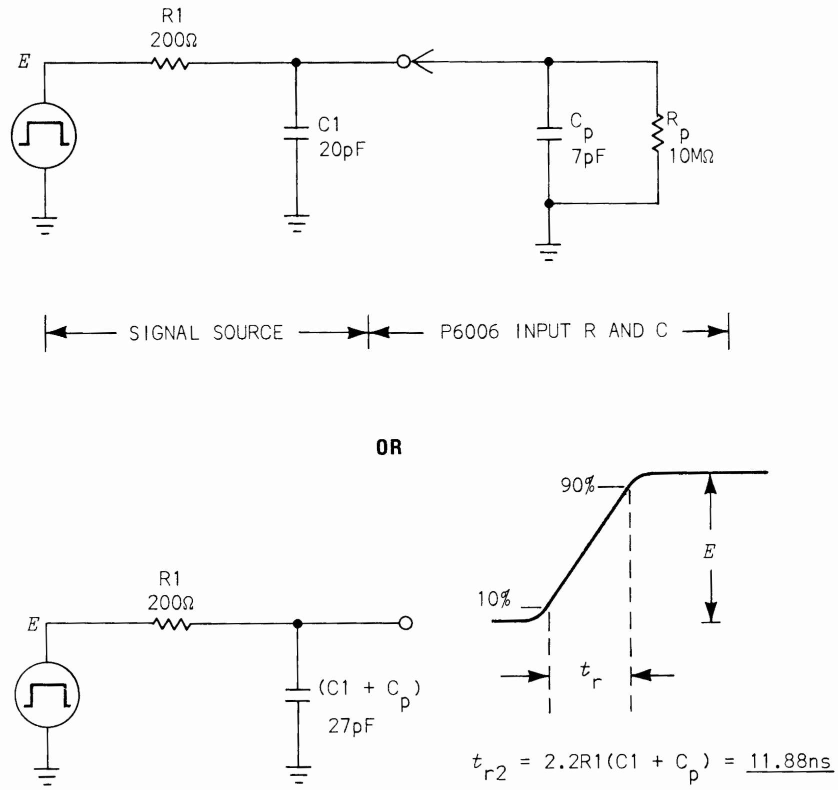


Fig. 3-3. P6006 probe added to signal source.

Assume Fig. 3-1 to be a *pulse* source. If the generator had a t_r of 0, the output t_r would be limited by the integration network of R1 and C1 and would be equal to 2.2 R1 C1. Fig. 3-2 shows this limitation as taken from the universal time constant charge curve of a capacitor. Applying this relationship to our signal source, the output t_r is:

$$t_{r1} = 2.2\ \text{R1C1} = 8.8\ \text{ns}.$$

adding probe

loading effect

If a typical passive probe, like the P6006, is used to measure this signal, the probe's specified input capacity and resistance is added to the circuit. See Fig. 3-3. The circuit is reduced to a simple RC equivalent by making the judgment that if $R_p > 10\text{R1}$, then R_p may be disregarded. The risetime formula of 2.2 R1 $(\text{C1}+C_p)$ is applied and the circuit t_{r2} = 11.88 ns. The *loading effect* of the P6006 to this signal source is the % change in t_r.

$$\frac{t_{r2} - t_{r1}}{t_{r1}} \times 100 = 35\%\ \text{change}$$

The result is this signal source output t_r is slowed by 35 % with the addition of a 7 pF, 10 MΩ input passive probe. Note that nothing has been said concerning the oscilloscope screen display thus far. Only the loading effect has been discussed, not the measurement system capability. To complete the measurement system capability use:

$$\sqrt{(t_r\ \text{source})^2+(t_r\ \text{probe})^2+(t_r\ \text{scope})^2} = t_r\ \text{displayed}$$

where:

t_r source = total t_r including probe input loading

t_r probe = as specified (P6006 = 5 ns)

t_r scope = as specified.

percent vs capacitance

The percentage of change that resulted from adding a passive probe to this pulse source is directly related to the amount of capacitance added. The calculation to determine the amount of change in risetime would be:

$$\frac{C_p}{C1} \times 100 = \frac{7\ \text{pF}}{20\ \text{pF}} \times 100 = 35\%$$

This is a valid approach if the R_p factor is large when compared to the source series resistance.

The majority of the passive probes manufactured by Tektronix have high input resistance for DC voltages or pulse considerations. However, there are three passive probes which have low values of input resistance. The P6034, P6035 and, more recently, the P6048. These probes were designed to have very low input capacity of 0.7 pF, 0.6 pF and 1 pF respectively.

considering R_p

If a P6048 (10X, 1 pF, 1 kΩ) were used to measure the signal source of Fig. 3-3, the probe loading circuit would change. See Fig. 3-4. In this instance R_p is not 10 times greater than R1 and must be considered. R1 and R_p form a DC divider, reducing the amplitude of the signal and modifying the source impedance. By using Thevenin's theorem, a new generator source voltage and a new source resistance is calculated resulting in:

$$t_r = 2.2\ \text{R2}\ (\text{C1}+C_p) = 7.7\ \text{ns.}$$

Note that in relating this risetime to the risetime of Fig. 3-1, our original circuit, the P6048 caused a change from 8.8 ns to 7.7 ns. The % of change was less than the first example using a P6006.

$$\% \text{ change} = \frac{8.8 \text{ ns} - 7.7 \text{ ns}}{8.8 \text{ ns}} \times 100 = 12.5\%.$$

It is interesting to note that in this case the addition of the probe did not degradate the signal by slowing the risetime but the resistance loading caused a modification of the source resistance and decreased the risetime making it faster than it should be. Also, the modified source voltage causes a different output amplitude than one would normally expect from a 10X probe. Had the generator voltage been one volt, with the addition of the P6048 probe, the source output voltage would have been 833 mV and the oscilloscope screen display would have been 83.3 mV.

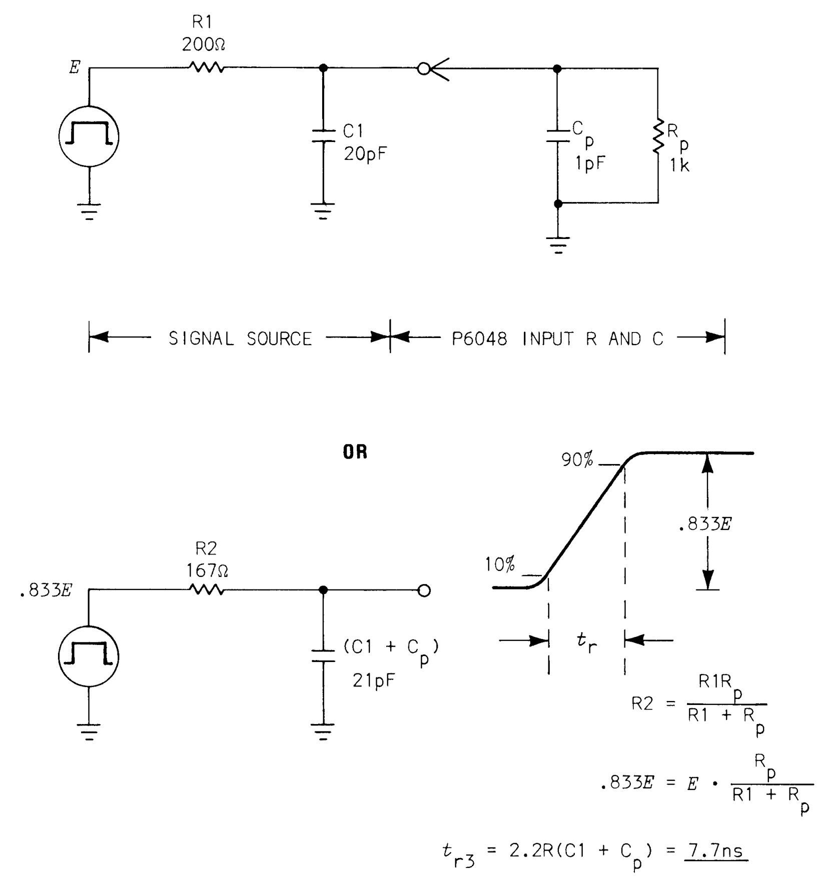


Fig. 3-4. P6048 probe added to signal source.

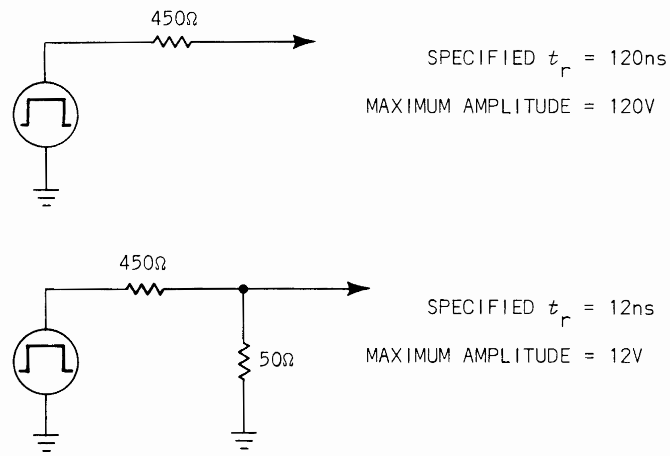


Fig. 3-5. Type 106 Generator, high amplitude output.

Pursuing this thought one step further, that of using a heavy load on a signal source and modifying the source impedance Fig. 3-5 shows the Type 106 Square-Wave Generator high amplitude output equivalent circuit. Note that the heavy loading technique results in a *decrease* in the signal risetime and a *decrease* in the available amplitude. Caution should be exercised in using heavy loading techniques. Excessive DC loading may be eliminated by using the probe's AC coupling capability.

heavy loading

The next consideration will be that of using the same probe types and the same source resistance and capacitance. The only difference will be in changing the generator from a pulse to a sinewave source. See Fig. 3-6. The approach is the same as before. Again determine the source's performance prior to the addition of a probe and then calculate the source's performance with the probe added. The difference between the two is the effect of the probe on the source or the *% of change* the probe will introduce into a measurement.

The bandwidth curve of Fig. 3-6 was developed by first assuming a frequency, f_o, then calculating the capacitive reactance of C1 at f_o. Next, determine the impedance (Z) of the circuit through a vector summation using R1 and the reactance of C1 (X_{C1}). Assuming a voltage across the computed Z allows a current determination. This current times the X_{C1} times 100 will result in E out as a % of E at f_o.

phase shift

In addition to the amplitude change of E out, phase shift is also present. The phase angle is the angle between the R1 and Z vector and is:

$$\text{TAN } \phi = \frac{\text{R1}}{Z}$$

effective capacitance and resistance

Before adding the P6006 or the P6048 to this signal source and determining the loading effect of each probe, a discussion of the effective resistance (R_p) and effective capacitive reactance (X_p) of each probe seems in order. As mentioned in Chapter 1, the input R and C specifications are determined by DC or low frequency measurements. These values are the ones used in determining t_r and amplitude loading effects of pulse or step function sources.

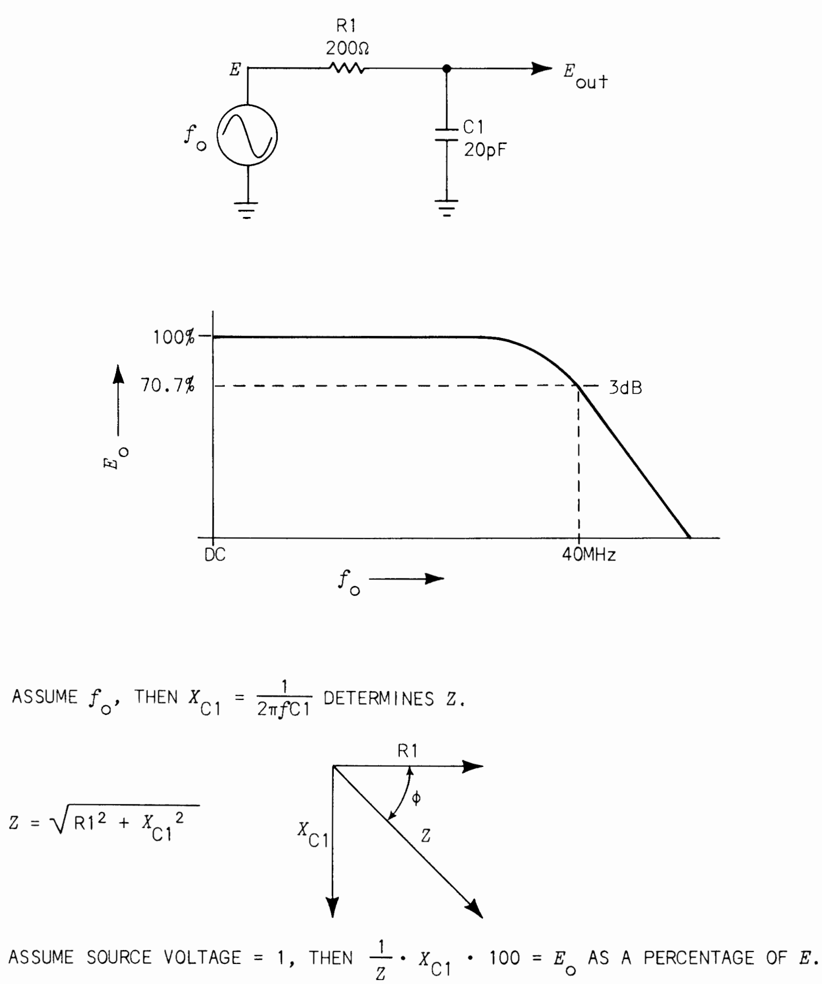
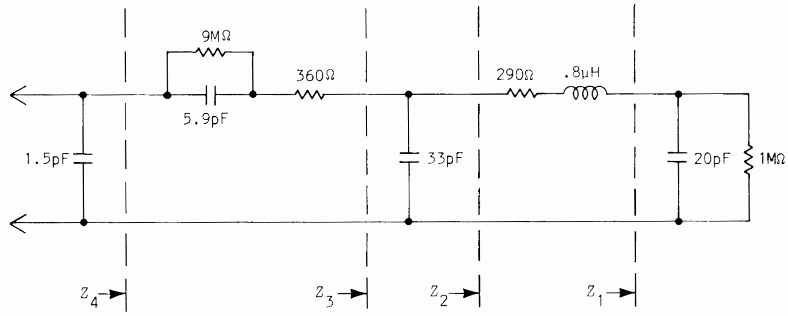


Fig. 3-6.



TO TRANSFORM IMPEDANCE BETWEEN SERIES AND PARALLEL FORMS USE:

$$Z^2 = (R_{series})^2 + (X_{series})^2 = \frac{(R_{parallel})^2 (X_{parallel})^2}{(R_{parallel})^2 + (X_{parallel})^2} = R_{series} R_{parallel} = X_{series} X_{parallel}.$$

Fig. 3-7. The equivalent circuit of a P6006 probe.

Also in Chapter 1, voltage derating curves hint that probe input impedance changed as a function of frequency.

transforms

Fig. 3-7 again shows the P6006 equivalent circuit. By assuming some f_o applied, this complex impedance may be reduced to a single impedance and expressed as a simple shunt R (R_p) and X_c (X_p). This is accomplished by dividing the circuit into several Z sections and then using series and parallel transforms. By beginning at the right side of the circuit and working to the left, the effective R_p and X_p of this probe may be *approximated*.

measure to be sure

Like attempting to calculate input capacity at low frequency (Chapter 1), the only technique that considers all probe elements is one of actual measurement. Tektronix chooses to measure the X_p and R_p of their probes with a Boonton R-X meter.* These measured values are displayed as curves in each probe's instruction manual. Fig. 3-8 shows the P6006 X_p and R_p curves. Note that the X_p and R_p curves in *no way* directly reflect the risetime or bandwidth capability of a particular probe. These curves do indicate the effective loads a sinewave source would see when the probe is attached.

*Boonton Electronics Corp., Parsippany, N.J.

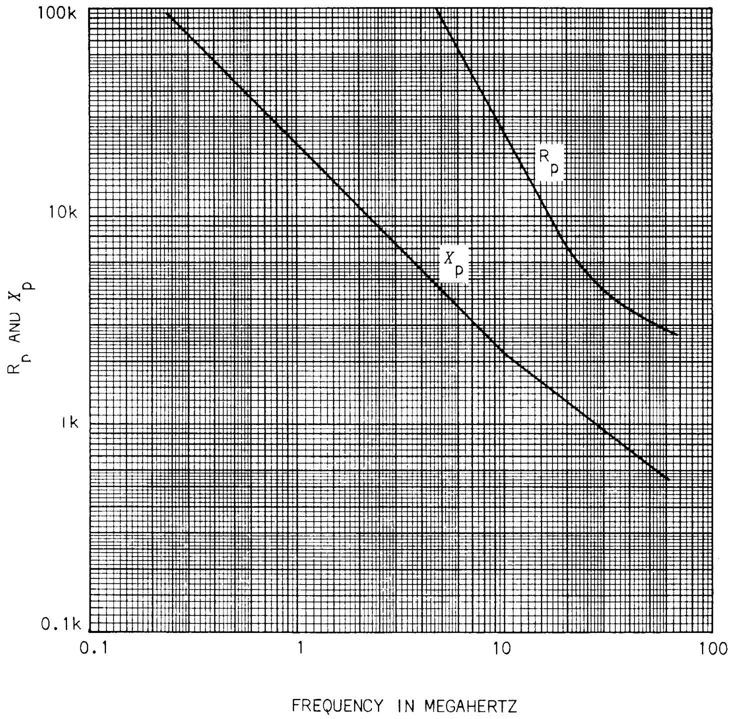


Fig. 3-8. P6006 input R_p and X_p vs frequency curves (3.5 ft cable).

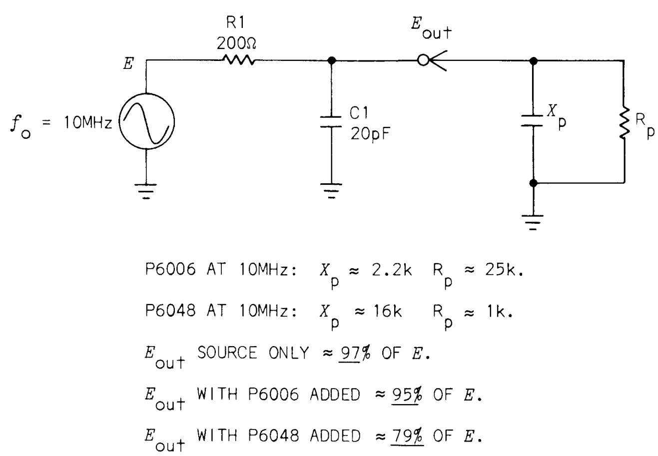


Fig. 3-9.

Continuing with the information of Fig. 3-6 and the loading values of the X_p and R_p curves, a % of change may be determined when using a P6006 or a P6048 as the measuring probe. See Fig. 3-9. First determine E out of the source only, by using Fig. 3-6 procedure. *Source only:*

$$X_{C1} \approx 800\ \Omega \qquad E \text{ out} \approx 97\% \text{ of } E$$

% of change

Now add the X_p and R_p of the P6006 probe. Because the R_p is greater than 10 R1, R_p may be disregarded. The source capacity and the X_p are combined and E out is again calculated. To combine C1 and X_p, convert X_p to C_p and add to C1 or convert C1 to X_{C1} and combine by: $\frac{X_p\ X_{C1}}{X_p+X_{C1}}$.

Source with P6006 added:

$$\frac{X_p\ X_{C1}}{X_p+X_{C1}} \approx 600\ \Omega \qquad E_o \approx 95\% \text{ of } E$$

Add the P6048 X_p and R_p values in place of the P6006 values. Note that R_p is <10 R1 and therefore, must be considered. See Fig. 3-10. As with pulse sources, effective R_p loading will determine a new source voltage amplitude and a new generator source resistance.

Source with P6048 added

$$X_{C2} \approx 760\ \Omega \qquad E_o \approx 79\% \text{ of } E$$

Notice that the % of change associated with the P6006 is less than the P6048 % of change.

$$\frac{97\% - 95\%}{97\%} = > 2\% \text{ with P6006}$$

$$\frac{97\% - 79\%}{97\%} = > 18\% \text{ with P6048.}$$

This discussion has not considered the measurement system but only the change of the signal source with the addition of a measurement probe. The results of these examples show that for pulse source measurements, the added capacity of the P6006 did degrade the signal t_r prior to entering the measurement system. The P6048 with a low input capacity and the modification of the source resistance, did allow a faster t_r indication with less % of change than the P6006.

loading and sinewaves

However, when dealing with a specific sinewave frequency, the degree of loading will be a function of that probe's X_p and R_p curves. The ability to predict the amplitude of a sinewave measurement is again a function of the:

1. Signal source and probe X_p and R_p loading
2. Probe bandwidth
3. Oscilloscope bandwidth

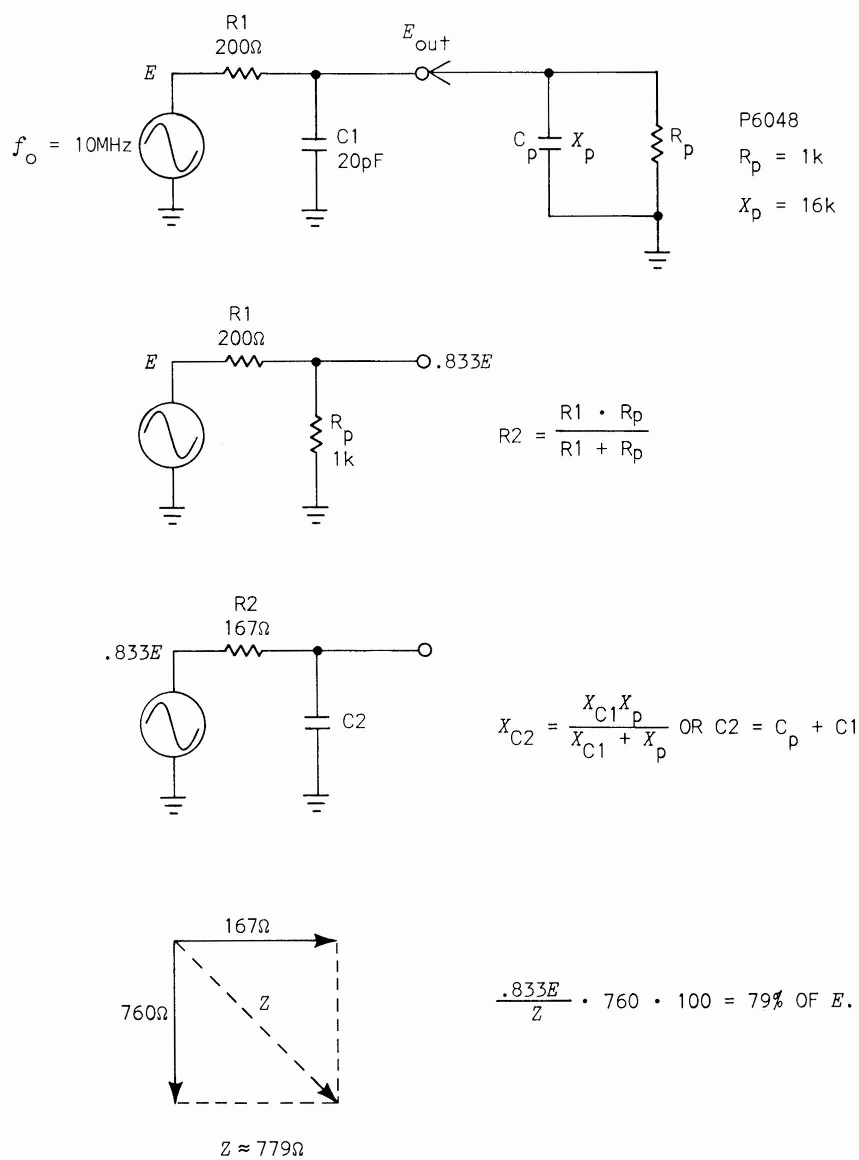


Fig. 3-10.

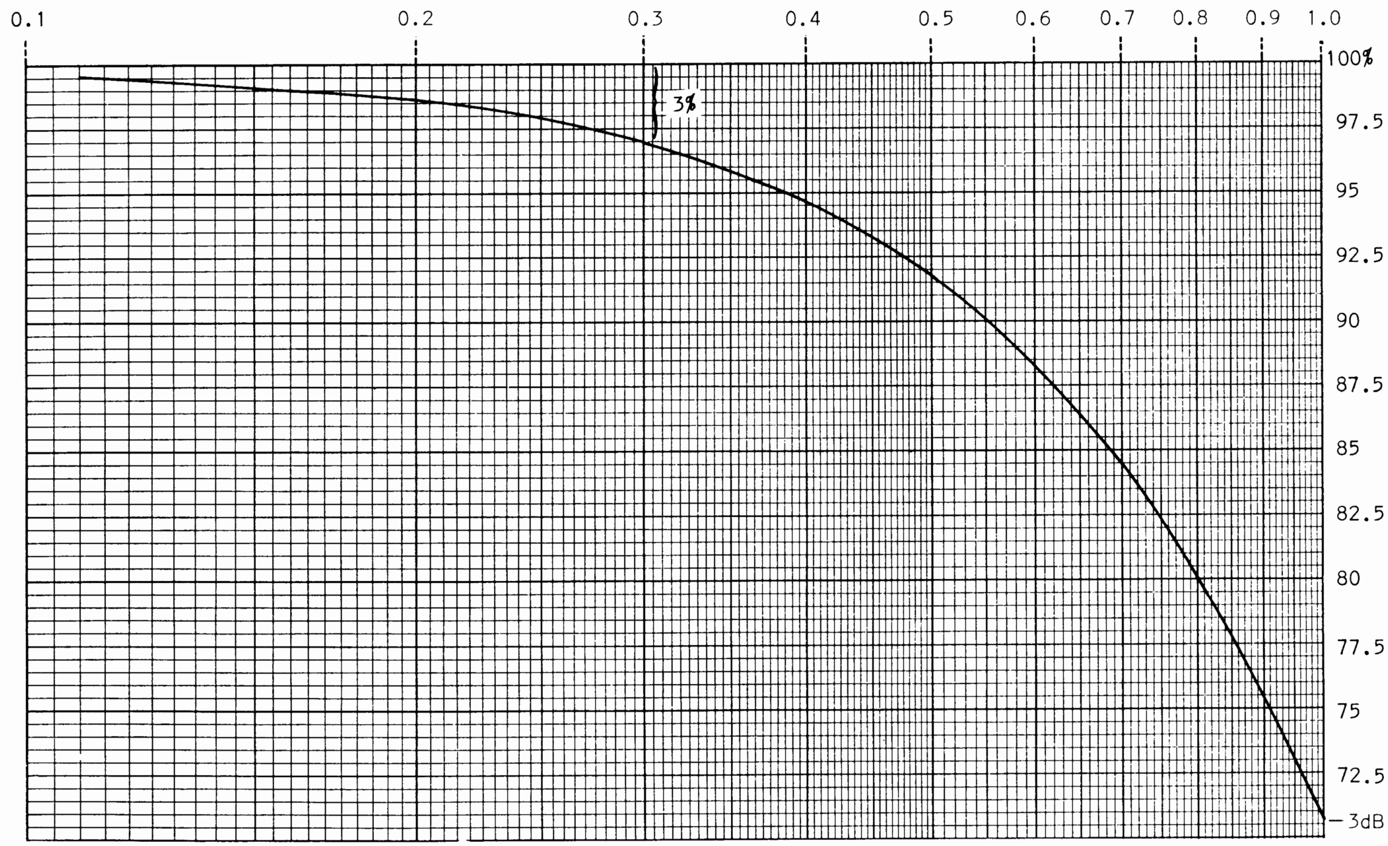


Fig. 3-11. Expanded frequency curve.

Fig. 3-11 is a plot of a Gaussian amplifier curve which may be used to approximate the displayed amplitude of a sinewave signal. To use the curve, first determine the t_r of the measurement system.

$$t_r \text{ system} = \sqrt{(t_r \text{ probe})^2 + (t_r \text{ scope})^2}$$

Then determine system bandwidth (bw) by:

$$\text{bw} = \frac{0.35}{t_r \text{ system}}$$

approximating amplitude

Normalize the curve and the system bw. For example: if bw is equal to 30 MHz, then 10 MHz will be displayed by the system with approximately 3% loss of signal amplitude. Determine signal amplitude change with the probe as in Figs. 3-9 and 3-10. Then determine the additional loss from the measurement system bw curve. i.e.: 2% loss of signal amplitude because of probe load or 98% signal left. Then 3% loss of 98% due to system bw. Again, the best technique and the most accurate, is to measure the system performance at the specified frequency.

VOLTAGE PROBES				
Recommended Use Area	**Probe Only Risetime**	**Probe Input R,C**	**Attenuation**	**Type**
DC to 3.5 GHz	0.1 ns	0.7 pF, 500 Ω	10X	P6034 Miniature
DC to 1.7 GHz	0.2 ns	0.6 pF, 5 kΩ	100X	P6035 Miniature
DC to 1 GHz	0.35 ns	2 pF, 100 kΩ	1X	P6038 Sampling
DC to 850 MHz	0.4 ns	3.6 pF, 10 MΩ	10X	P6032
DC to 230 MHz	1.5 ns	5.5 pF, 10 MΩ	1X	P6045 FET
DC to 150 MHz	1.2 ns	10 pF, 10 MΩ	10X	P6047 Miniature
	2 ns	2.5 pF, 10 MΩ	100X	P6009
DC to 100 MHz	3 ns	7.5 pF, 10 MΩ	10X	P6008
	3.5 ns	10 pF, 1 MΩ	0.1X	P6046 Differential Probe & Amplifier
	2.6 ns	1 pF, 1 kΩ	10X	P6048 Miniature
DC to 50 MHz	4 ns	2.7 pF, 100 MΩ	1000X	P6015 High Voltage Up to 40 kV
	2 ns	10 pF, 10 MΩ	10X	P6010 Miniature
DC to 33 MHz	7 ns	3 pF, 100 MΩ	1000X	P6013A High Voltage Up to 12 kV
	5 ns	7 pF, 10 MΩ	10X	P6006
	7 ns	2 pF, 10 MΩ	100X	P6007
	12 ns	50 pF, 1 MΩ	1X	P6011 Miniature
	5 ns	11.5 pF, 10 MΩ	10X	P6012 Miniature
	7 ns	12 pF, 8 MΩ	10X	P6023
	10 ns	50 pF, 1 MΩ	1X	P6027
	10 ns	50 pF, 1 MΩ	1X	P6028
DC to 21 MHz	17 ns	13.5 pF, 10 MΩ	10X	P6049 Miniature

CURRENT PROBES			
Recommended Use Area	**Probe Risetime**	**Minimum Defl. Factor**	**Type**
35 kHz to 1 GHz	0.35 ns	5 mV/mA	P6040/CT 1
1.2 kHz to 150 MHz	0.5 ns	1 mV/mA	P6041/CT 2
8.5 kHz to 150 MHz	2.2 ns	1 mA/mV	P6022/Passive Termination
100 Hz to 70 MHz	5 ns	1 mA/div	P6022/134 Amplifier
450 Hz to 60 MHz	5.8 ns	2 mA/mV	P6021/Passive Termination
DC to 50 MHz	7 ns	1 mA/div	P6042/Amplifier
12 Hz to 40 MHz	9 ns	1 mA/div	P6021/134 Amplifier

Fig. 4-1. List of all current Tektronix probes (active highlighted).

4

UNDERSTANDING SPECIFICATIONS

Fig. 4-1 and 4-2 display the active probes available from Tektronix. As in Chapter 1, both figures show the same information. The active probe may contain a tube, transistor, field-effect transistor or a combination of these devices which allow high input impedance, low output impedance and signal gain.

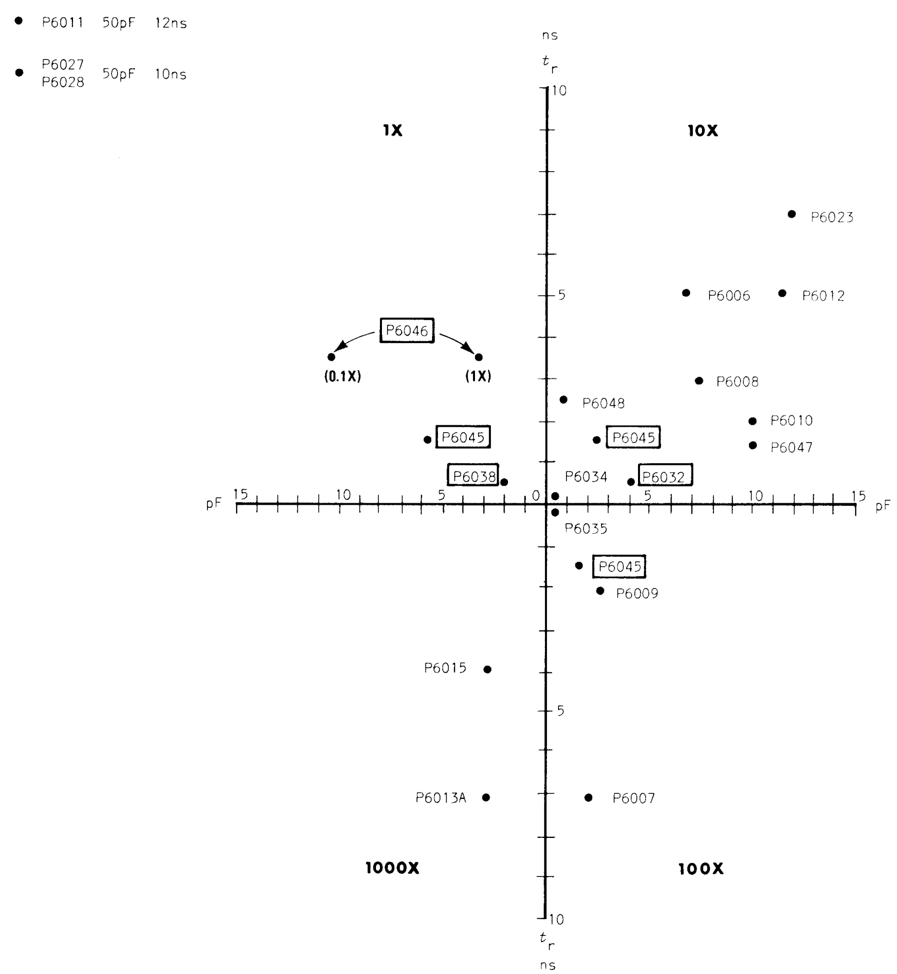


Fig. 4-2. Identical information to Fig. 4-1 showing faster probes toward the center.

DC-to-230 MHz
1X VOLTAGE PROBE

The P6045 FET Probe offers new capabilities for measuring small, high-frequency signals. Unlike many general-purpose probes which require built-in attenuation to reduce circuit loading, the P6045 utilizes a field effect transistor, resulting in reduced loading without sacrificing the gain of the measurement system.

This new DC-to-230 MHz probe can be used with conventional oscilloscopes (1-MΩ inputs) and 50-Ω sampling oscilloscopes. Its small size makes it easy to use, particularly for applications involving compact circuitry. The probe also features a DC-offset control for measuring very small AC signals with DC potentials up to one volt.

Accessories supplied with the probe include 10X and 100X attenuator heads and an AC-coupling capacitor. Optional accessories include a probe power supply, and a tunnel diode pulser for checking the response of the probe.

The Accessory Power Supply permits the P6045 to be used with all Tektronix conventional oscilloscopes and 50-Ω sampling oscilloscopes. It provides the power required to operate one P6045. The Type 454 oscilloscope provides two P6045 probe power connectors.

CHARACTERISTICS

PROBE GAIN is adjustable to 1X.

RISETIME is 1.5 ns or less.

ABERRATIONS are less than +3%, −3%, total 6% P-P when used with real-time oscilloscopes, or less than +4%, −4%, total 8% P-P when used with sampling oscilloscopes.

BANDWIDTH is DC to 230 MHz at 3-dB down. Low-frequency 3-dB point with AC-coupling capacitor is less than 16 Hz.

INPUT RESISTANCE is 10 megohms.

INPUT CAPACITANCE is approximately 5.5 pF.

OUTPUT LOAD IMPEDANCE is 50 Ω. A switch on the compensating amplifier provides internal 50-Ω termination, or the probe can be terminated externally. This switching provision allows the P6045 to be used with either 50-ohm or 1-megohm systems. The probe may require recompensation when the termination is changed. Compensation is adjusted at the factory for 1-megohm systems.

DC-OFFSET RANGE is ±1 V, selected by variable front-panel control.

OUTPUT DYNAMIC RANGE is ±0.5-V peak.

INPUT DYNAMIC RANGE is ±0.5-V peak around a reference voltage which can be offset by 0 to ±1 V DC.

NOISE is less than 0.4 mV over a bandwidth of DC to 8 MHz, less than 1.5 mV over a bandwidth of DC to 230 MHz.

MAXIMUM INPUT SURGE VOLTAGE is ±100 V DC.

PROBE POWER REQUIREMENTS are +12.5 V, ±5% at approx 50 mA; −12.5 V, ±5% at approx 100 mA.

CABLE is 6 ft long. Output connector is locking BNC.

ACCESSORY POWER SUPPLY operates from 93 V-to-140 V or 186 V-to-280 V line.

Fig. 4-3. P6045 specifications.

The active probe, better known as a cathode follower or FET probe, evolved from a requirement to provide a high input impedance (minimum C, maximum R equal to or better than high attenuation passive probes) without the necessity of using high attenuation and without losing wide bandwidth capability. Also, the additional requirement of having an impedance matching or transforming capability was desired. See Chapter 5, Considerations in Use.

Fig. 4-3 shows the specifications of the Type P6045 FET Probe.

Probe Gain is adjustable to 1X.

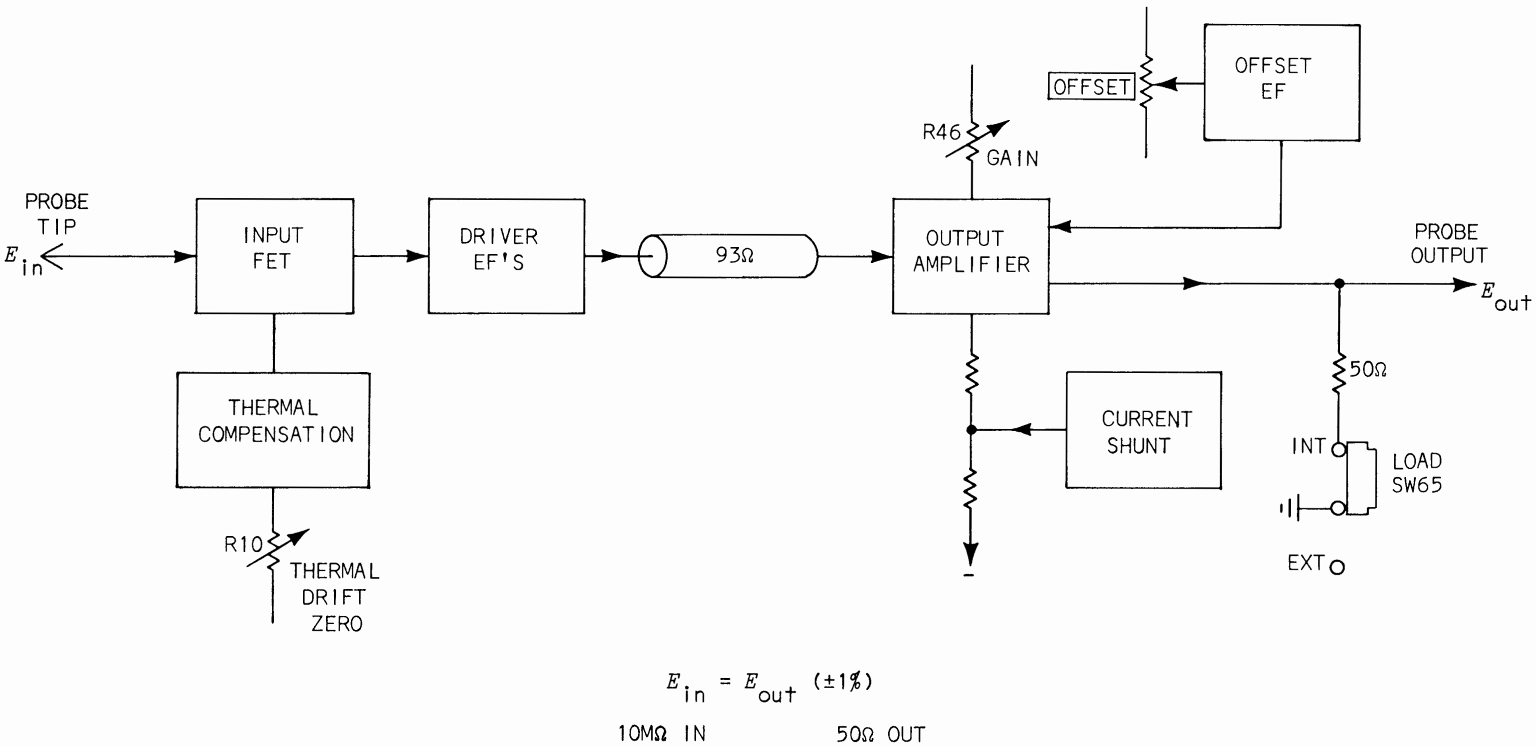


Fig. 4-4. Block diagram of the P6045 circuit.

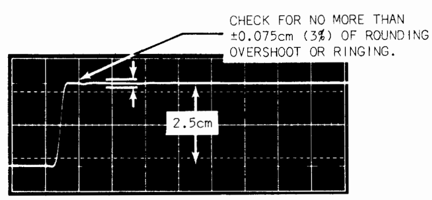
Because of the impedance matching capability of a source follower and 2 emitter followers, the probe's 6 foot long cable offers little attention to fast t_r signals but some loss occurs. This cable is the input to a wideband amplifier with an adjustable gain which is capable of bringing the signal back to unity. Fig. 4-4 shows the P6045 block diagram.

Risetime is 1.5 ns or less.

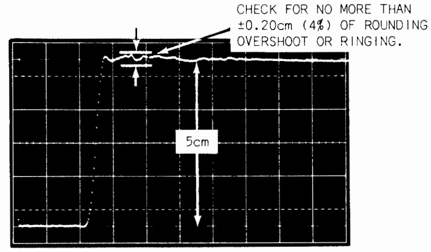
This is a *probe only* risetime specification. The active probes are measured and specified exactly as described under passive probes. Refer to Chapter 1 for further information.

Aberrations are less than +3%, -3%, total 6% P-P when used with realtime oscilloscopes or less than +4%, -4%, total 8% P-P when used with sampling oscilloscopes.

This specification is again a *probe only* specification and is intended to show what "worst case" distortions might be added to a step function. The two % ranges result due to a change in bandwidth of the testing oscilloscope and a change in the probe amplifier's termination. Fig. 4-5 shows typical step response distortions.



(A) ABERRATIONS WITH REALTIME OSCILLOSCOPE



(B) ABERRATIONS WITH SAMPLING OSCILLOSCOPE

Fig. 4-5. Typical step response distortions.

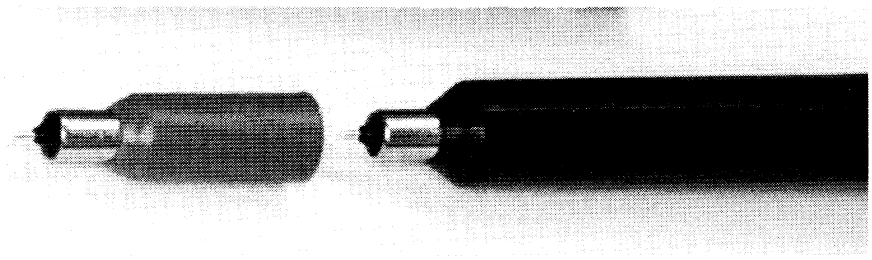


Fig. 4-6. Series DC blocking capacitor.

Not all aberration specifications have total P-P values as a sum of the +%, -% values. The intent is to indicate that aberration may be all above the step response top (+3%), or all below the step response top (-3%) but the total peak to peak aberrations will not exceed some %. i.e.: +3%, -3%, total 4% P-P.

Bandwidth is DC to 230 MHz at 3 dB down. Low frequency 3 dB point with AC coupling capacitor is less than 16 Hz.

The upper bandwidth specification is derived by:

$$\text{bw} \simeq \frac{0.35}{t_r}.$$

Where: bw = Bandwidth

t_r = Probe only risetime

0.35 = Constant used by Tektronix. Product of risetime and -3 dB frequency response when step transient response contains ≤ 2% overshoot.

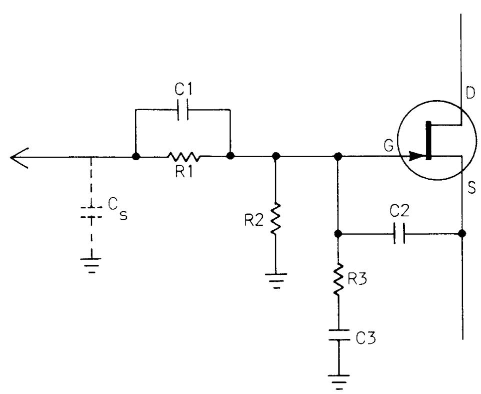
The low frequency AC coupling response develops as a result of inserting a series DC blocking capacitor and is similar to Chapter 2, Fig. 2-9. This capacitor is a plug-on-tip accessory shown in Fig. 4-6.

Input Resistance is 10 megohms.

Input Capacitance is approximately 5.5 pF.

The input specifications of active probes, like passive probes, are measured at some low frequency or DC. Because of the use of active circuit elements at the probe tip, the DC input resistance is easily located on a schematic and is generally a single resistor. The input capacity is again composed of some small amount of environmental capacity plus a series bypass capacitor and the input capacity of the active element. Fig. 4-7 shows a partial schematic of an FET probe input circuit. Again, the input characteristics change as frequency increases. See Chapter 6.

Output Load Impedance is 50 Ω.



C1 = 200pF } INPUT SURGE VOLTAGE PROTECTION
R1 = 120kΩ }
R2 = 9.9MΩ
C2 = SELECTED VALUE FOR INPUT CAPACITY UNIFORMITY
R3, C3 = 5.1k, 2.5pF COMPENSATION FOR INPUT CAPACITANCE CHANGE WITH FREQUENCY ALSO COMPENSATES FOR INPUT CHARACTERISTICS OF FET.
C_s = ENVIRONMENTAL CAPACITY

Fig. 4-7. FET probe partial schematic.

This specification indicates the amplifier must be terminated in 50 Ω for proper operation. See Fig. 4-4. An internal switch arrangement allows moving the probe from a high impedance system to a low impedance system (50 Ω) without requiring additional external loads or terminations. However, due to a change in termination, the amplifier may require some recompensation for optimum transient response.

DC Offset Range is ±1 V, selected by a variable front panel control.

This specification indicates the amount of input DC voltage that may be offset and still allow the probe to handle DC coupled signals at maximum sensitivity. i.e.: a 20 mV P-P sinewave superimposed on a 1 V DC level may still be DC coupled through the probe. See Chapter 5.

Output Dynamic Range is ±0.5 V peak.

This specification indicates the maximum linear output signal that can be developed across the 50 Ω termination. If attempts are made to obtain output signals beyond specification, significant distortion will occur.

Input Dynamic Range is ±0.5 V around a reference voltage which can be offset by 0 to ±1 V DC.

This specification reflects the probe gain of 1X and is dependent upon the amplifier's Output Dynamic Range.

Noise is less than 0.4 mV over a bandwidth of DC to 8 MHz, less than 1.5 mV over a bandwidth of DC to 230 MHz.

This specification again is a *probe only* specification and is measured with the probe tip connected to a 50 Ω source resistance. The specification gives an indication of the probe's noise distribution and may be used to approximate the amount of observable noise when the probe is used with a measurement system.

*Tangentially measured noise** specifications may be added if both specifications were determined using the same input and/or output termination (50 Ω in the case of the P6045). The approximate displayed noise will be specified probe noise times the measurement system gain plus the specified system noise. This value may be modified by the measurement system bandwidth.

Maximum Input Surge Voltage is ±100 V DC.

The active probe, unlike the passive probe, is more susceptible to damage from over-voltage. General purpose active probes are usually protected by series current limiting elements (see Fig. 4-7, R1, C1). Damage occurs if excessive current (heating) is caused to flow through the FET gate-source junction. See Chapter 5.

Probe Power Requirements are +12.5 V, ±5 % at ≈ 50 mA; -12.5 V, ±5 % at ≈ 100 mA.

This specification must be complied with or all other specifications may be out of tolerance. Any power source meeting these requirements may be used to power the probe.

---

*Tangential noise measurement: A procedure to determine displayed noise wherein a flat-top pulse or square-wave input signal is adjusted in amplitude until the two traces (or portions of two traces) thus produced appear to be immediately adjacent or contiguous. Measurement of the resulting signal amplitude determined a noise value which correlates closely with the value interpreted by the eye from a sampling display and is called the *tangential noise value*. This noise value is approximately equal to 2 times an RMS noise value.

DIFFERENTIAL PROBE AND AMPLIFIER

CHARACTERISTICS

Probe and Amplifier

DEFLECTION FACTOR is 1 mV/div to 200 mV/div in 8 calibrated steps, 1-2-5 sequence, accurate within 3% (with an oscilloscope deflection factor of 10 mV/div).

BANDWIDTH is DC-to-100 MHz at 3-dB down.

RISETIME is 3.5 ns or less.

COMMON-MODE REJECTION RATIOS with deflection factors of 1 mV/div to 20 mV/div are at least 10,000:1 at 50 kHz, 5,000:1 at 1 MHz and 1,000:1 from 10 MHz to 50 MHz.

COMMON-MODE LINEAR DYNAMIC RANGE is ±5 V (DC + peak AC), ±50 V with 10X attenuator.

INPUT RC is 1 MΩ paralleled by ≤10 pF.

INPUT COUPLING is AC or DC, selected by a switch on the probe. Low-frequency response AC-coupled is 3-dB down at 20 Hz, 2 Hz with 10X attenuator.

DISPLAYED NOISE is 280 μV or less (tangentially measured).

MAXIMUM INPUT VOLTAGE is ±25 V (DC + peak AC), ±250 V with 10X attenuator.

OUTPUT IMPEDANCE is 50 Ω through a BNC-type connector. A 50-Ω termination is supplied with the amplifier for use with 1-megohm systems.

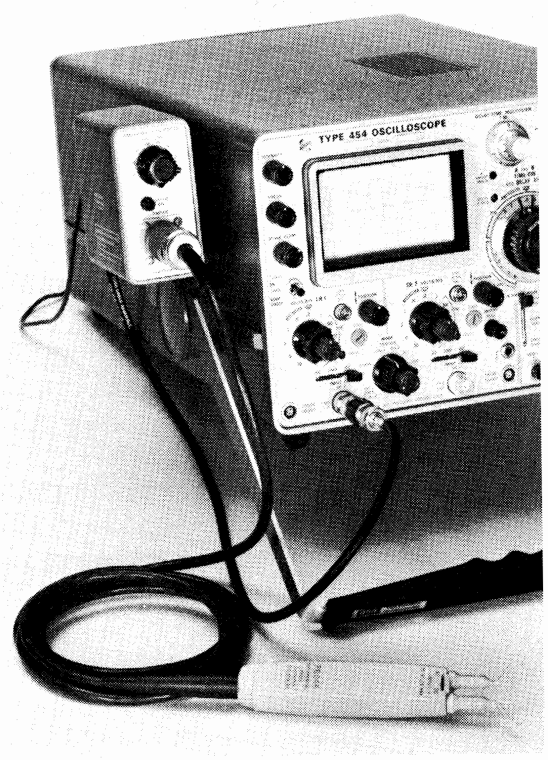
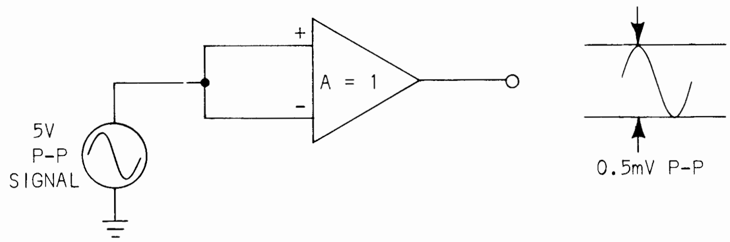
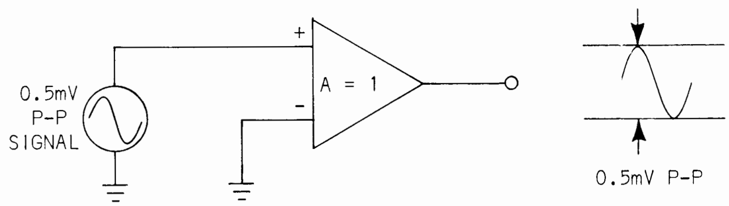


Fig. 4-8. P6046 specifications.



(A) OUTPUT CAUSED BY INABILITY TO COMPLETELY REJECT COMMON-MODE SIGNALS.



(B) EQUIVALENT OUTPUT CAUSED BY SINGLE-ENDED SIGNAL.

$$\frac{5\text{V}}{0.5\text{mV}} = 10{,}000{:}1 \text{ CMRR}$$

(C) CMRR = RATIO OF AMPLITUDE OF COMMON-MODE SIGNAL (A) TO AMPLITUDE OF SINGLE-ENDED SIGNAL (B) WHICH PRODUCES EQUIVALENT RESULTS.

Fig. 4-9. Common-mode rejection ratio.

Fig. 4-8 shows a special purpose active probe, the Type P6046 Differential Probe and Amplifier.

Common-Mode Rejection Ratio (CMRR) is a ratio that expresses the ability of a differential amplifier in preventing signals that are identical in both amplitude and time (common-mode signals) from affecting its output. The "ideal" differential probe or amplifier would amplify only the difference signal between its two inputs and would completely reject all common-mode signals. Since the "ideal" capability does not exist, some amount of common-mode signal will be present in the amplifier output. Fig. 4-9 shows the relationships necessary to determine CMRR.

Common-Mode Linear Dynamic Range specification would not be necessary with an "ideal" differential probe or amplifier. However, amplifiers do have limitations relating to the maximum signal amplitude that can be handled and still maintain linear operation and high CMRR. If common-mode input signals exceed this specification, the CMRR will drop to some low value. The degree of CMRR change is directly related to the type of signal and the amount of overdrive.

Temperature Range - The P6045 is intended for general laboratory instrument use, as are most of our active probes, and will meet its specifications over an ambient temperature range from 0°C to +50°C after being calibrated at +25°C, ±5°C. With a more specialized probe, the P6046 Differential Probe, ambient temperature variations may affect some performance specification such as CMRR. For additional information see Chapter 5.

5

CONSIDERATIONS IN USE

Most considerations in use of passive probes are applicable to active probes. However, because of the sophistication of active probes, additional considerations are necessary. A primary point is

mistreatment

active probes are not forgiving for being mistreated. *The input surge voltage limitation is a necessary specification that must be observed by the user.* To disregard this limit factor will result in damage to the probe. Remember that the capability of these probes to handle small signals and to "transform" impedances from very high values to low output values is the direct result of active components which have limitation on how much the input or output circuit can change without distortion resulting.

One form of distortion might result when considering the probe OFFSET control as just another oscilloscope vertical position control. If the OFFSET control were turned full clockwise and the trace recentered with the oscilloscope's vertical POSITION control, distortion in the form of a compressed signal amplitude would likely occur. The purpose of the offset capability is to permit the input signal to be positioned to the center of the Dynamic Range of the probe amplifier so the best transient response is obtained.

The best technique to stay away from this possible distortion problem is:

1. First, disconnect the probe or ground the oscilloscope input and center the trace with the oscilloscope's vertical POSITION control.
2. Use a VOLT/DIV setting which will insure the Dynamic Range Limits are off screen. (i.e., if limits are ±500 mV, use a setting of 100 mV/DIV. At 100 mV/DIV, limiting occurs at ±5 divisions.)

avoiding distortion

3. With the probe attached to the oscilloscope, use only the OFFSET control for signal positioning. DO NOT use the oscilloscope vertical POSITION control. Fig. 5-1 shows the P6045 offset capability.

An additional consideration concerning the OFFSET control is that this control is not intended, unless so specified, as a "slide back" control to observe small portions of a large over drive signal. Should the amplifier saturate, the *recovery time is undefined.*

attenuator heads

Low frequency compensation is still necessary with active probe plug-on attenuator heads. These attenuator heads allow the extensions of an active probe's Dynamic Range so that larger signals may be measured safely. The head's attenuation factor is a Dynamic Range multiplier factor. i.e.: probe only, ±0.5 V range; probe with 10X head, ±5.0 range. These heads are compensated passive dividers (Fig. 5-2). The probe input capacity is reduced (See Chapter 1 for input capacity reduction with passive attenuation) and the overall attenuation accuracy of the probe with an attenuator head decreases. i.e.: probe only, ±1 %; probe with 10X head, ±3.5 %. The compensation technique is the same as "Terminally compensated" passive probes. See Chapter 1, Fig. 1-7.

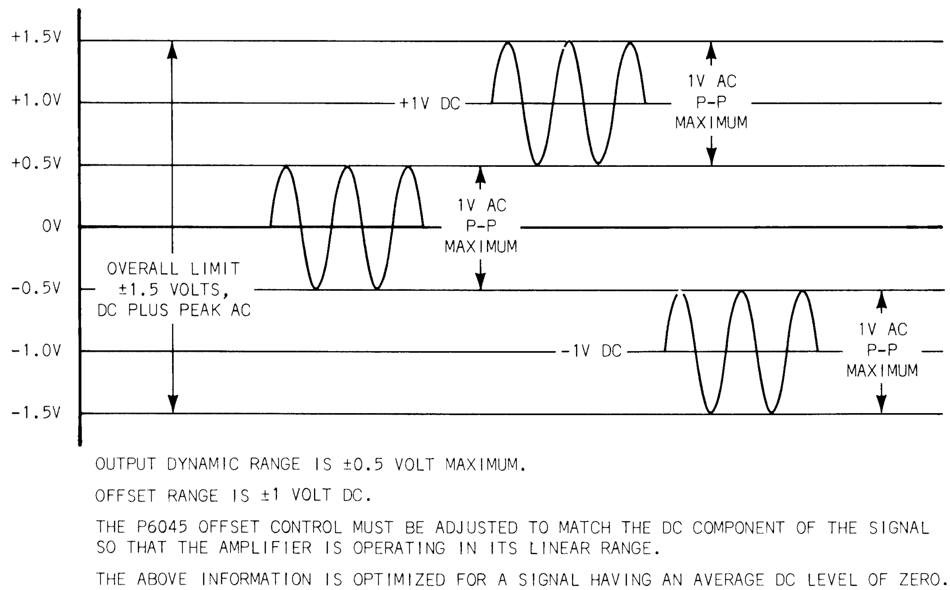


Fig. 5-1. P6045 amplifier dynamic range and DC offset limits.

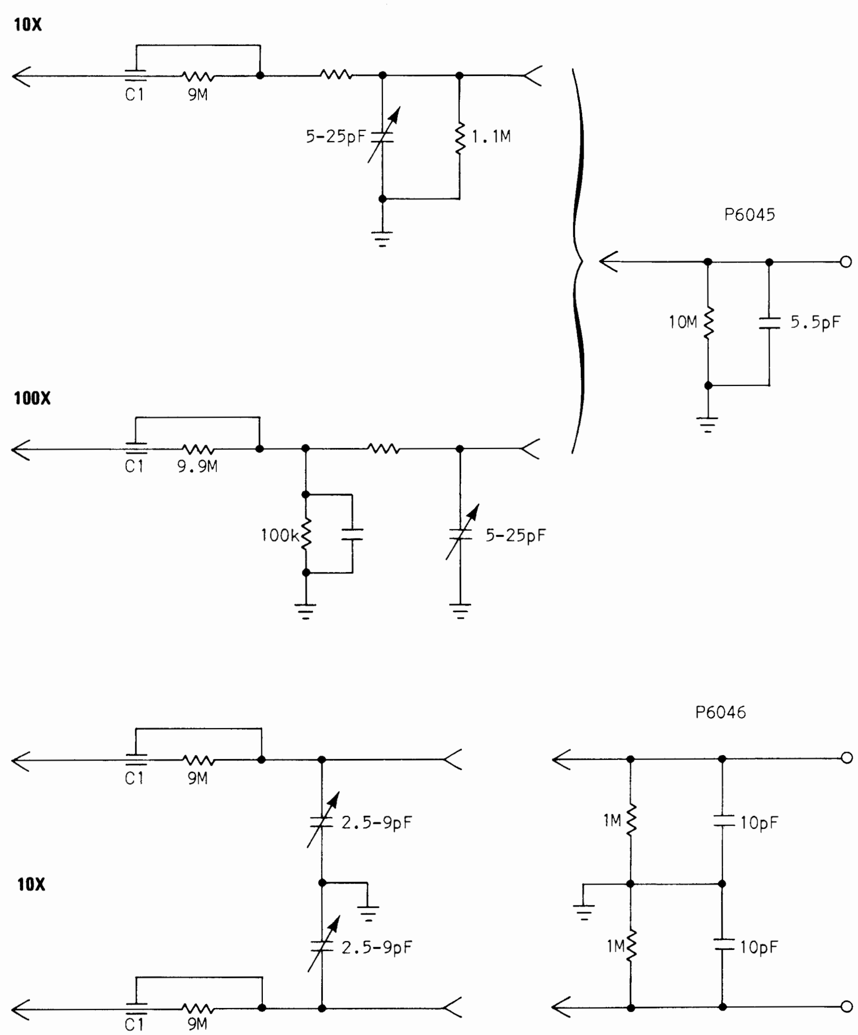


Fig. 5-2. Plug-on attenuator heads for active probes.

Caution should be exercised when using an active probe on unknown voltage sources. Remember that the general purpose active probe has over-voltage protection elements but the special purpose differential probe cannot tolerate these additional elements and still maintain a high/wideband CMRR.

unknown voltage sources

A good procedure to follow, when dealing with questionable sources, is to always insure that the circuit under test ground and the probe/oscilloscope ground are at the same potential. Then use an attenuator head on the probe until the actual signal amplitude and its DC levels are determined.

Ground lead inductance problems exist with active probes as they did with passive probes. See

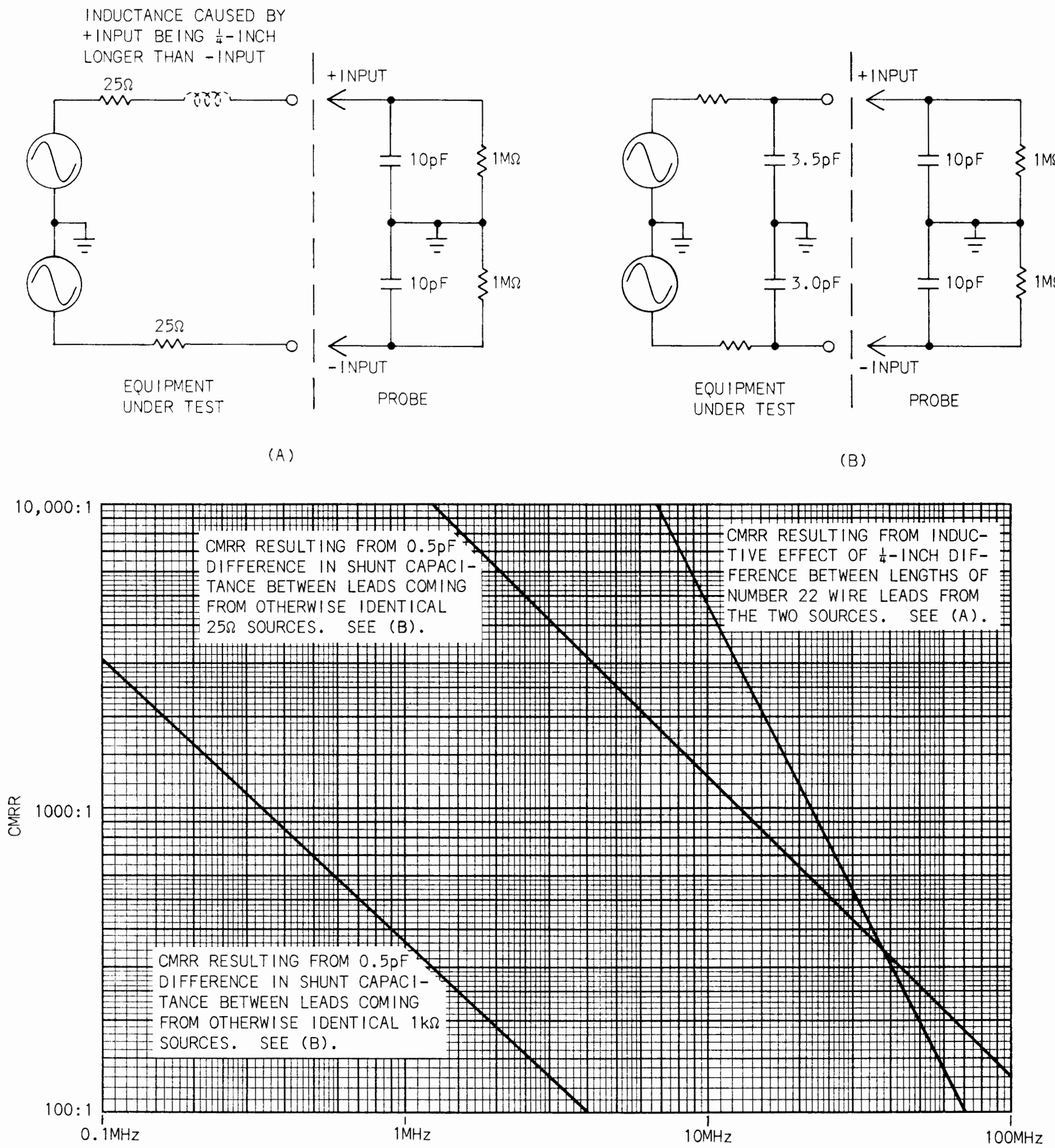
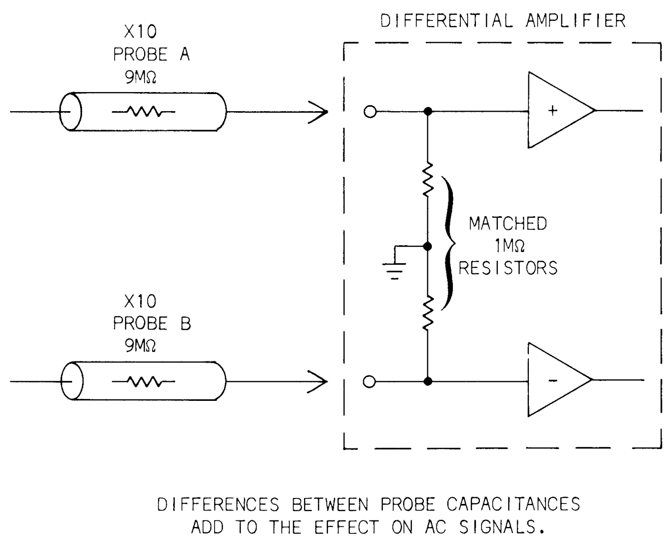


Fig. 5-3. Impedance effects upon apparent CMRR.

Chapter 1. It's interesting to note that most hardware developed for passive probes is just as useful and usable with active probes. (i.e.: probe to BNC adapters and bayonet ground adapters.) The P6046 Differential Probe has lead inductance considerations but the effect is much more significant than a "ringing" or series resonance consideration. Fig. 5-3A shows the changes in the CMRR that result from an imbalance of series inductance of two signal sources.

Source Impedance -- Difference in signal source capacity can also cause reduction in CMRR. Fig. 5-3B shows this difference in CMRR between 25 Ω and 1 kΩ matched sources with 0.5 pF of source capacity difference. The initial impression from Fig. 5-3 is that CMRR is extremely difficult to maintain. To reinforce this thought, Fig. 5-4 shows typical CMRR obtainable at DC when using simple passive probes to apply input signals to a high CMRR differential amplifier.



WORST CASE DIFFERENCE BETWEEN PROBE A AND PROBE B	CMRR LIMITATION INTRODUCED BY PROBES
1% (0.5% RESISTORS)	111:1
2% (1% RESISTORS)	55:1
10% (5% RESISTORS)	11:1

Fig. 5-4. Circuit showing CMRR limitations which can be introduced by probe differences.

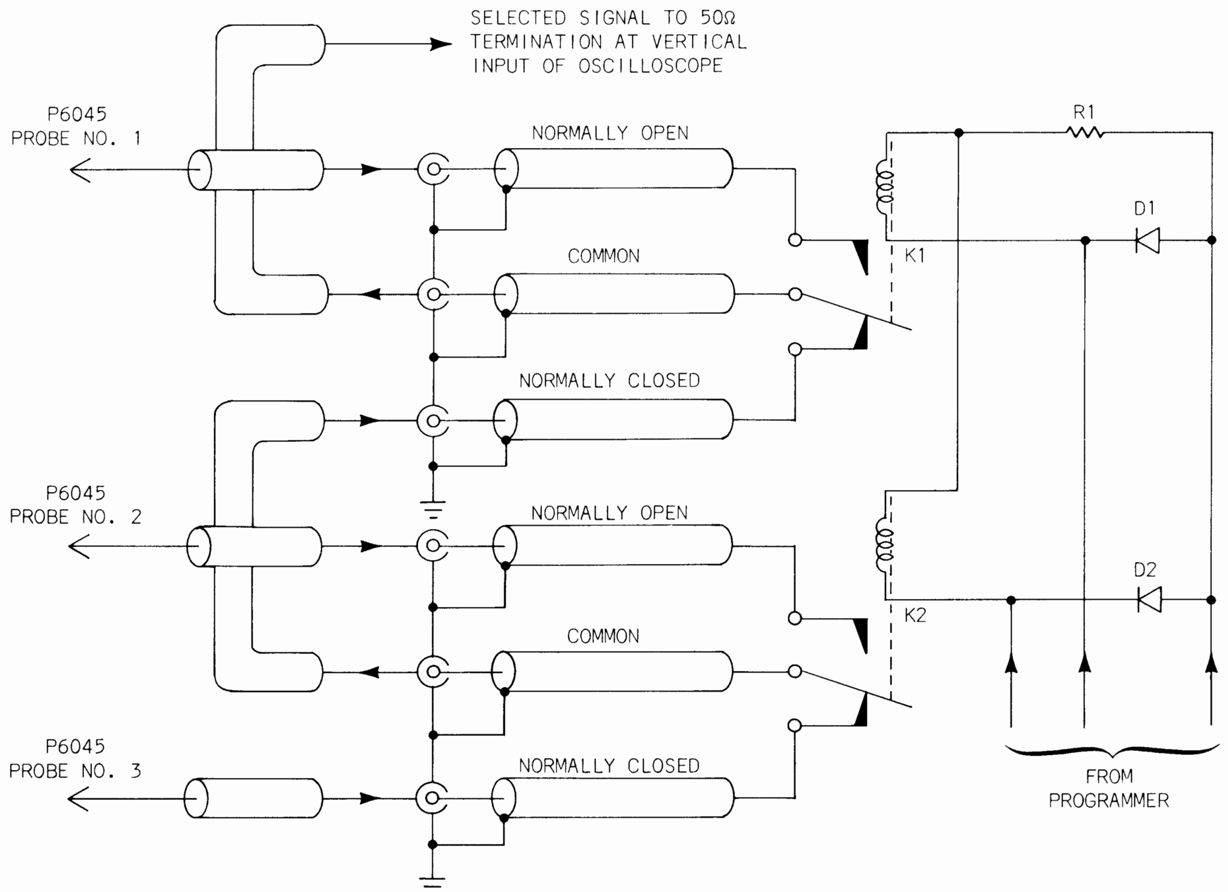


Fig. 5-5. 50 Ω coaxial signal-switching system with P6045 probe inputs.

Low output impedance allows the active probe to be used in a variety of signal transferring techniques before presenting a signal under test to an oscilloscope for measurement. The self-contained probe/amplifier and a power supply allow remote signal acquisition and then transmission of the signal through multiple switches to the measurement system. Fig. 5-5 shows a 50 Ω switching system where any one of three FET probes may feed one output.

High input impedance -- Again, the active probes are similar to the passive probe and the input R_p and X_p change as a function of frequency. Fig. 5-6A, B and C show the R_p and X_p characteristics of the P6045 and P6046 probes.

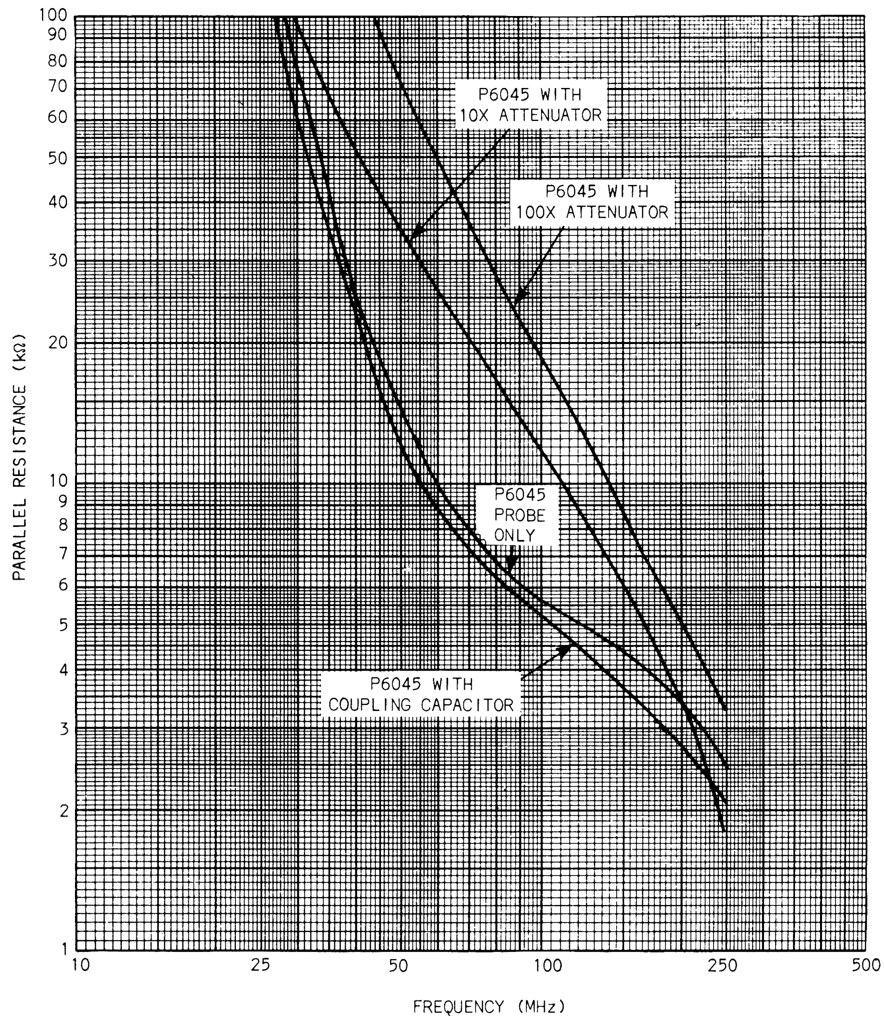


Fig. 5-6A. Typical parallel input resistance vs frequency curves of the P6045 probe.

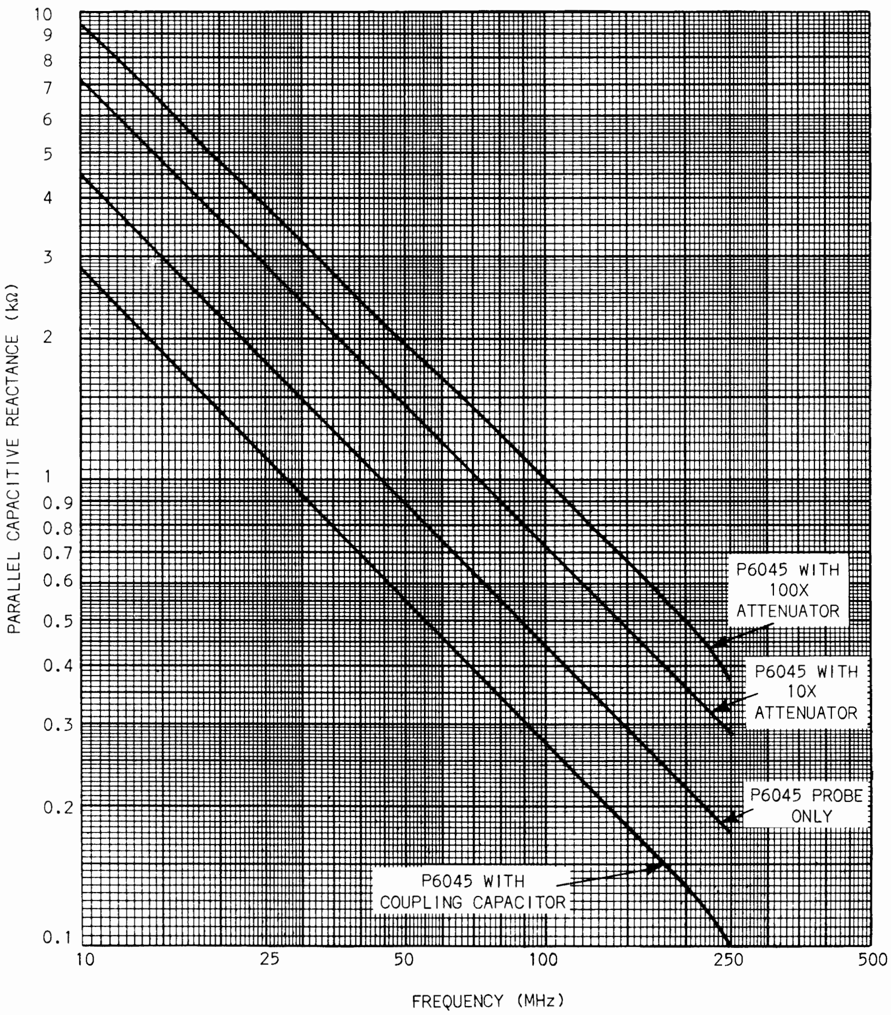


Fig. 5-6B. Typical input capacitive reactance vs frequency curves of the P6045 probe.

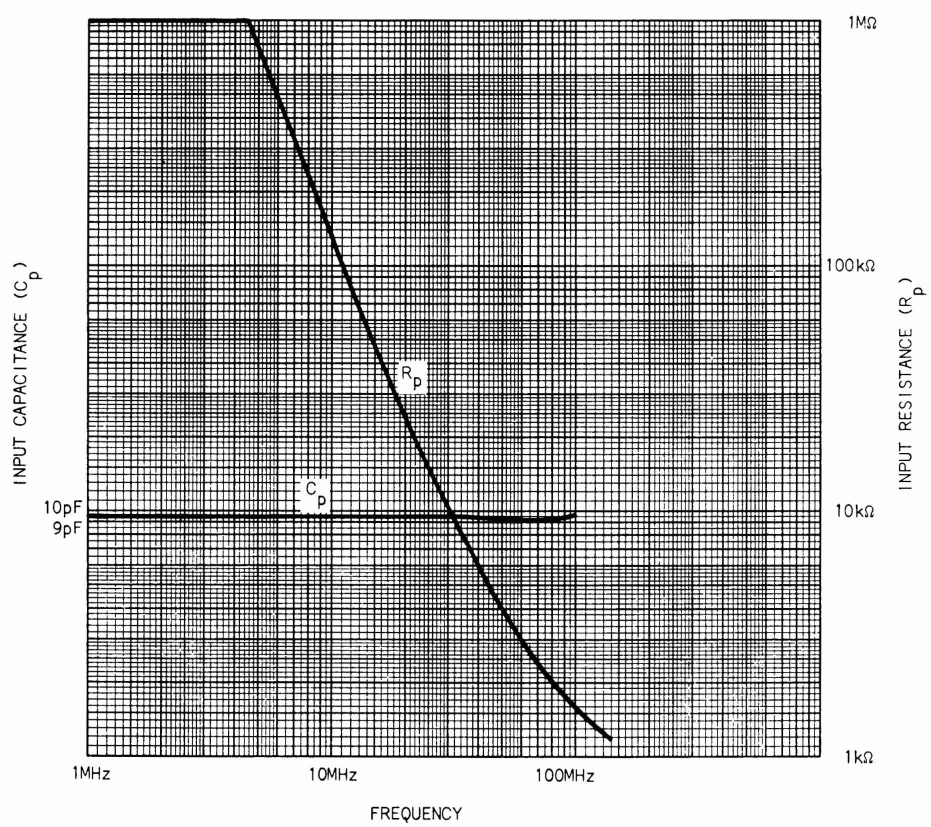


Fig. 5-6C. P6046 input capacitance (C_p) and resistance (R_p) vs frequency.

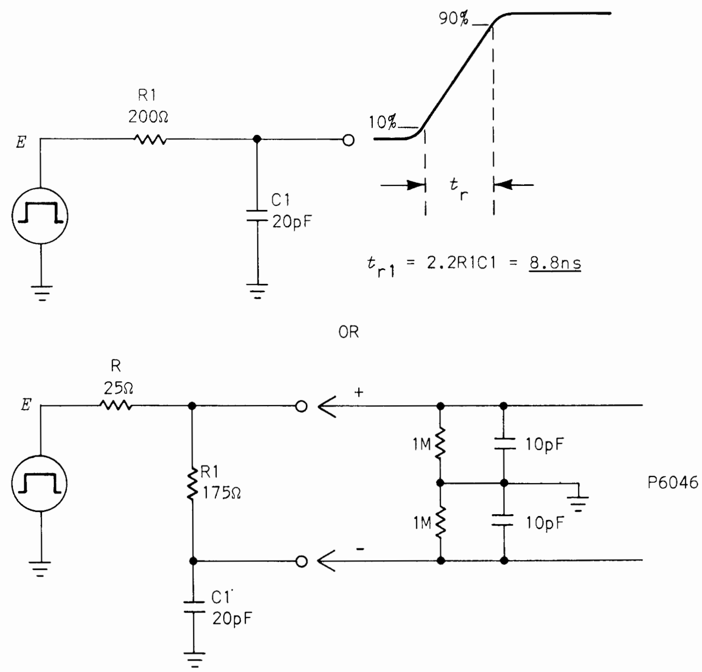


Fig. 6-1. Typical signal source and a rearranged version for P6046.

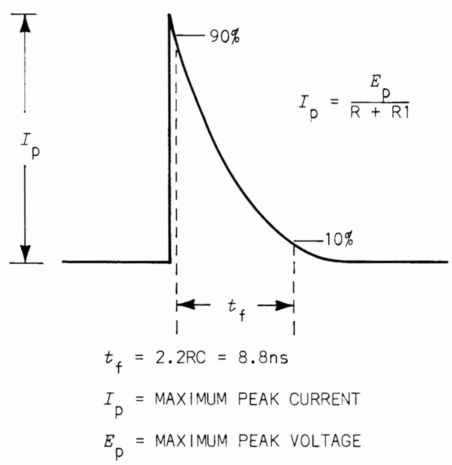


Fig. 6-2A. Ideal current waveform.

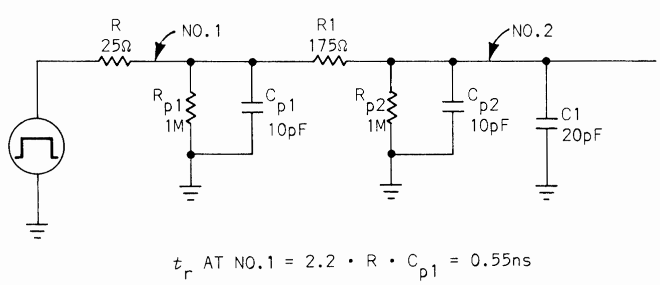


Fig. 6-2B. Typical signal source with P6046 added.

Fig. 6-2.

6

SIGNAL MEASUREMENT EVALUATION

measurement evaluation

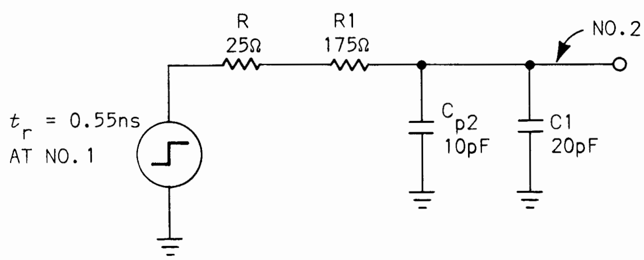
The evaluation of measurements made with active probes, such as the general purpose P6045, is exactly the same as discussed in Chapter 3. Even the special purpose differential probe, when used in a single-ended configuration with one input grounded, may be considered as a passive probe. Additional considerations arise when using the P6046 to measure and evaluate differential signals.

signal source

Fig. 6-1 shows the same signal source used in Chapter 3 and a redrawn version dividing the 200 Ω source R into a terminated 50 Ω step generator (25 Ω) driving a 175 Ω resistor and a 20 pF shunt capacitor. The objective in using a differential probe to measure the voltage developed across R1 might be to determine the charging current of C1. (A current probe could be used to make this measurement. See Chapter 9.) In this instance, R1 serves as a current metering resistor. The approach will be the same as Chapter 3. First, evaluate the circuit without the probe, then add the probe and determine the changes.

output signal

The output signal t_r is 8.8 ns and should follow the universal time constant curve. (Chapter 3, Fig. 3-2.) Assuming the components to be ideal (pure R and C, *no* inductance), the current waveform should be maximum when the step occurs and then decay at a rate determined by the circuit time constant and having a falltime (t_f) equal to the voltage t_r or 8.8 ns. Fig. 6-2A shows the *ideal* current waveform. Fig. 6-2B shows the circuit with the P6046 probe added.



t_r AT NO.2 = 2.2(R + R1)(C_{p2} + C1) = 13.4ns

IF (t_r AT NO.1) X 5 < t_r AT NO.2,
t_r AT NO.1 MAY BE DISREGARDED.

IF (t_r AT NO.1) X 5 ≥ t_r AT NO.2,
COMBINE BY t_r OUTPUT = $\sqrt{(t_r \text{ AT NO.1})^2 + (t_r \text{ AT NO.2})^2}$.

Fig. 6-3.

Assuming a step generator with a t_r of 0, the first TC of interest is R, R_{p1} and C_{p1}. Applying the same judgment that was used in Chapter 3, disregard R_{p1}. The t_r at No. 1 = 2.2 R C_{p1} = 0.55 ns. Since the loads from No. 1 to ground are much greater than R, an equivalent circuit may be drawn with the generator t_r = 0.55 ns and still having R = 25 Ω. See Fig. 6-3. Again using the same R_p judgment, the t_r at No. 2 = 2.2 (R + R1) (C_{p2} + C1) = 13.4 ns.

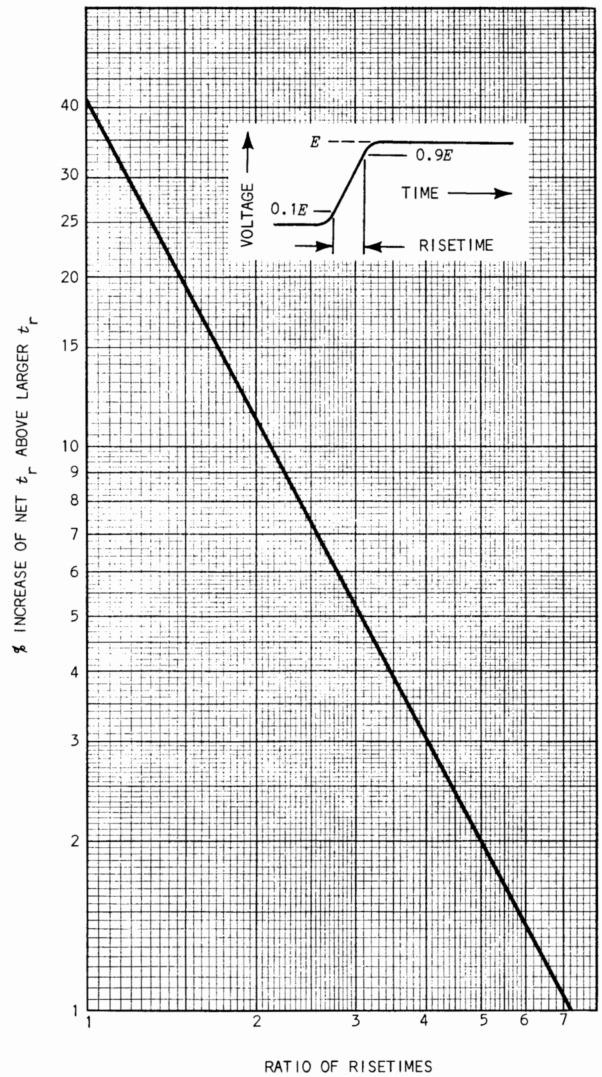


Fig. 6-4. Percent increase in the t_r above the t_r of the slower of two cascaded devices.

combining t_r values

Fig. 6-3 also shows considerations necessary in combining t_r values. The X5 factor should hold calculations to ≈ 2 %. See Fig. 6-4. Taking the values of t_r and amplitude of the step generator response at No. 1 and No. 2 test points and subtracting these algebraically will determine the

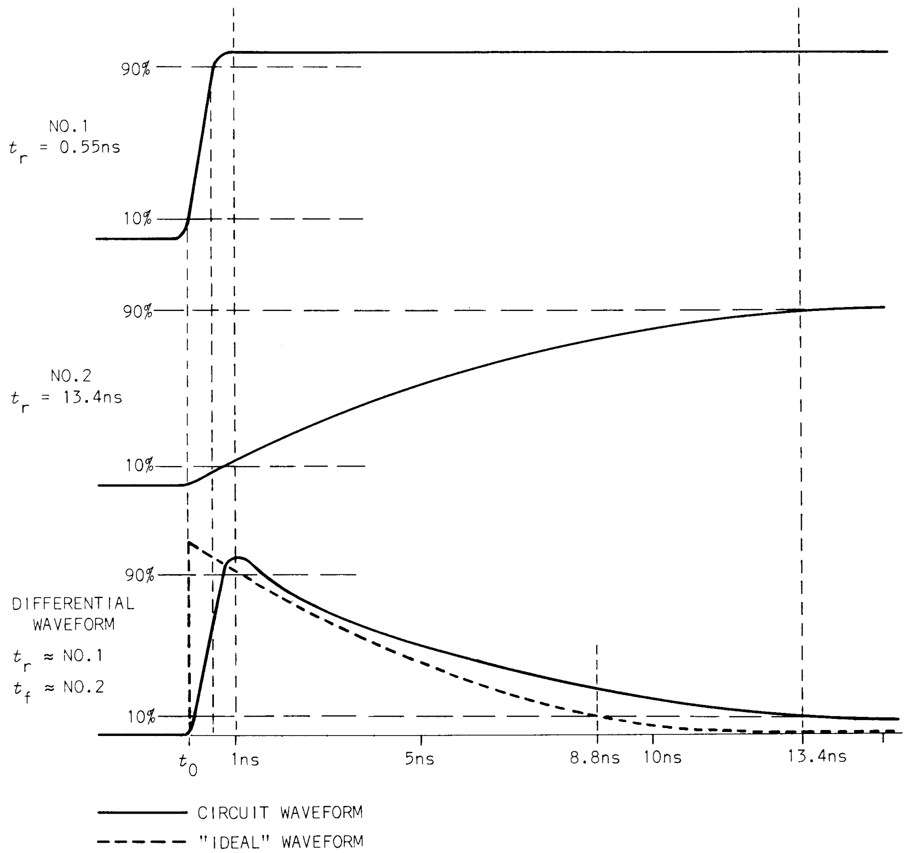


Fig. 6-5. Difference between No. 1 and No. 2 waveforms.

shape of C1 charging current's waveform. See Fig. 6-5. Note that the difference in the *ideal* current waveform and *circuit's* differential voltage waveform of Fig. 6-5 is due to the extra capacity introduced to the circuit under test by the probe and the reduced amplitude results from the t_r at No. 1 not being equal to zero.

determining displayed signal

As in Chapter 3, nothing has been said of the measurement system capability. Only the affect of adding a probe to the circuit has been considered. To determine the actual displayed signal, the system t_r must be determined by:

$$t_{r\ system} = \sqrt{(t_{r\ scope})^2 + (t_{r\ probe})^2}\ .$$

This increase in $t_{r\ system}$ must be added to the No. 1 t_r by the square root of the sum of the squares and the waveform of No. 1 changed to a slower t_r. Waveform No. 2 should also change because the

t_r system X5 is ≥ t_r at No. 2. See Fig. 6-4. The slower signal at No. 1 is again algebraically subtracted from the *slower* signal at No. 2 resulting in a smaller differential signal whose peak amplitude is dependent upon the rate of rise limitation of the vertical measurement system and the ratio of the risetimes between the two signals. Fig. 6-6 shows the information contained in Fig. 6-5 plus two additional t_r values for t_r at No. 1. Notice the resulting differential signals are smaller in amplitude and reach peak values later in time.

The ability of the probe to subtract signal No. 2 from No. 1 is a function of the CMRR versus frequency curve. Each portion of the step function's t_r and initial top section contain frequency components having specific amplitude and phase relationships. If the input signals to the differential probe are

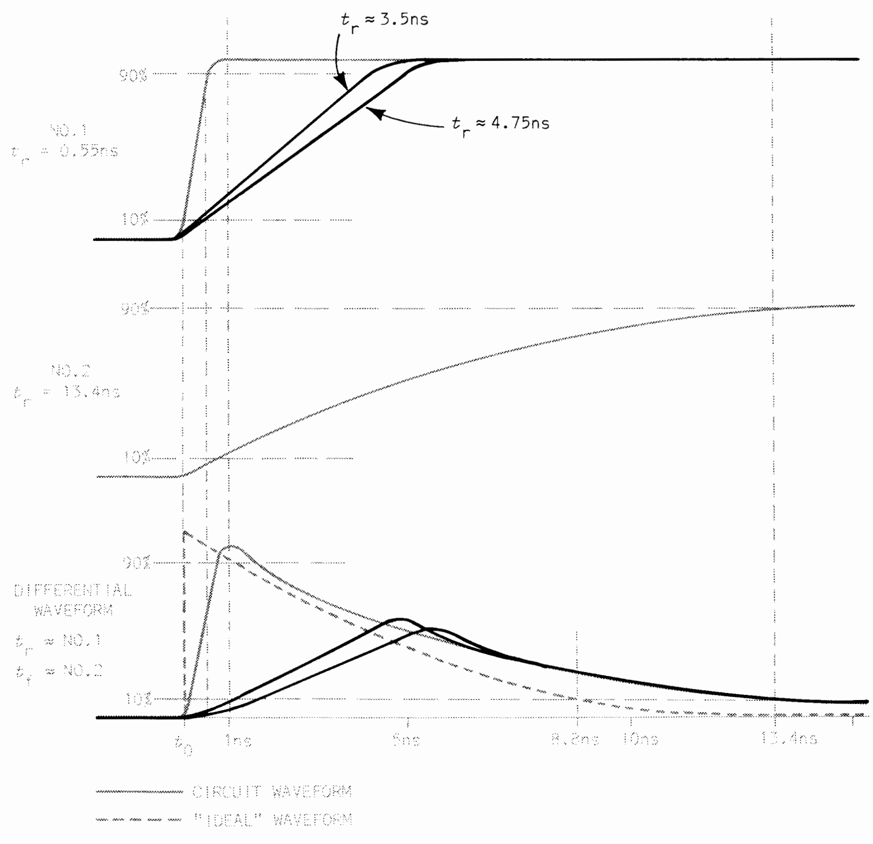


Fig. 6-6. Previous information plus two additional t_r values for No. 1.

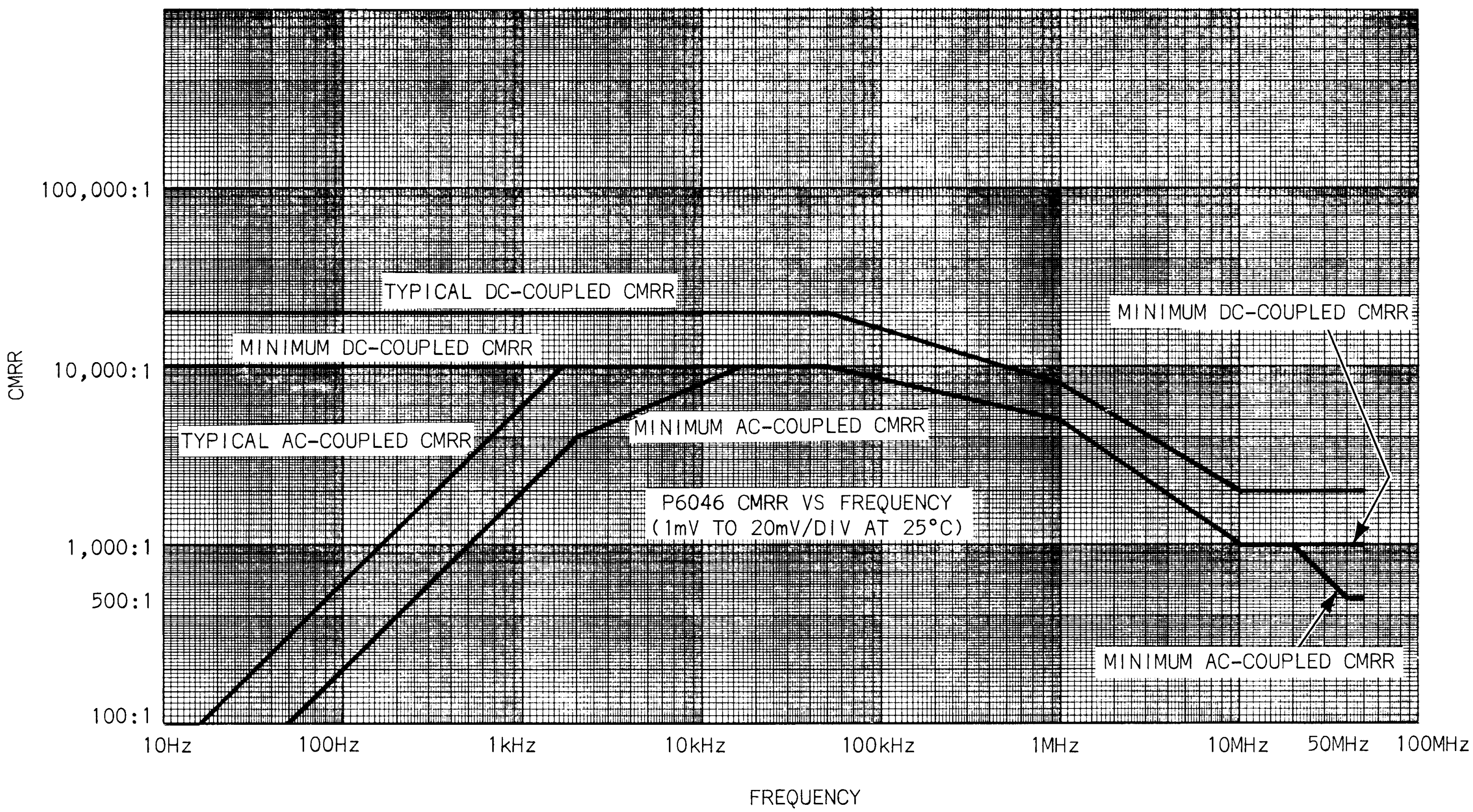


Fig. 6-7. P6046 CMRR vs frequency for 1 mV through 20 mV/division at 20°C.

CMRR vs frequency

equal in all respects, the probe will have the CMRR shown in Fig. 6-7. Note that even CMRR of 100:1 will reduce unwanted common mode signals to the 1 % amplitude level.

The analysis of differentially measured signals at high frequency or signals having very fast t_r portions is a very complex problem. Differential measurements under marginal conditions (at the very limit of the state of the art) is best evaluated by actual signal measurements and signal comparisons. The calculations in this chapter will serve as a first order approximation only.

VOLTAGE PROBES				
Recommended Use Area	**Probe Only Risetime**	**Probe Input R,C**	**Attenuation**	**Type**
DC to 3.5 GHz	0.1 ns	0.7 pF, 500 Ω	10X	P6034 Miniature
DC to 1.7 GHz	0.2 ns	0.6 pF, 5 kΩ	100X	P6035 Miniature
DC to 1 GHz	0.35 ns	2 pF, 100 kΩ	1X	P6038 Sampling
DC to 850 MHz	0.4 ns	3.6 pF, 10 MΩ	10X	P6032
DC to 230 MHz	1.5 ns	5.5 pF, 10 MΩ	1X	P6045 FET
DC to 150 MHz	1.2 ns	10 pF, 10 MΩ	10X	P6047 Miniature
	2 ns	2.5 pF, 10 MΩ	100X	P6009
DC to 100 MHz	3 ns	7.5 pF, 10 MΩ	10X	P6008
	3.5 ns	10 pF, 1 MΩ	0.1X	P6046 Differential Probe & Amplifier
	2.6 ns	1 pF, 1 kΩ	10X	P6048 Miniature
DC to 50 MHz	4 ns	2.7 pF, 100 MΩ	1000X	P6015 High Voltage Up to 40 kV
	2 ns	10 pF, 10 MΩ	10X	P6010 Miniature
DC to 33 MHz	7 ns	3 pF, 100 MΩ	1000X	P6013A High Voltage Up to 12 kV
	5 ns	7 pF, 10 MΩ	10X	P6006
	7 ns	2 pF, 10 MΩ	100X	P6007
	12 ns	50 pF, 1 MΩ	1X	P6011 Miniature
	5 ns	11.5 pF, 10 MΩ	10X	P6012 Miniature
	7 ns	12 pF, 8 MΩ	10X	P6023
	10 ns	50 pF, 1 MΩ	1X	P6027
	10 ns	50 pF, 1 MΩ	1X	P6028
DC to 21 MHz	17 ns	13.5 pF, 10 MΩ	10X	P6049 Miniature

CURRENT PROBES			
Recommended Use Area	**Probe Risetime**	**Minimum Defl. Factor**	**Type**
35 kHz to 1 GHz	0.35 ns	5 mV/mA	P6040/CT 1
1.2 kHz to 150 MHz	0.5 ns	1 mV/mA	P6041/CT 2
8.5 kHz to 150 MHz	2.2 ns	1 mA/mV	P6022/Passive Termination
100 Hz to 70 MHz	5 ns	1 mA/div	P6022/134 Amplifier
450 Hz to 60 MHz	5.8 ns	2 mA/mV	P6021/Passive Termination
DC to 50 MHz	7 ns	1 mA/div	P6042/Amplifier
12 Hz to 40 MHz	9 ns	1 mA/div	P6021/134 Amplifier

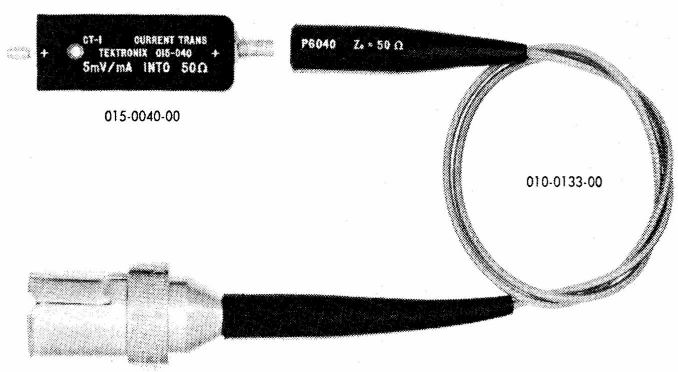
Fig. 7-1. List of all Tektronix probes (current highlighted).

7

UNDERSTANDING SPECIFICATIONS

In addition to our many voltage probes, Tektronix manufactures a full complement of current measuring probes. Fig. 7-1 highlights their present performance capabilities. Current probes may be subclassified as passive or active and having split core or closed core capability, (split core capability allows the probe to be clipped around the current carrying conductor).

35 kHz-to-1 GHz CURRENT PROBE



The P6040/CT-1 Current Probe is designed for use with Tektronix 50-Ω sampling units, such as the Type 1S1, 1S2, 3S1, 3S2, 3S5 and 3S6 Sampling Plug-In Units. With the use of a 50-Ω termination, the P6040/CT-1 can be used with wide-band, non-sampling oscilloscopes for making fast-risetime current measurements.

Several CT-1 current transformers may be placed throughout the circuit and monitored by one or more P6040 Probes. For a longer length probe, additional 50-Ω cable can be used in series with the probe.

P6040 PROBE

The P6040 Probe is an inter-connecting cable for the CT-1, used between the transformer and oscilloscope input.

If several CT-1 Transformers are in a circuit, the P6040 Probe can be used to monitor any one of them.

The P6040 can be used with other test-point connectors, such as Amphenol series 27 Sub-Minax or Sealectro Sub-Miniature RF.

IMPEDANCE is 50 ohms.

ATTENUATION is 1X.

OUTPUT CONNECTOR is a GR type.

CABLE LENGTH is 18 inches. Additional 50-Ω cable can be used in series with the probe. RG8/U or RG58A/U is recommended for best preservation of the CT-1 Transformer high-frequency response.

CT-1 CURRENT TRANSFORMER

SENSITIVITY is 5 mV/mA into a 50-ohm load. Accuracy is better than ±3%.

DECAY TIME CONSTANT is 5 μs, approximated by 1% per 50 ns; limit, 1 μs.

RISETIME is less than 350 ps.

FREQUENCY RESPONSE is 35 kHz to 1 GHz (30% down points).

INSERTION IMPEDANCE with a 50-ohm termination is 1 ohm shunted by approximately 5 μH; 2 ohms shunted by approximately 5 μH without a 50-ohm termination.

CAPACITIVE LOADING to a bare wire passing through the CT-1 transformer is typically 1.5 pF for #14 gauge, 0.6 pF for #20 gauge.

MAXIMUM VOLTAGE OF CIRCUIT UNDER TEST is 1000 V DC.

DIRECT CURRENT reduces the L/R time constant by a factor of 2 at 0.6 A.

PULSE CURRENT RATING is 100 A peak, with an amp-second product of 1 A-μs. When the A-s product is exceeded, the core saturates reducing the CT-1 output to zero.

RMS CURRENT RATING is 500 mA maximum.

TEMPERATURE RATING is −25° C to +65° C.

PHYSICAL DIMENSIONS are $^3/_8$ x $^9/_{16}$ x $1^{13}/_{16}$ inches plus 6-32 x $^1/_4$ inch mounting stud.

P6040/CT-1 CURRENT PROBE, order 015-0041-00

CT-1 CURRENT TRANSFORMER, order 015-0040-00

P6040 PROBE, order 010-0133-00

OPTIONAL ACCESSORY

GR to BNC, 50-Ω thru-line termination, order 017-0083-00 .

Fig. 7-2. P6046/CT-1 specifications.

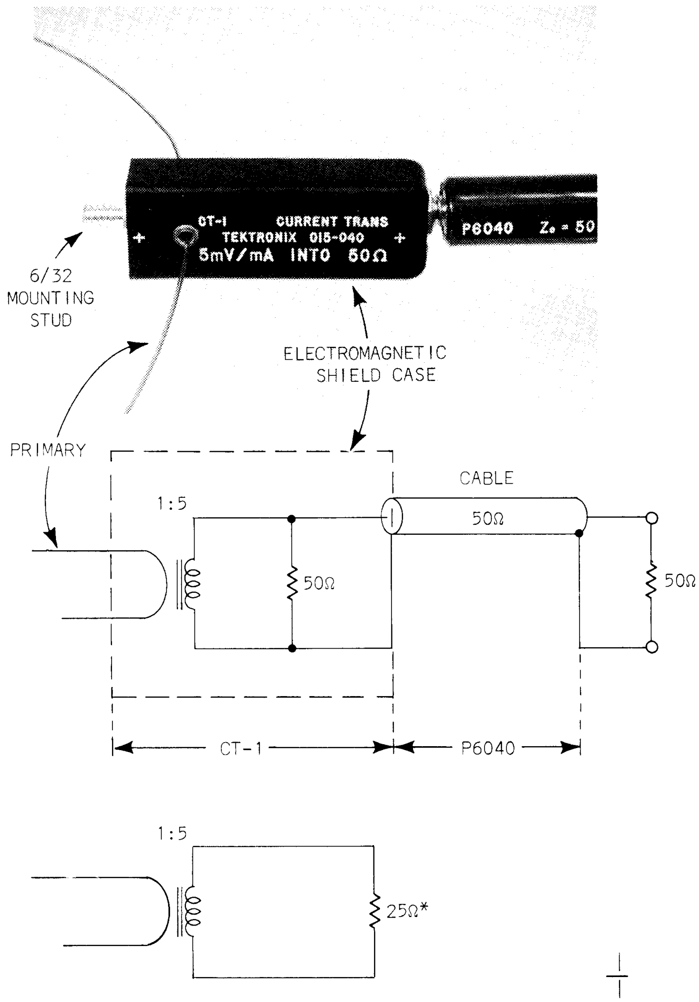
PASSIVE CURRENT PROBES

Fig. 7-2 shows the specification of the CT-1 (Current Transformer-1). The CT-1 is a small, closed core, passive device. For use, the current carrying conductor must be broken and inserted through the small hole in the case.

Sensitivity is 5 mV/mA into a 50 Ω load.

Accuracy is better than ±3 %.

All Tektronix current probes use a current transformer having a single-turn primary and a multi-turn secondary. The basic sensitivity of the device is determined by the turns ratio of the transformer and the load placed upon the transformer secondary. Additional sensitivity capability exists with Tektronix split core current probes by the use of a current probe amplifier.



*25Ω LOAD WHEN CT-1 IS PROPERLY TERMINATED.

Fig. 7-3. Schematic of a CT-1 current probe.

Fig. 7-3 shows the schematic of a CT-1 current probe. If 5 mA of signal current were caused to flow in the primary circuit, the secondary signal current would be 1 mA. This 1 mA of current through a 25 Ω termination would develop 25 mV of signal amplitude. By comparing the output voltage to the input current: 25 mV/5 mA or 5 mV/mA. The accuracy of this current to voltage conversion is dependent upon the current transformer turns ratio and the value and accuracy of the terminating resistance.

Decay Time Constant is 5 μs, approximated by 1 % per 50 ns; limit, 1 μs.

The decay time constant specification indicates the pulse supporting capability of the current probe. This time constant is the secondary inductance (*L*) divided by the terminating resistance (*R*) and is referred to as the *L*/*R* ratio of the probe. From the simple time constant equation TC = *L*/*R*, the secondary inductance can be determined (specification) by:

$$5\ \mu s = \frac{L}{25\ \Omega} \therefore\ L = 125\ \mu H.$$

By reversing the equation the decay time constant may be determined by:

$$\frac{125\ \mu H}{25\ \Omega} = 5\ \mu s.$$

From the universal time constant curve (Fig. 7-4), the *L*/*R* decay will be almost linear during the

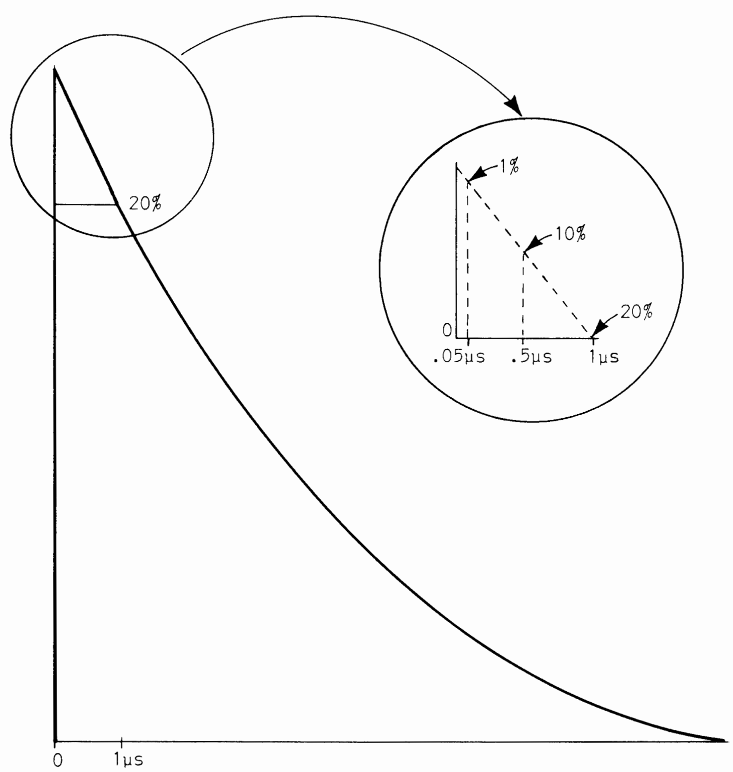


Fig. 7-4. Universal time constant curve.

first 20% of one TC. With one TC = 5 μs specification, 20% of one TC = 1 μs limit, approximated by 1% per 50 ns.

Risetime is less than 350 ps.

Frequency Response is 35 kHz to 1 GHz (30% down points).

The risetime (t_r) of a current probe is primarily dependent upon stray and leakage inductance, the distributed capacitance and the resistance of the secondary circuit. Fig. 7-5 shows a typical arrangement in determining this specification.

The frequency response specification as stated indicates the -3 dB bandwidth point. (A -3 dB bandwidth specification implies a 45° phase angle shift of the testing signal.) The upper frequency -3 dB point is set by the t_r limiting factor and is calculated by: $\text{Bandwidth} = \frac{0.35}{t_r}$. The low frequency -3 dB point is set by the L/R of the secondary circuit and is determined by: $X_L = R$.

Insertion Impedance with a 50 Ω termination is 1 Ω shunted by approximately 5 μH; 2 Ω shunted by approximately 5 μH without a 50 Ω termination.

Insertion impedance is a reflected impedance from the current transformer's secondary circuit. Fig. 7-6 shows the CT-1 insertion impedance and its calculations. For additional information, see Chapter 9.

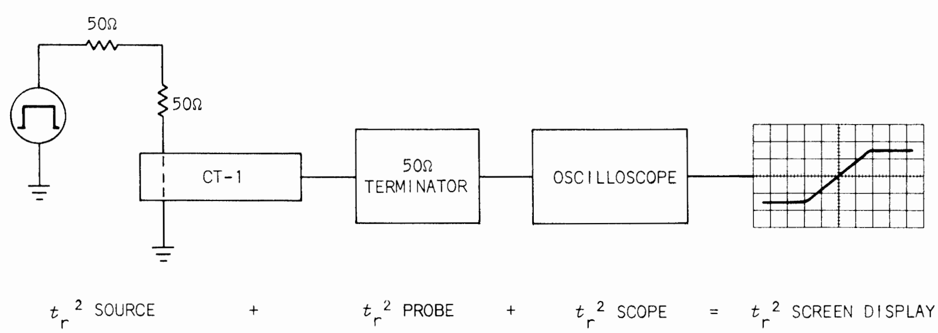
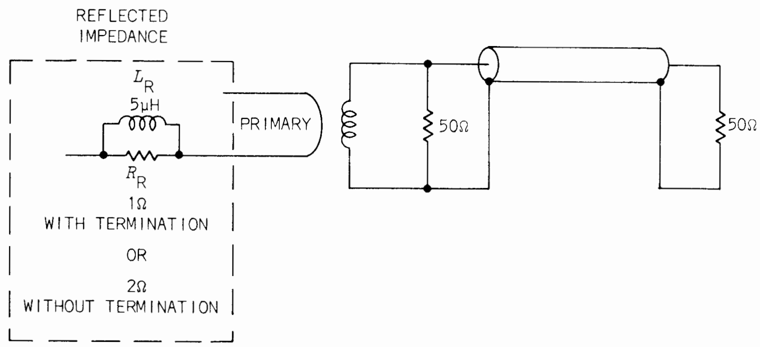


Fig. 7-5. Typical method of determining t_r.



$$R_R = \frac{25\Omega}{5^2} = 1\Omega\text{(TERMINATED) OR } \frac{50\Omega}{5^2} = 2\Omega\text{(UNTERMINATED)}$$

$$L_R = \frac{125\mu H}{5^2} = 5\mu H$$

$$\text{REFLECTED RESISTANCE } (R_R) = \frac{\text{SECONDARY LOAD RESISTANCE}}{(\text{TURNS RATIO})^2}$$

$$\text{REFLECTED INDUCTANCE } (L_R) = \frac{\text{SECONDARY INDUCTANCE}}{(\text{TURNS RATIO})^2}$$

Fig. 7-6. CT-1 insertion impedance and calculations.

Capacitive Loading to a bare wire passing through the CT-1 transformer is typically 1.5 pF for No. 14 gauge, 0.6 pF for No. 20 gauge.

Capacitive loading is attributable to the proximity of the current transformer's windings and electromagnetic shielding (metal case) to the diameter and length of the portion of the current carrying conductor passing through the current transformer. For additional information see Chapter 9.

Maximum Voltage of Circuit Under Test is 1000 V DC.

The passive current probe, like a passive voltage probe, has a maximum voltage capability which is fixed by some physical breakdown of a mechanical or electrical component at or around the point of measurement. This specification results from the dielectric standoff ability of the small plastic insert, located in the center of the current

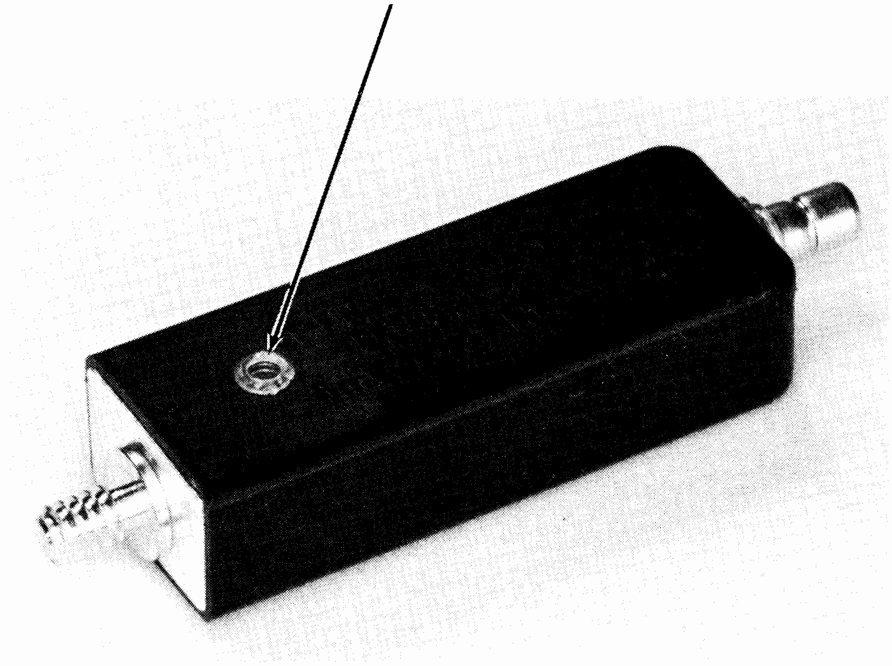


Fig. 7-7. Close-up of CT-1 showing insulating insert.

transformer core. See Fig. 7-7. Additional voltage capability may be obtained by using a teflon insulated wire for the current monitoring conductor.

Direct Current reduces the L/R time constant by a factor of 2 at 0.6 A.

This specification indicates the effect a DC current will have on a passive current probe. DC current causes a re-biasing of the operating point of the core to a new level and reduces the core's permeability. This change in permeability reduces the effective secondary inductance which decreases the L/R time constant and increases the low frequency -3 dB point of the probe. The high frequency capability of the probe is generally not altered. Fig. 7-8A displays the CT-1 bandwidth change with a DC bias current.

saturation threshold

Most of the specifications of this nature indicate either a "change in time constant" or are stated as a "DC saturation threshold." By definition "saturation threshold" is the point where the L/R

time constant first starts to change. Saturation threshold *does not* mean a complete termination of signal transferring ability. Fig. 7-8B shows amounts of DC primary current (DC ampere turns) versus the change in the -3 dB low frequency point of a split core current probe.

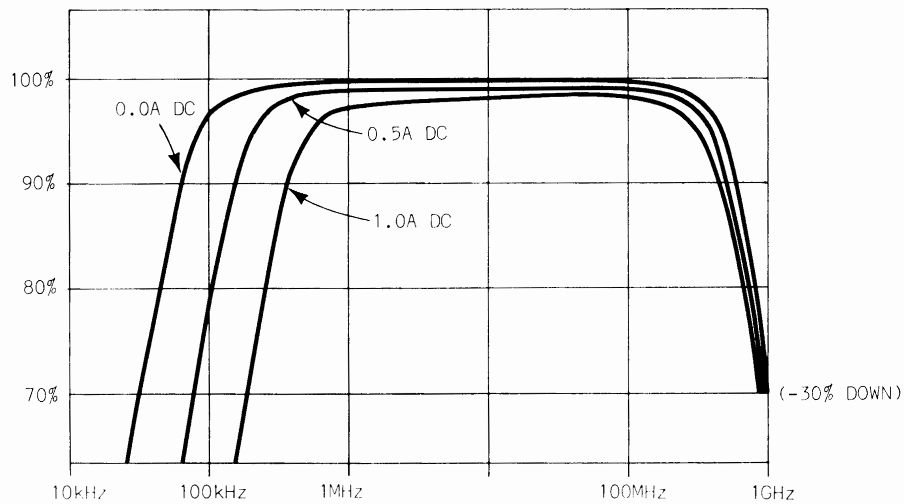


Fig. 7-8A. CT-1 bandwidth change with a DC bias current.

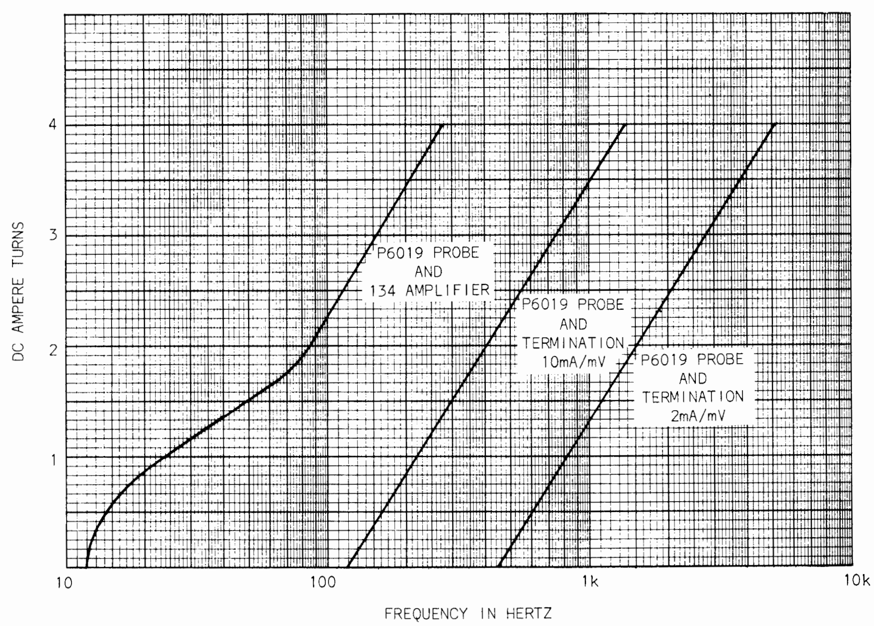


Fig. 7-8B. Type P6019 low frequency 3 dB point vs DC ampere turns.

Fig. 7-8.

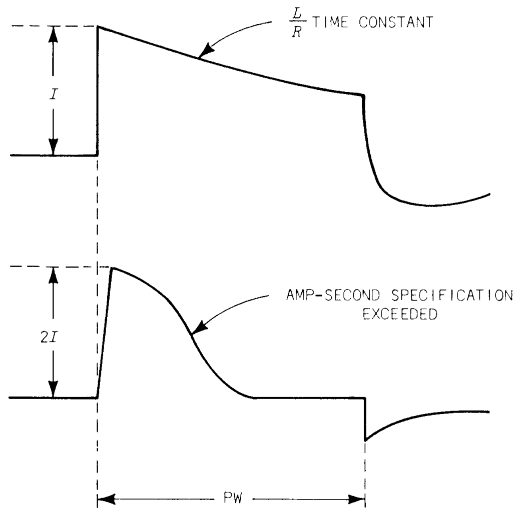


Fig. 7-9. CT-1 output showing effects of exceeding amp-second product.

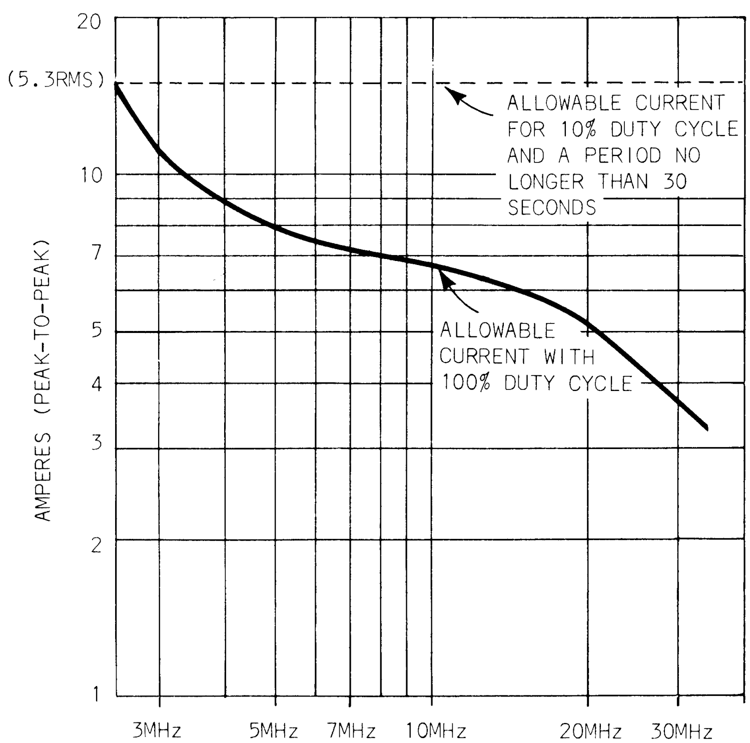


Fig. 7-10. Derating curve.

Pulse Current Rating is 100 A peak with an amp-second product of 1 A-μs. When the A-s product is exceeded, the core saturates reducing the CT-1 output to zero.

amp-second

The amp-second product is related to the volt-second product of a standard voltage transformer. When used in this specification, however, the amp-second product indicates the energy handling capabilities of the core in a *current* transformer. This specification directly relates the core's ability to transfer a sustained high energy flux field. When the amp-second product is exceeded, the output of the device will reduce to zero. Fig. 7-9 shows the CT-1 output when the amp-second product is exceeded. For additional information concerning amp-second product, see Chapter 8.

RMS Current Rating is 500 mA maximum.

This specification is an indication of the power handling capability of the current transformer's secondary circuit. The power limit may be the wattage capability of the terminating resistance or the wire size used in the secondary windings. In the case of the CT-1, with its 5:1 turns ratio, 500 mA RMS of primary current would produce 100 mA RMS of secondary current. 100 mA RMS flowing through the terminating resistance develops power equal to the wattage rating of that resistance.

Current probes, like voltage probes, may have maximum amplitude versus frequency derating curves. These curves occur due to heating affects of induced energy into the current transformer's electromagnetic shield case. The increasing temperature causes increased losses and tends to be self-regenerating. (The Mumetal* shield or electromagnetic case may act as a shorted turn which can develop very high circulating currents, generating significant heating). Fig. 7-10 shows a derating curve of a split core passive current probe.

Temperature Rating is -25 °C to +65 °C.

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*Reg. T.M. Allegheny Ludlum Steel Corp.

Some passive current probes are rated for somewhat severe environment. In the case of the CT-1, the +65 °C upper limit results from the melting temperature of the plastic insert and plastic case. Beyond specified temperatures, the L/R time constant will show significant changes resulting in questionable accuracy and bandwidth limitations.

ACTIVE CURRENT PROBES

The Tektronix active current probe utilizes a *Hall effect* device in addition to a passive current transformer. Fig. 7-11 shows the P6042 specifications. The combining of these two elements in a "forced complement" arrangement extended high speed current measurements down to DC. Fig. 7-12 shows a basic diagram of the P6042 and the "forced complement" bandwidth curves.

forced complement

Sensitivity to DC current in the active current probe is a function of a special semiconductor Hall device manufactured by Tektronix. This device, conducting current in the direction of its length, will develop an output voltage across its width which is proportional to a DC or low frequency flux field. The sensitivity limiting factor is one of compromise with the Hall device noise and thermal characteristics.

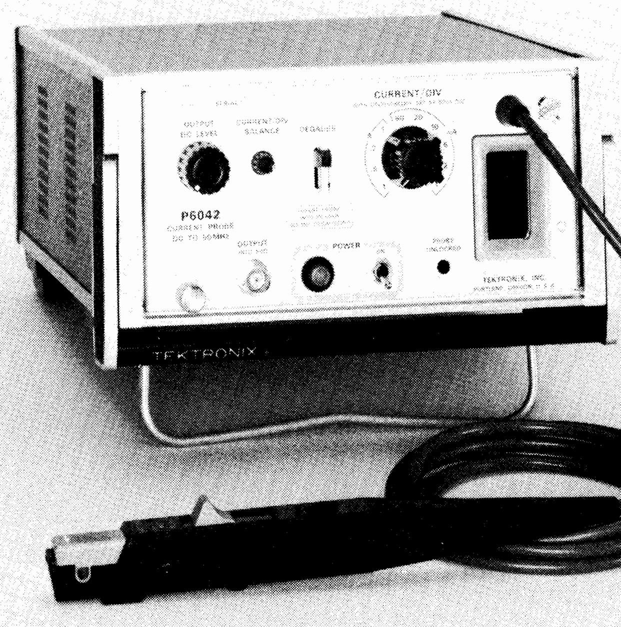
Bandwidth is DC to 50 MHz at 3 dB down.

Risetime is 7 ns or less. This specification is the same as the passive current probe risetime information (Fig. 7-5).

Noise and Thermal Drift are both dependent upon the Hall effect device characteristic. These, again, are compromises and "state-of-the-art" dependent.

Maximum Input Current is 10 A (DC plus peak AC). An additional footnote indicates "peak to peak" current derating is necessary for CW frequencies higher than 10 MHz. At 50 MHz the maximum allowable current is 2 A.

DC-TO-50 MHz
1 mA/DIV CURRENT PROBE



The new P6042 is a DC-to-50 MHz current probe designed for use with all Tektronix oscilloscopes. Utilizing a variation of the Hall effect, the P6042 offers new capabilities for making both high-frequency and DC current measurements. AC Signals with DC components can be displayed on the oscilloscope with true waveform presentation. The probe is particularly useful for evaluating the performance of semiconductor circuits where a wide range of parameters exist. Fast switching transients, low-frequency response, and DC level can all be displayed simultaneously.

The probe can also be used to measure the sums or differences of currents in separate wires. When the probe is clipped around two wires carrying current in the same direction, the sum is displayed. By reversing one of the wires, the difference is displayed. For increased sensitivity, several loops can be placed through the probe, increasing the sensitivity by the number of loops.

The P6042 consists of an amplifier with built-in power supply, 6-foot probe cable, and probe head. The probe is easy to use. Simply place the conductor* in the slot of the probe head and close the spring-loaded slide . . . no need to break the circuit under test. A warning light on the front panel of the amplifier indicates when the slide is in the unlocked position. A compartment is provided in the front panel for use in degaussing, and for convenient storage of the probe head when the system is not in use.

*Up to 0.150-inch diameter.

CHARACTERISTICS

Probe and Amplifier

SENSITIVITY is 1 mA/div to 1 A/div in 10 calibrated steps, 1-2-5 sequence, accurate within 3% (with an oscilloscope deflection factor of 50 mV/div).

BANDWIDTH is DC to 50 MHz at 3-dB down.

RISETIME is 7 ns or less.

DYNAMIC RANGE is + and − 10 divisions of display.

NOISE (periodic and random deviation) is 0.5 mA or less, plus 0.2 or less major divisions of display. Random trace shift is 1.5 mA or less.

THERMAL DRIFT is 2 mA/°C or less, plus 0.2 or less major division of display per °C.

MAXIMUM INPUT CURRENT is 10 A (DC plus Peak AC).*

MAXIMUM VOLTAGE OF CIRCUIT UNDER TEST is 600 V (DC plus Peak AC).

OUTPUT IMPEDANCE is 50 Ω through a BNC-type connector. A 50-Ω termination is supplied with the probe for use with 1-megohm systems.

*Peak-to-peak current derating is necessary for CW frequencies higher than 10 MHz. At 50 MHz, the maximum allowable current is 2 A.

Fig. 7-11. P6042 specifications.

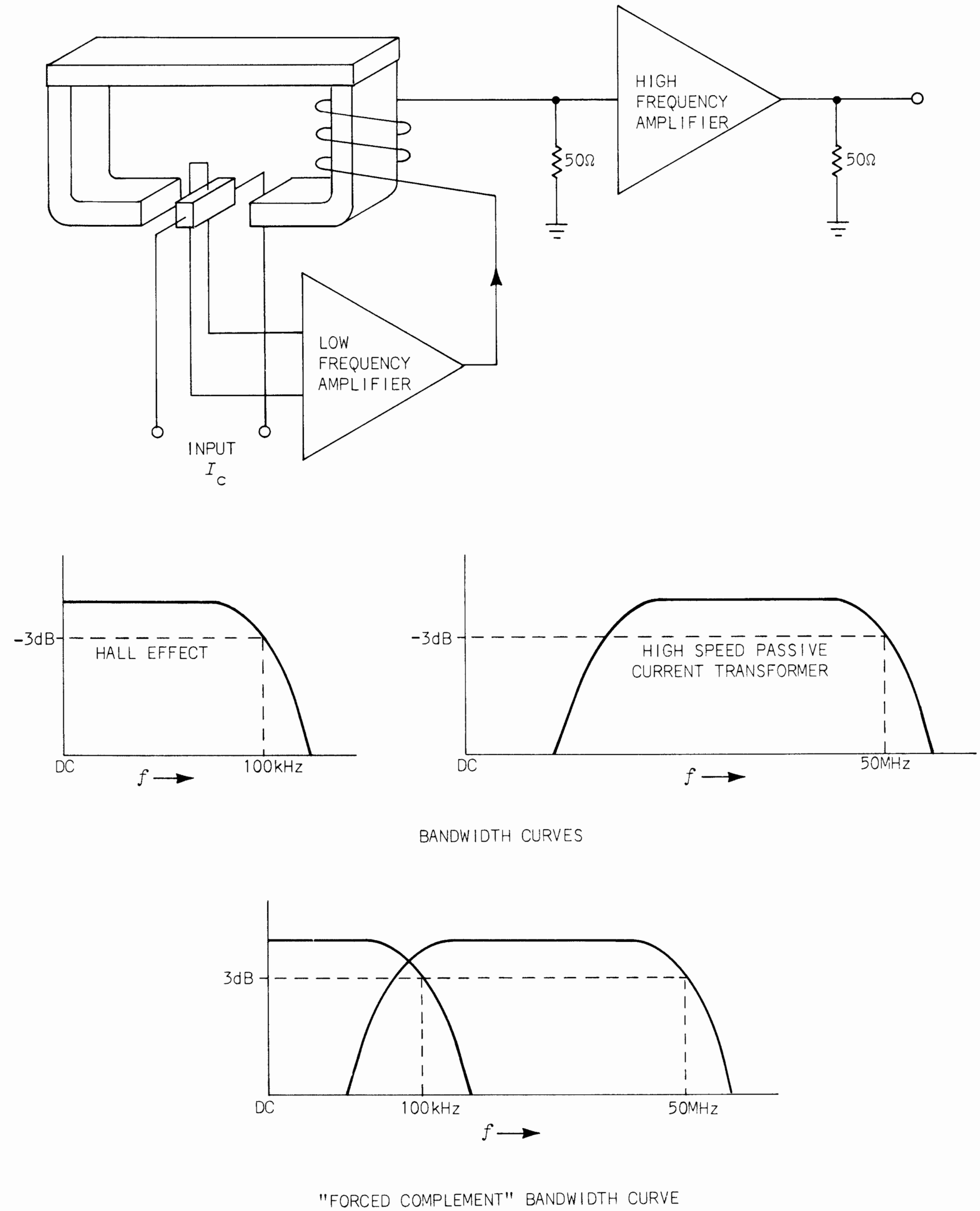


Fig. 7-12. P6042 diagram and bandwidth curves.

The active current probe differs from the passive current probe in that within the ±10 A capability, DC current does *not* cause saturation problems. The primary design objective in this type of probe was to be able to measure DC current. Refer to Fig. 7-12. A primary DC current will upset the balance of voltage across the Hall effect device. This voltage change is coupled to the low frequency amplifier which causes an output current to be delivered through the high speed transformer to the input of the high frequency amplifier. The current flowing through the high speed current transformer builds a flux field which is equal and opposite to the initial DC current flux field. A null in these opposing flux fields establishes a steady-state current to the high frequency amplifier input. This current develops a DC output voltage proportional to the initial input DC current. This balance or null technique continues as long as the low frequency amplifier can supply enough current to maintain a bucking flux field. The capability of providing this nulling current limits the maximum input current to 10 A (DC plus AC peak).

Derating of maximum current versus frequency and maximum voltage of the circuit under test are the same as passive current probes.

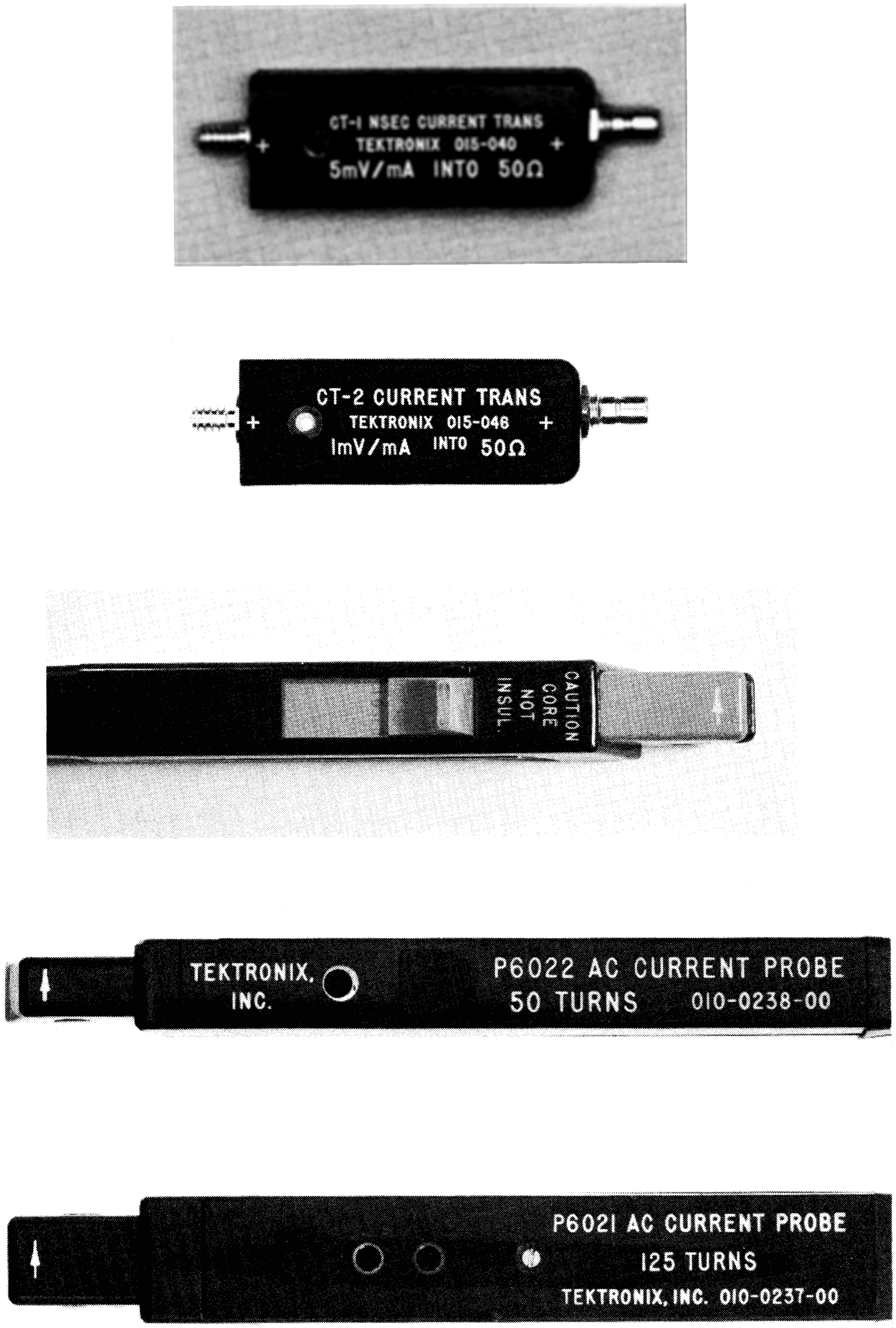


Fig. 8-1. Output polarity indication.

8

CURRENT PROBES CONSIDERATIONS IN USE

Current Flow Direction

Current probes, unlike voltage probes, convert flux fields to voltage equivalents which may be a positive going or negative going signal, depending upon the direction of current flowing through the conductor under test. All Tektronix current probes are marked with a plus symbol (+) or an arrow (→) to identify output signal polarity. By connecting the (+) symbol to the more positive voltage part of the circuit or causing electron flow against the arrow, a positive going output signal will result. See Fig. 8-1.

Minimize Loading

One of the advantages of using a current probe is the ability to monitor signal currents at ground points and not introduce extra capacity to high impedance points. Also, the probe may be connected to the B+ or V_{CC} side of a load resistor without contributing excessive loading or a shifting of the circuit operating point. An exception of this general statement would be the possibility of changing the operating current of a low impedance switching device. An example might be a switching tunnel diode firing point could be shifted by the reflected current probe impedance. This impedance might inhibit a low amplitude trigger pulse from reaching the peak current point and keep the tunnel diode in its low state. See Fig. 8-2.

Ground Clip and Use

Most current probes have a ground clip or grounding point which is part of the probe's electromagnetic shielding case. This ground is normally not used in a high sensitivity application (i.e.: 1 or 2 mA signals) due to the possibilities of distortion from undesirable chassis currents which may be present. The ground requirement generally occurs

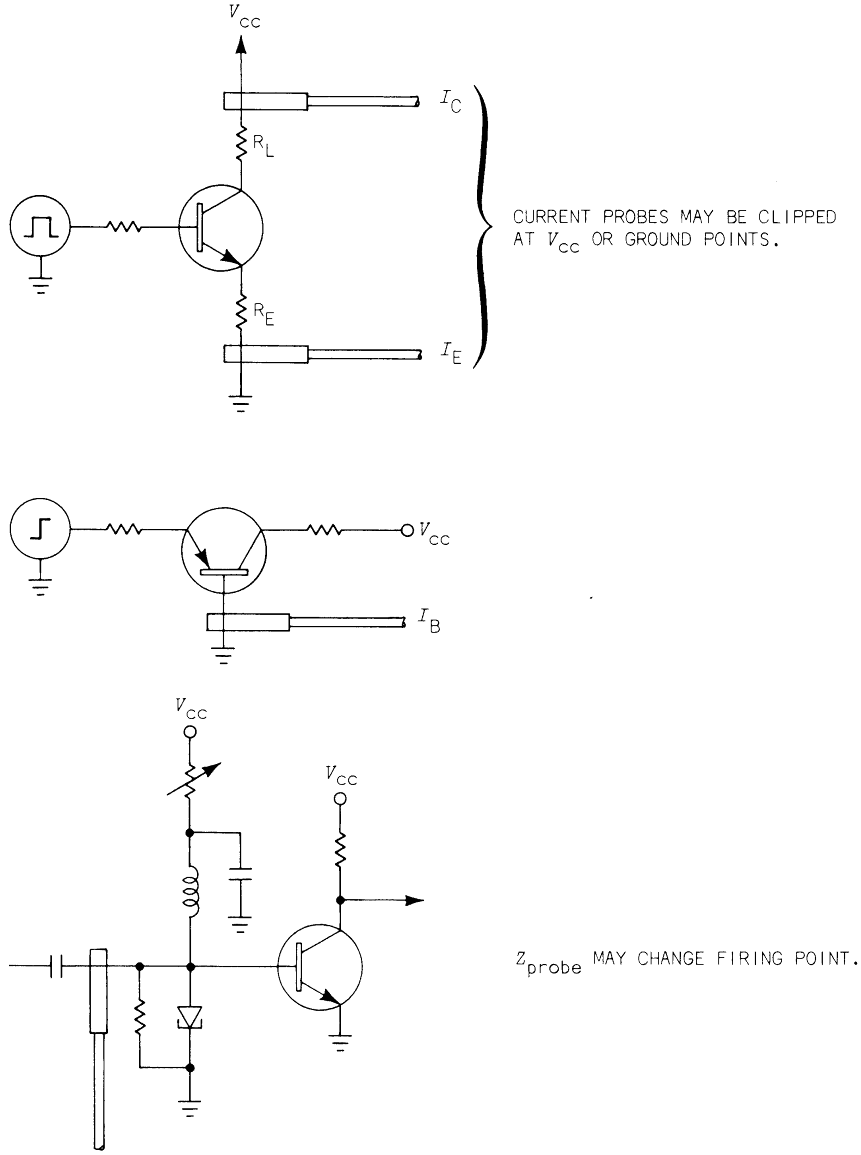


Fig. 8-2. Signal monitoring points.

in the presence of unwanted high frequency fields which couple through the case and distort the signal current under test. See Fig. 8-3.

Performance

Remember that current probe specifications are handled in the same manner as voltage probes. t_r specifications are for the *probe only*. To determine the system capability use:

$$t_r \text{ system} = \sqrt{(t_r \text{ probe})^2 + (t_r \text{ scope})^2}$$

Saturation from DC Currents

bucking flux field

Consideration should be exercised when measuring small current signals combined with a DC bias current. Remember that the passive current probe low frequency -3 dB point will move to a higher frequency at saturation threshold. Attempts to measure low frequency signals having a DC bias should best be left to the DC current probe (P6042). If an AC probe must be used, a technique of adding a second conductor through the probe's transformer core, having a "bucking" flux field equal to the undesired field but opposite in direction, will allow the saturation effects to be canceled.

For example, assume a low frequency signal current of 50 mA peak to peak was superimposed upon a DC bias current of 1 amp. While the AC signal would be simple to measure, the 1 amp bias causes the current probe to saturate. By running a second conductor through the current transformer core and

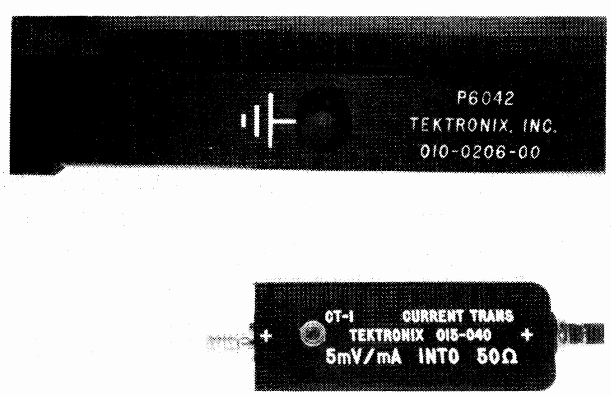


Fig. 8-3.

applying 1 amp of DC current in opposition to the unwanted bias current, their flux fields will cancel and the signal measurement may be accomplished. If 1 amp of current for "bucking" purpose is not available, additional turns of the second conductor will serve the same purpose. If 100 mA of current is available, then 10 second conductor turns will produce a 1 amp "bucking" flux field.

Current Addition or Subtraction

CMRR bucking

The "buck" technique gives rise to a useful technique of adding or subtracting current flux fields. By using two conductors under test passing through the same current transformer core, the flux fields will cancel (null) if exactly opposite to one another in all respects. The current probe then acts as a very high CMRR device and is almost unsurpassed in differential measurement techniques. No amplifier considerations are involved, only opposing or aiding flux fields determine the probe output.

High Current Develops High Voltage

Current probes such as the CT-1 are designed to be used with or without a termination. This probe contains an internal termination so that with or without an external termination, the current transformer secondary has a load.

damage by secondary voltages

The split core passive current probe may be used with either a passive termination or an active amplifier (low frequency extending capability). Each changes the L/R time constant by presenting a different current transformer secondary load. If the probe is disconnected from the passive termination or the amplifier, the probe secondary is unloaded. With high currents flowing in a conductor under test, secondary currents equal to the primary current divided by the turns ratio will exist. If the probe should be disconnected from its load with large primary current flowing, very large secondary *voltages* will develop in an attempt to maintain a secondary current. Damage to the probe may result from these voltages. Remember, always remove the probe from the conductor under test before disconnecting the probe from its termination.

Sensitivity Increase

turns ratio vs sensitivity

Chapter 7 discussed the current probe sensitivity and related the turns ratio and secondary load factors. At that time a single primary turn was used and most discussion could be related to the number of turns in the transformer's secondary. If the conductor under test is looped through the current transformer's core a second time, the probe sensitivity is doubled. (The turns ratio, $\frac{\text{Turns Secondary}}{\text{Turns Primary}}$, is halved.) The primary turns may be increased in number, with each turn increasing the sensitivity. With this increase in sensitivity, the primary inductance increases, the reflected impedance increases by the square of the turns ratio and the primary capacity to ground increases. Still, the improvement in probe sensitivity may offset these undesirable aspects and allow measurements of very small signals. (This technique may result in noise limiting factors.)

Setting Low Frequency Compensation

AC passive current probes may use an active amplifier to extend the low frequency -3 dB point to some value beyond the probe and passive termination capability. The active amplifier presents a very low R to the probe as a secondary load, thus making the secondary L/R time constant as long as possible. In addition, the amplifier has a low frequency boost capability which shifts the probe's effective L/R to a much longer value.

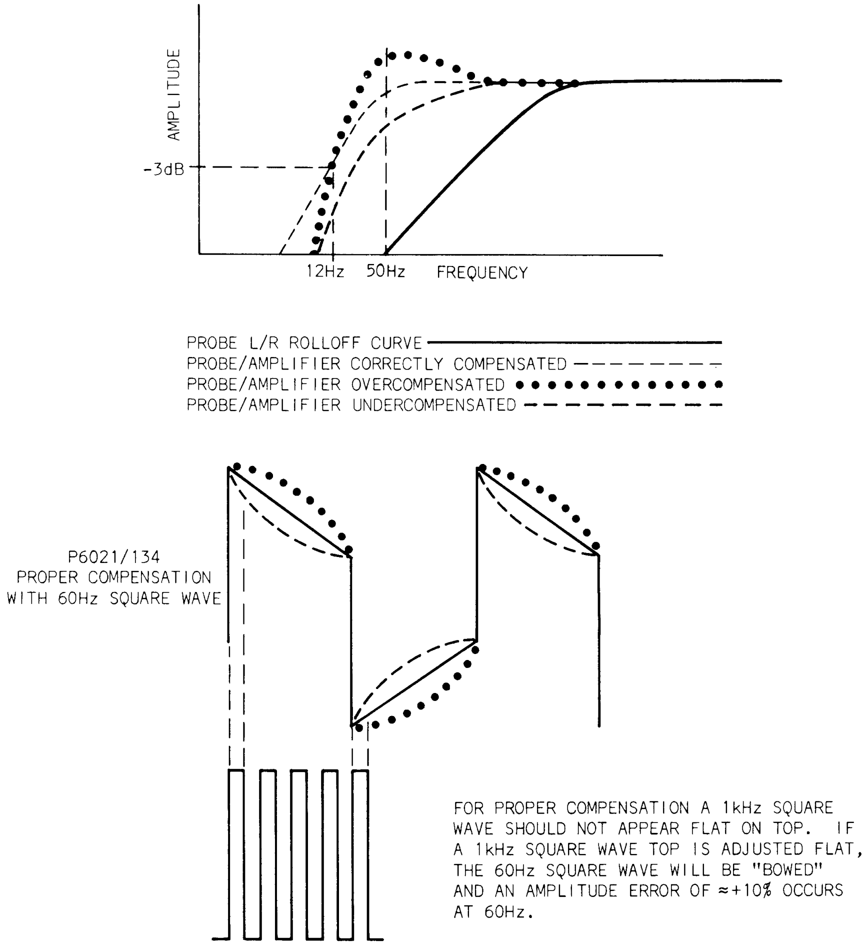


Fig. 8-4. Effects of low frequency compensation control.

Fig. 8-4 displays the effect of improper adjustment of the low frequency compensation control. Note that for proper low frequency compensation, a low frequency square wave should be used. The adjustment frequency is correct if the slope of the top of the square wave may be adjusted between a concave to a convex slope. The proper adjustment is to set the control so the displayed waveform has a linear sloping top.

Magnetic Fields

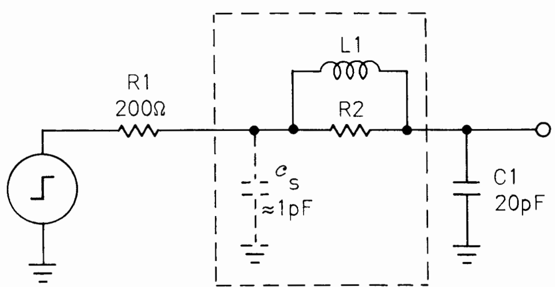
All current probes are shielded from external electromagnetic and electrostatic fields. Occasionally, this shielding is not sufficient to completely eliminate these unwanted fields from distorting a signal under test. A technique which has proven successful is to utilize a differential measurement capability and another current probe in the same relative position but not connected around the conductor under test. Because of the second probe's position in the distorting fields, this distortion is sensed by the differential measurement system as a Common Mode Signal and rejected, leaving the signal under test free of distortion. This external field "pick up" may be used to trace interfering fields to their sources. This is accomplished by watching the displayed distortion increase with probe position. AC passive current probe's external field sensitivity may be improved by opening the split core transformer.

common mode and distorting fields

Remember that the DC current probe (P6042) senses the presence of steady-state flux fields. Ferrous leads of components may become magnetized and cause a possible error in measurements. Check for magnetic fields with the circuit under test turned off.

Handling Current Probes

Current probes are designed to be as rugged as possible, consistent with good high frequency response and size. However, as with all precision devices, the probe and cable should be handled with care to avoid damage. Special care should be taken that the cable not be crushed, kinked or pulled. Avoid dropping the probe, as some of the most sensitive circuitry is located within the probe assembly. Additional caution should be used when clipping the probe around a conductor. The self wiping surfaces of the split core transformer must make complete and continuous contact when the probe is closed. Any remaining air gap will cause a change in the low frequency capability of the probe. The low frequency -3 dB point will increase to some higher frequency value.



$$L1 = \frac{\text{CURRENT PROBE SECONDARY INDUCTANCE}}{\text{CURRENT PROBE TURN RATIO}^2}$$

$$R2 = \frac{\text{CURRENT PROBE SECONDARY LOAD RESISTANCE}}{\text{CURRENT PROBE TURN RATIO}^2}$$

c_s = STRAY CAPACITANCE. DEPENDENT UPON TYPE OF MATERIAL AND DIAMETER OF CURRENT CONDUCTOR.

Fig. 9-1. Reflected impedance vs circuit impedance > 25 Ω.

9

SIGNAL MEASUREMENT EVALUATION

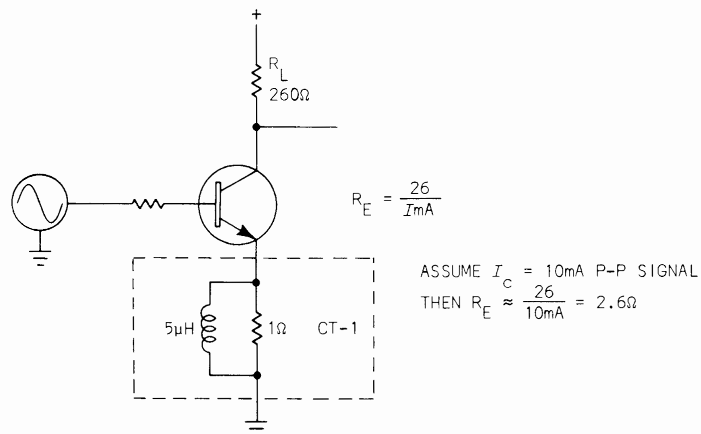
reflected impedance

Current probes offer the least loading of any signal measuring device. The only exception would be a permanently installed monitoring device designed as part of the circuit under test. This technique is necessary at very high frequencies and results in a non-loading probe. Typically, a current probe's reflected impedance will offer no appreciable change to circuits having impedances larger than ≈ 25 Ω. In the circuit under test used with passive and active probe signal measurement evaluation, the split core current probes would introduce only 0.004 Ω shunted by 2.8 μH or 0.025 Ω shunted by 0.6 μH. Even the CT-1 closed core current probe would reflect only 1 Ω shunted by 5 μH when properly terminated. See Fig. 9-1.

The important consideration when measuring > 25 Ω impedance circuits is still a function of the added stray capacity. As Fig. 9-1 indicates, this capacity will vary depending upon the size and type of material of the current conductors (No. 20 AWG size wire ≈ 0.6 pF; No. 14 AWG ≈ 1.5 pF; a 1/4 W metal film resistor ≈ 2.2 pF). This stray capacity effect is considered in the same manner as the input capacity of passive or active voltage probes. The current required to charge the current probe's stray capacity will be part of the current measured but *will not* be part of the current going to the load.

The reflected inductance and resistance from the probe's secondary circuit will exist as a series impedance for the duration of the L/R time constant. (i.e.: in the case of the CT-1, the time constant is ≈ 5 μs.) For frequencies or step functions containing information ≥50 kHz, this reflected resistance will add to the circuit resistance and the peak current will be reduced.

In the circuit of Fig. 9-1, the additional 1 Ω of a CT-1 would change the peak current and the circuit time constant by only 1/2 %. ($\frac{1\ \Omega}{200\ \Omega} = 1/2\ \%$).



$A_1 \approx \frac{R_L}{R_E} \approx 100$ WITHOUT CURRENT PROBE

$A_2 \approx \frac{R_L}{R_E + R_R} \approx \frac{260\Omega}{3.6\Omega} \approx 72.2$ WITH CURRENT PROBE ATTACHED

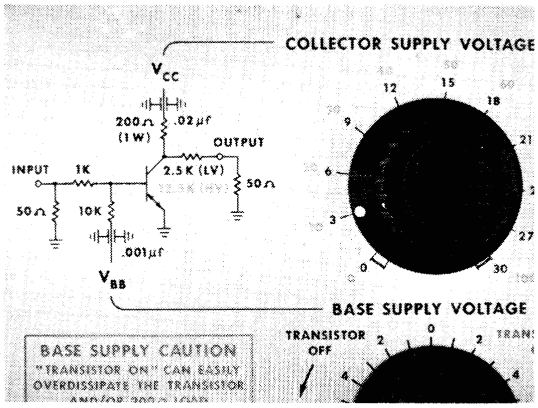
≈ -27.8% CHANGE IN SIGNAL GAIN WITH THE ADDITION OF A CURRENT PROBE.

Fig. 9-2. Reflected impedance vs low circuit impedance.

low impedance circuits

Split core current probes with a greater number of secondary turns would introduce an even smaller amount of change. However, low impedance circuits will be greatly affected by the reflected resistance and inductance of a current probe. Fig. 9-2 displays a grounded emitter voltage amplifier assumed to have a collector current of 10 mA. By using (A_V) Gain $\approx \frac{\text{RL}}{\text{RE}}$ and RE = $\frac{26}{1 \text{ mA}}$ then the $A_V \approx 100$. When a CT-1 current probe is used to monitor emitter current, the reflected R and L change RE from 2.6 Ω to 3.6 Ω. This change reduces the A_V of the stage by ≈ 27.8 %. A split core current probe would have less affect but the affect would still be noticed.

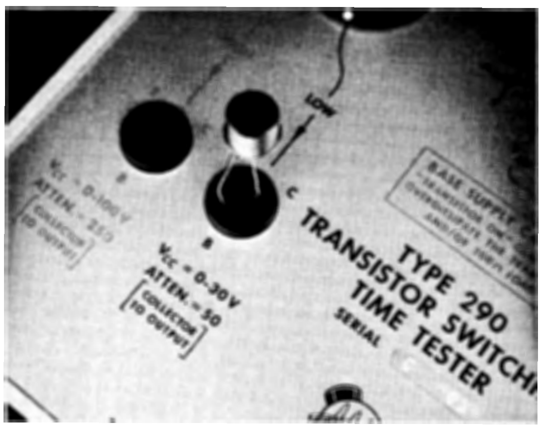
Fig. 9-3 shows a test which demonstrates the effects of reflected impedance. A Tektronix Type 290 Switching Time Tester circuit was used with the transistor under test biased in a class A operating condition. The base drive signal was 100 mV of 50 kHz from a Type 191 Constant Amplitude Signal Generator. The input and output voltage signals were monitored before and after the insertion of a terminated CT-1 around the emitter lead. The amplitude change of the large output signal may be determined using the information contained in Fig. 9-2.

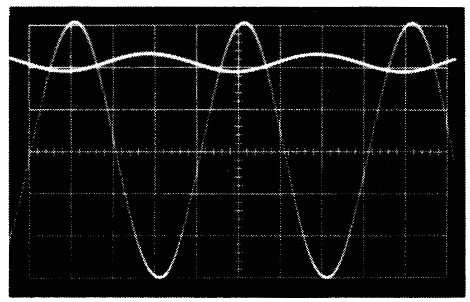


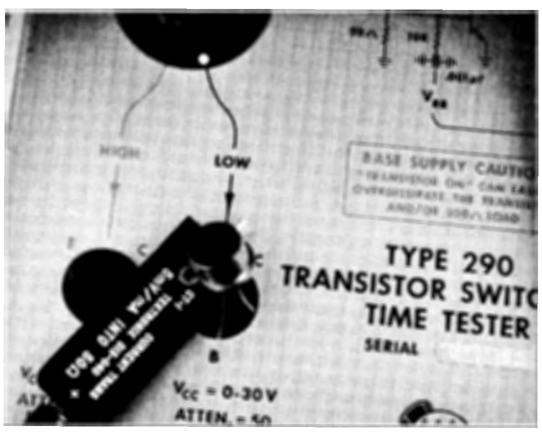
V_{CC} = 3V

I_C = 10mA

BASE DRIVE INPUT = 100mV$_{p-p}$ AT 50kHz







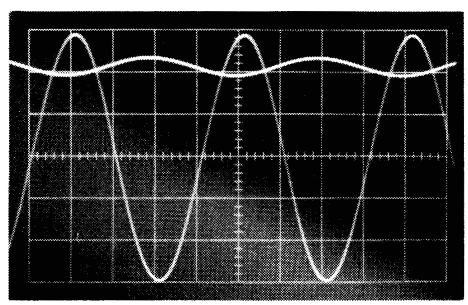


Fig. 9-3. Reflected impedance effects.

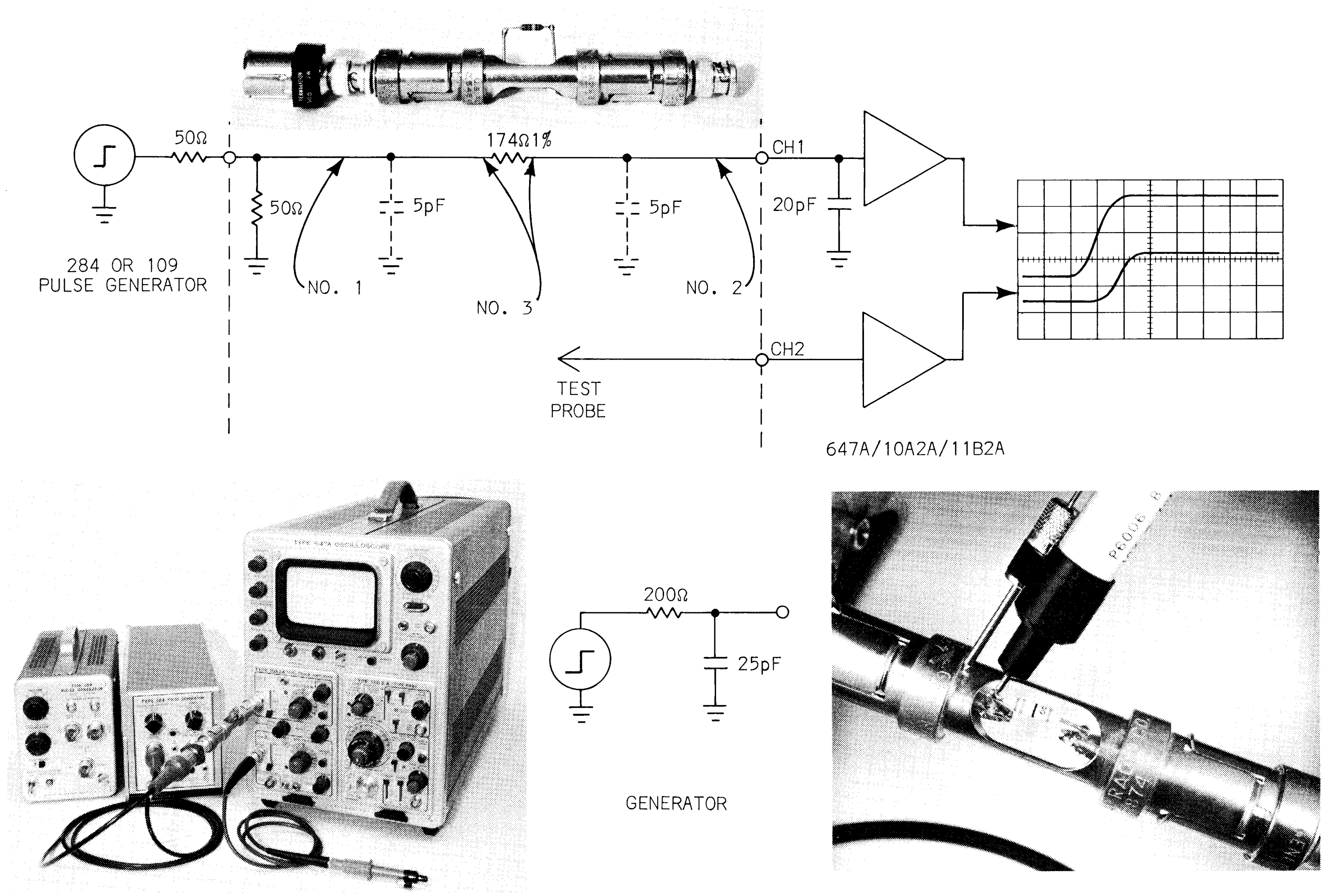


Fig. 10-1. Measurement validation set-up.

10

MEASUREMENT VALIDATION

The Signal Measurement Evaluation chapters of passive, active and current probes may be verified using the test set-up shown in Fig. 10-1. The following photographs were taken using those previously discussed probes and measuring a step function signal at points No. 1, No. 2 or No. 3. The measurement system used was a:

Type 647A Oscilloscope

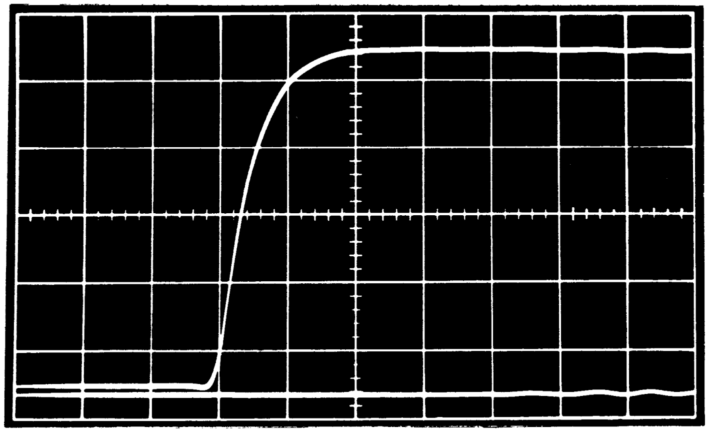
Type 10A2A Dual Trace Vertical Plug-in

Type 11B2A Time Base Plug-in

Type 284 Pulse Generator (passive and active probe source)

Type 109 Pulse Generator (current probe source).

As Fig. 10-1 indicates, CH 1 of the measurement system displays the circuit under test output signal without loading the signal. (The 20 pF input capacity of the 10A2A is used as part of the circuit under test.) CH 2 displays the test probe output.



CIRCUIT OUTPUT WITHOUT PROBE

P6006 PASSIVE PROBE

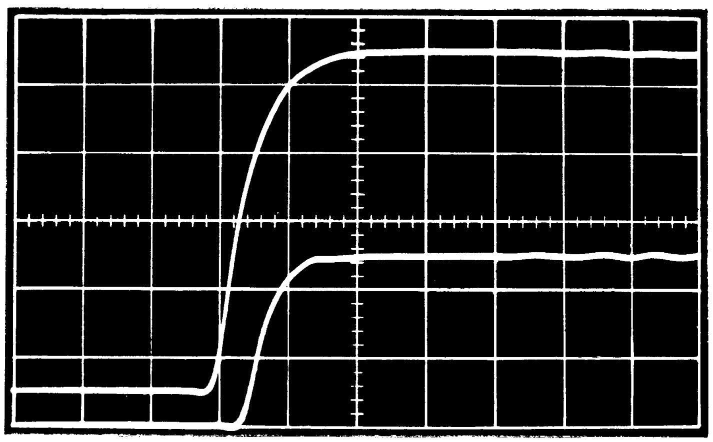
PROBE $t_r \leq$ 5ns

647A/10A2A $t_r \leq$ 3.5ns

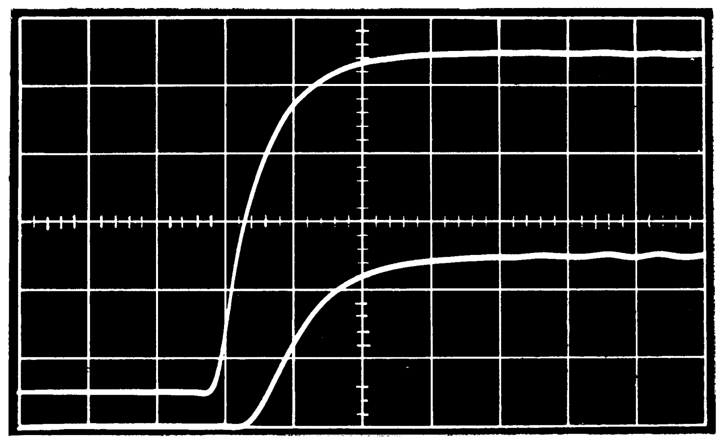
CH 1 = 50mV/DIV

CH 2 = 10mV/DIV

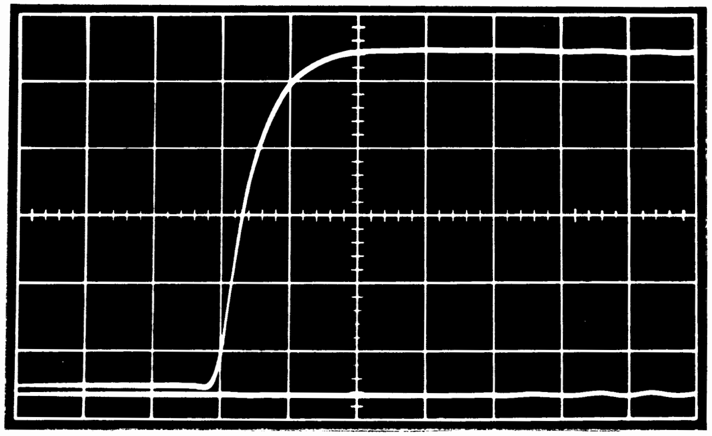
TIME/DIV = 10ns/DIV



CIRCUIT AND PROBE OUTPUTS
PROBE AT NO. 1



CIRCUIT AND PROBE OUTPUTS
PROBE AT NO. 2



CIRCUIT OUTPUT WITHOUT PROBE

P6048 PASSIVE PROBE

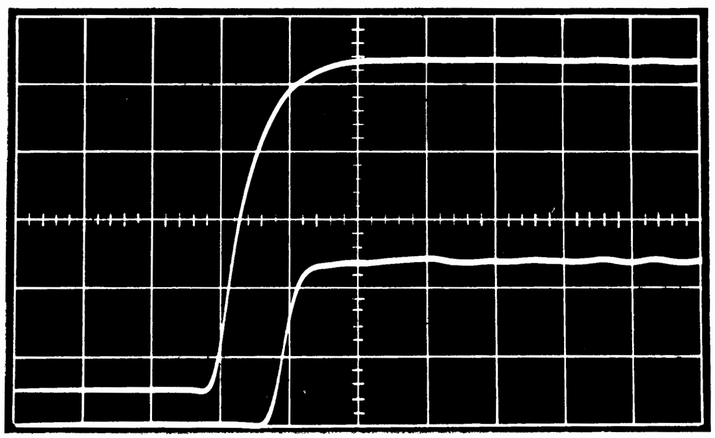
PROBE $t_r \leq$ 2.6ns

647A/10A2A $t_r \leq$ 3.5ns

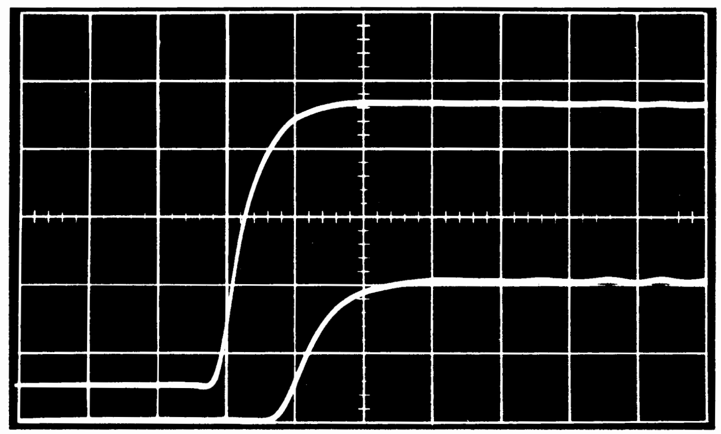
CH 1 = 50mV/DIV

CH 2 = 10mV/DIV

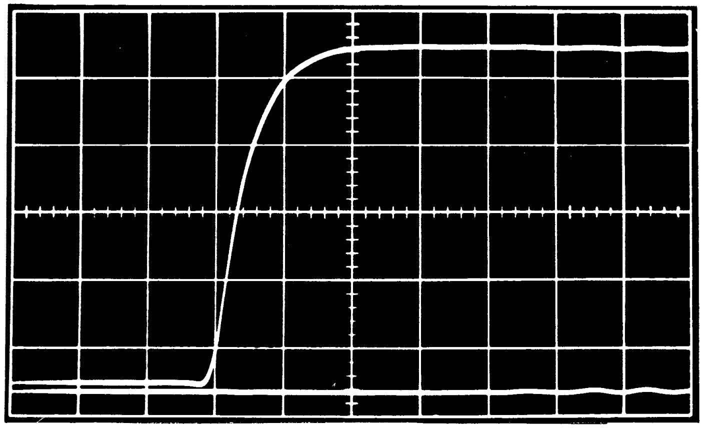
TIME/DIV = 10ns/DIV



CIRCUIT AND PROBE OUTPUTS
PROBE AT NO. 1



CIRCUIT AND PROBE OUTPUTS
PROBE AT NO. 2



CIRCUIT OUTPUT WITHOUT PROBE

P6045 1X ACTIVE PROBE

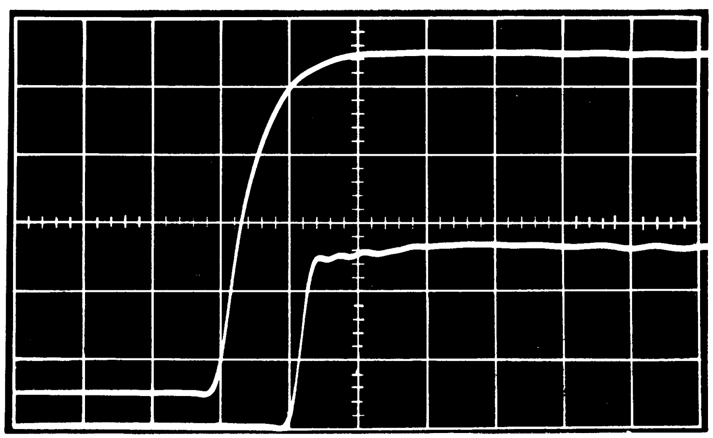
PROBE $t_r \leq 1.5ns$

647A/10A2A $t_r \leq 3.5ns$

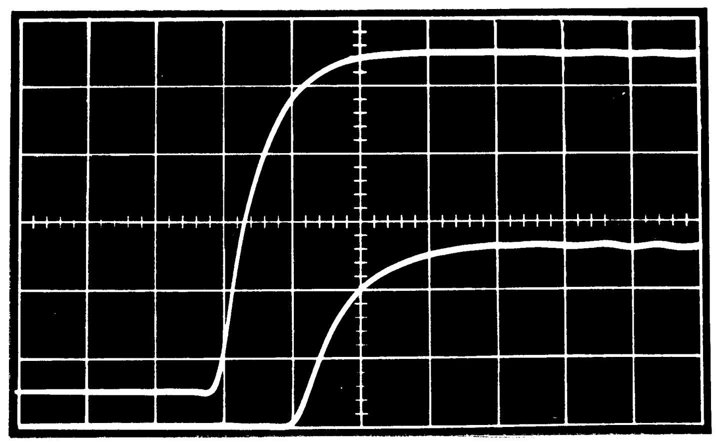
CH 1 = 50mV/DIV

CH 2 = 100mV/DIV

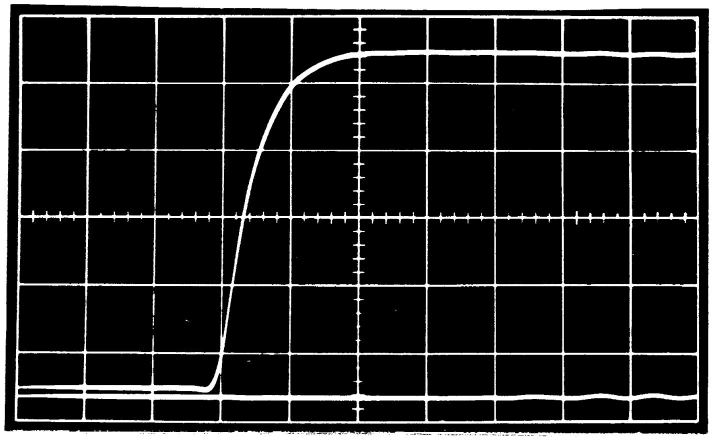
TIME/DIV = 10ns/DIV



CIRCUIT AND PROBE OUTPUTS
PROBE AT NO. 1



CIRCUIT AND PROBE OUTPUTS
PROBE AT NO. 2



CIRCUIT OUTPUT WITHOUT PROBE

P6046 ACTIVE DIFFERENTIAL PROBE

PROBE $t_r \leq 3.5$ns

647A/10A2A $t_r \leq 3.5$ns

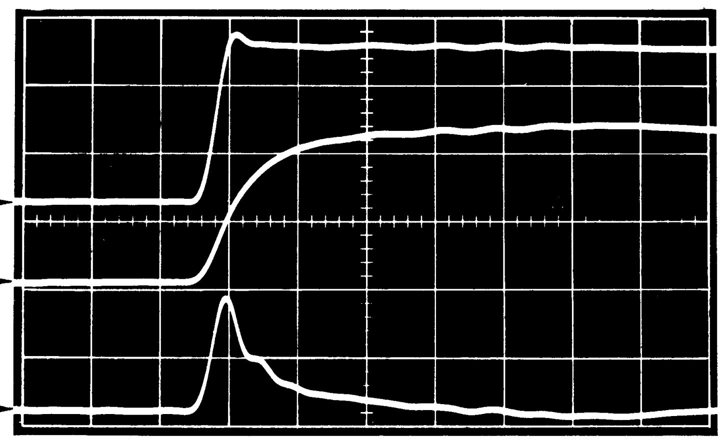
CH 1 = 50mV/DIV

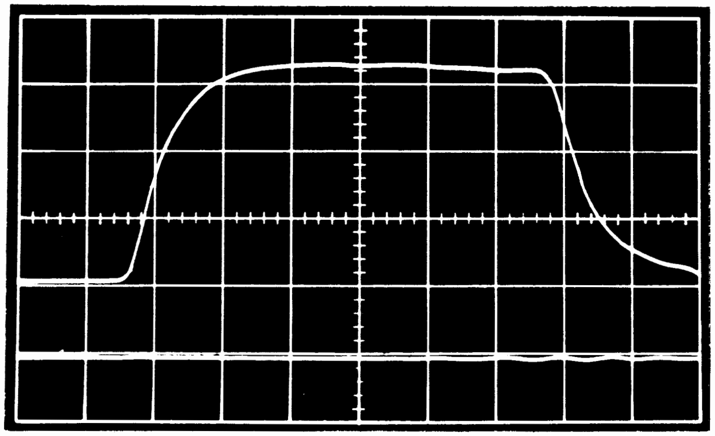
CH 2 = 100mV/DIV

PROBE AT NO. 1

PROBE AT NO. 2

PROBE AT NO. 3





CIRCUIT OUTPUT WITHOUT PROBE

CT-1 CLOSED CORE CURRENT PROBE

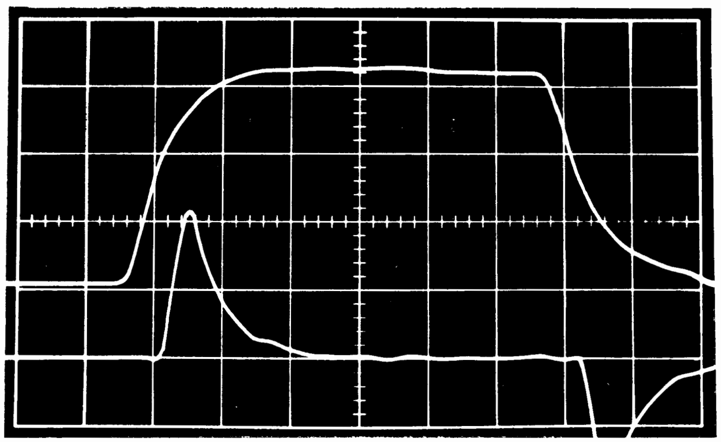
PROBE $t_r \leq 0.35$ns

647A/10A2A $t_r \leq 3.5$ns

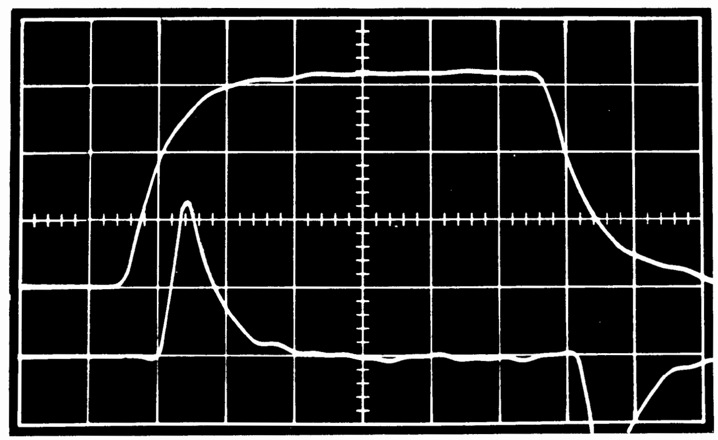
CH 1 = 2V/DIV

CH 2 = 50mV/DIV

TIME/DIV = 10ns/DIV



CIRCUIT AND PROBE OUTPUTS
PROBE AT NO. 1



CIRCUIT AND PROBE OUTPUTS
PROBE AT NO. 2

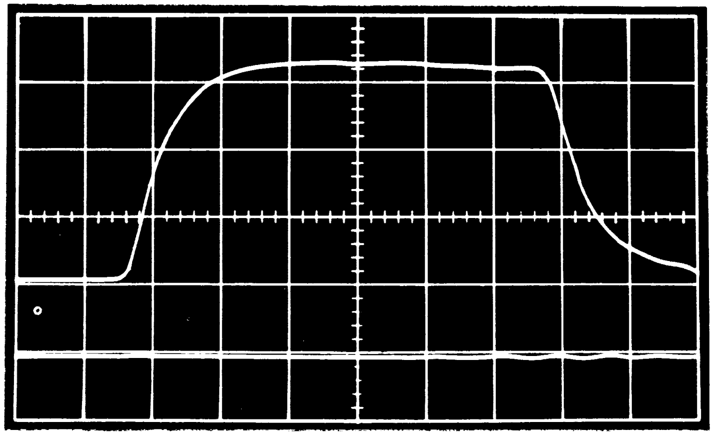
P6019/134 SPLIT CORE CURRENT PROBE/AMPLIFIER

PROBE/AMPLIFIER $t_r \leq 5.8ns$

647A/10A2A $t_r \leq 3.5ns$

CH 1 = 2V/DIV

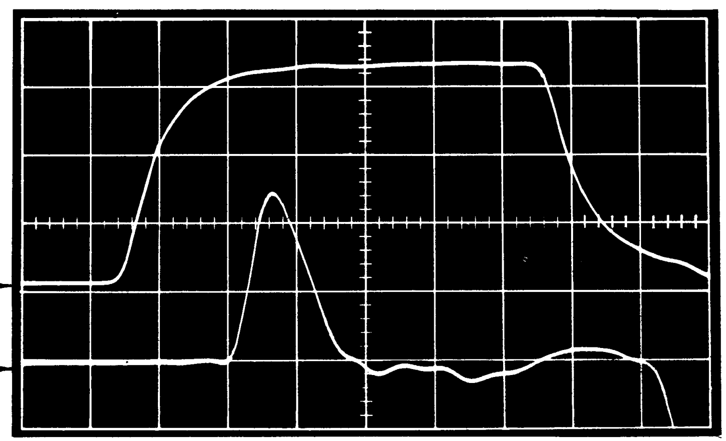
CH 2 = 5mA/DIV



CIRCUIT OUTPUT WITHOUT PROBE

CIRCUIT OUTPUT

PROBE OUTPUT (CLIPPED AROUND RESISTOR NO. 3)



NOTES

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