Service Scope

USEFUL INFORMATION FOR USERS OF TEKTRONIX INSTRUMENTS

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A PRACTICAL APPROACH TO TRANSISTOR AND VACUUM TUBE AMPLIFIERS

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Electronic Instrumentation Group

Display Devices Development

Two articles published in past issues of Service Scope contained information that, in our experience, is of particular benefit in analyzing circuits. The first article was "Simplifying Transistor Linear-Amplifier Analysis" (issue #29, December, 1964). It describes a method for doing an adequate circuit analysis for trouble-shooting or evaluation purposes on transistor circuits. It employs the "Transresistance" concept rather than the complicated characteristic-family parameters. The second article was "Understanding and Using Thevenin's Theorem" (issue #40, October, 1966). It offers a step-by-step explanation on how to apply the principles of Thevenin's Theorem to analyze and understand how a circuit operates.

Now, in this issue of Service Scope, we present the first of three articles that will offer a practical approach to transistor and vacuum-tube amplifiers based on a simple DC analysis. These articles will, by virtue of additional information and the tying together of some loose ends, combine and bring into better focus the concepts of "transresistance" and the principles of Thevenin's Theorem. We suggest that a "refresher" reading of the two previous articles will enable our readers to more readily follow the information in this and the two following issues of Service Scope.

The Editor

Part I

THE TRANSISTOR AMPLIFIER

INTRODUCTION

Tubes and transistors are often used together to achieve a particular result. Vacuum tubes still serve an important role in electronics and will do so for many years to come despite a determined move towards solid state circuits.

Whether a circuit is designed around vacuum tubes or transistors or both, it is important to recognize the fact that the two are in many ways complementary. It is wrong to divorce vacuum tubes and transistors as separate identities each peculiar to their own mode of operation. Indeed, as this series of articles will show there is an analogy between the two. It is true of course, that the two are entirely different in concept; but, so often we come across a situation where one can be explained in terms of the other that it is very desirable to recognize this fact.

Transistor and vacuum tube data give us very little help in the practical sense. Parameter Curves and electrical data show the behavior of these devices under very defined conditions. In short, they are more useful to the designer than the technician. We are often reduced to explaining most circuits in terms of an ohms law approach; so, it seems pointless not to pursue this approach to its logical conclusion.

In this first article we will look at a transistor amplifier as a simple DC model; and then, in the second article, look at a vacuum-tube amplifier in a similar light. We will assume that both devices are operated as linear amplifiers and then use the results in a practical way.

One must bear in mind that this approach cannot be assumed in all cases. It is, as it is meant to be, a simple analysis but the results will prove to be a valuable tool in trouble-shooting and understanding circuits.

Let us consider the general equation for current through a P.N. diode junction.

$$I = I_o \left[\exp \frac{V}{\rho V_e} - 1\right] \qquad (1)$$

where V = applied volts

I_o = reverse bias current

ρ = constant between 1 & 2

and $V_e = \frac{kT}{q}$ where k = Boltzmans Const., 1.38×10^{-23} Joule/°Kelvin

T = absolute temperature in degree Kelvin at room temperature, i.e., $T = 300°K$

q = electronic charge 1.602×10^{-19} Coulomb.

$$V_e = \frac{300}{11600} = 0.026 \text{ volts}$$

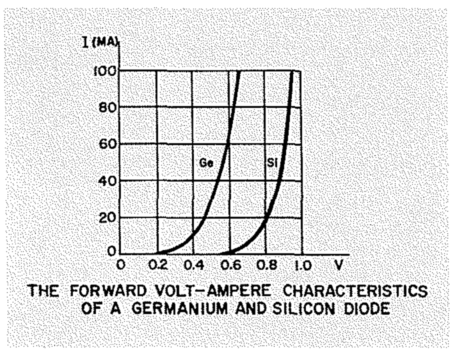


Figure 1.

Figure 1 shows a typical forward volt/amp characteristic for germanium and silicon diodes. Figure 2 is a plot of the collector current or the base current versus the base-to-emitter voltage of a transistor; point A on this curve is a typical operating point.

OBJECTIVE

The objective of this paper is to present a practical approach to Transistor and Vacuum-tube amplifiers based on a simple DC analysis.

The articles will be published in the following sequence.

1. The Transistor Amplifier.
2. The Vacuum-tube Amplifier.
3. An analysis of a typical Tektronix hybrid circuit (Type 545B vertical) based on conclusions reached in (1) and (2).

As a corollary they will bring forward some important relationships between vacuum tubes and transistors.

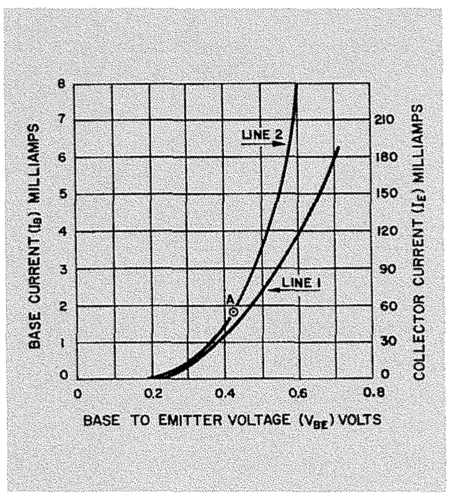


Figure 2. Line (1) is a plot of the base current versus the base-to-emitter voltage (V_{BE}). Line (2) is a plot of the collector current versus the base-to-emitter voltage (V_{BE}). Point "A" is a typical operating point.

One is quite justified in looking at a transistor in terms of the two-diode concept, refer to Figure 3. Therefore, assuming diode A to be forward biased and diode B to be reverse biased, as would be the case if we were to operate the transistor as a linear amplifier, the current through diode A will conform to equation (1). Let us take a closer look at Figure 2.

We define conductance in the general case as

$$g = \frac{I}{V}$$

and therefore at our operating point "A" the dynamic conductance

$$g' = \frac{\Delta I}{\Delta V} \qquad (2)$$

hence

$$g' = \frac{I_o \exp \frac{V}{\rho V_e}}{\rho V_e}$$

$$= \frac{I + I_o}{\rho V_e} \qquad (3)$$

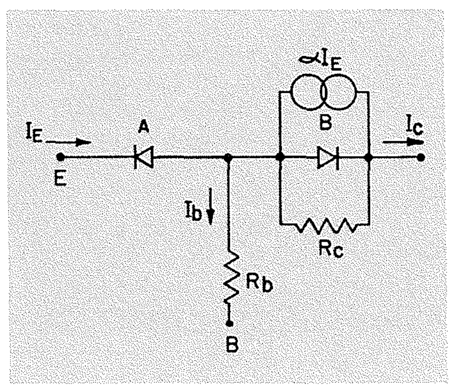


Figure 3. Illustration of the two-diode concept of a transistor.

but $I >> I_0$ then $g' = \frac{I}{\rho V_e}$

$$\text{or } g' = \frac{I}{0.026\rho} \text{ mhos} \quad (4)$$

The term "ρ" takes into account the recombination of carriers in the junction region. It is approximately unity for germanium and approximately 2 for silicon. At a typical operating point this term can usually be neglected. Therefore, we may say that

$$g' = \frac{I}{26} \text{ if I is in milliamps.} \quad (5)$$

Now resistance is the reciprocal of conductance and therefore the value of conductance at point "A" can be given in terms of resistance

$$r_e = \frac{26}{I}\ \Omega\text{'s} \quad (6)$$

This resistance (r_e) is commonly known as the dynamic emitter resistance.

At this point we will depart from our simple model and look at the transistor in another form; but, bear in mind our first thoughts. Transistor parameters are derived from various equivalent circuits depending upon the configuration i.e., common emitter, common base, or common collector. We will not consider any detailed analysis in this approach; but, to understand the approach it is necessary to know how these parameters are derived. It will be simple enough to derive another set of parameters once we have our basic model constructed.

The simplest and easiest equivalent circuit of a transistor is the "Tee" equivalent. It is a very good approximation about the behavior of a transistor, especially at DC and low frequencies. We can also represent either the common emitter or the common base simply by interchanging R_b and R_e. Figure 4 is a "Tee" equivalent circuit of the common emitter and the common base configurations.

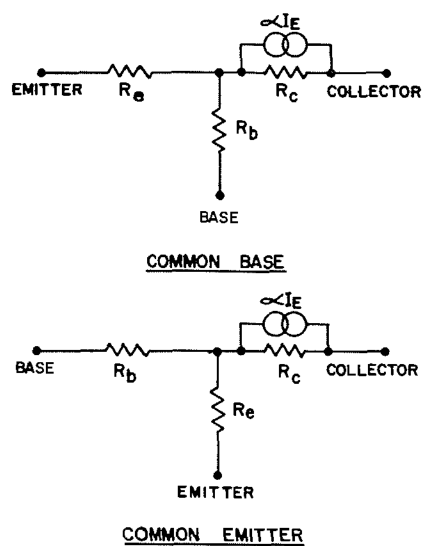


Figure 4. "Tee" equivalent circuits for the common-base and common-emitter configurations of transistors.

Firstly, let us define the term β (the small-signal current gain) as

$$\beta = \frac{\Delta I_c}{\Delta I_b} \quad (7)$$

and since $I_E = I_c + I_b$

$$\text{then } I_E = I_c \left(1 + \frac{1}{\beta}\right) \quad (8)$$

usually $\beta >> 1$ then $I_E \approx I_c$

Equation (8) shows us that only $\frac{1}{\beta}$ of the emitter current flows into the base. Hence, it is reasonable to suppose that any impedance in the emitter, when viewed from the base, will be β times as great; and, any impedance in the base, when viewed from the emitter, will be β times as small. That is to say, the dynamic resistance multiplied by β must equal R_e in our equivalent "Tee" circuit.

Hence $R_e = \beta r_e$

Our equivalent circuit shows a resistance R_b. This resistance is known as the base-spreading resistance. It is a physical quantity and can be expressed in terms of resistivity associated with the base-emitter junction. It can vary between a few ohms to hundreds of ohms, depending upon the type of transistor; and therefore, must be taken into consideration. Looking into the emitter we see it as an impedance whose value is divided by β and appears in series with the dynamic emitter resistance (r_e). Hence the emitter current encounters an impedance in the base/emitter junction which is equal to the sum of the dynamic resistance plus $\frac{R_b}{\beta}$, the latter term we will designate R_r and the sum of these two resistances we will designate R_t.

$$\text{Hence } R_t = r_e + R_r \quad (9)$$

The value of R_r can vary anywhere between $2\,\Omega$ to $24\,\Omega$ depending on the value of R_b. R_b is difficult to measure and rarely given in electrical data on transistors. A figure of 250 Ω's is a typical value at low frequencies. Therefore, if β were 50 then R_r would be 5 Ω's.

Now if we look into the base in the common emitter or the common collector configuration it is reasonable to suppose we will see the resistance (R_t)—plus any other impedance which may be wired to the emitter terminal—multiplied by β, then

$$R_{in} = \beta(R_t + R_E) \quad (10)$$

where R_E = the external emitter resistance.

If $R_E >> R_t$ then $R_{in} = \beta R_E$

So far we have had very little to say about R_e shunted by the current generator $\propto I_E$. If our equivalent "Tee" circuit consisted of resistances alone, it would be passive; i.e., it could supply no energy of its own. But a transistor can amplify energy to the signal. To represent this we have shown a current generator shunting R_e. The value of R_e will depend on the circuit configuration; i.e., tens of kilohms for a common emitter configuration, to many megohms for a common base configuration. In our approach it is not necessary to pursue this matter any further since we will not be considering a transistor in any extreme condition.

Now in a more practical sense, let us look at Figure 5, a typical common-emitter configuration.

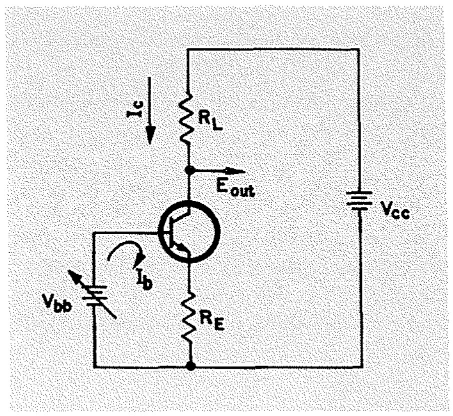


Figure 5. A typical common-emitter circuit.

Now we will assume $R_e >> R_L$.

Now by inspection

$$E_{out} = V_{cc} - \Delta I_c R_L \quad (11)$$

$$\text{hence } \Delta E_{out} = -\Delta I_c R_L \quad (12)$$

The input impedance we see looking into the base of a transistor in the common emitter configuration is

$$R_{in} = \beta(R_E + R_t) \quad (10)$$

$$\text{also } \Delta I_b = \frac{\Delta V_{bb}}{R_{in}}$$

$$= \frac{\Delta V_{bb}}{\beta(R_E + R_t)} \quad (13)$$

we also recall that

$$\beta = \frac{\Delta I_c}{\Delta I_b} \quad (7)$$

$$\text{hence } \Delta I_c = \beta \Delta I_b \quad (14)$$

Therefore substituting equation (13) in equation (14)

$$\Delta I_c = \beta \frac{\Delta V_{bb}}{\beta(R_E + R_t)} \quad (15)$$

and from equation (15)

$$\Delta V_{bb} = \Delta I_c\ (R_E + R_t) \quad (16)$$

we define the voltage gain as

$$A_{(v)} = \frac{\Delta E_{out}}{\Delta V_{bb}}$$

Then from equation (12) and equation (16)

$$A_{(v)} = -\frac{\Delta I_c\, R_L}{\Delta I_c\ (R_E + R_t)} \qquad (17)$$

$$= -\frac{R_L}{R_E + R_t}$$

and if $R_E >> R_t$ then

$$A_{(v)} = -\frac{R_L}{R_E} \qquad (18)$$

If we analyze the common-base configuration in a similar manner we arrive at the same result with the one exception that the sign is positive.

The conclusion we can draw from this analysis is that the gain of a transistor stage is set by external conditions provided that the emitter resistance is sufficiently great enough to "swamp" our internal resistance (R_t). In the absence of an emitter resistance

$$A_{(v)} = \frac{R_L}{R_t}$$

There is one very important fact we must remember about R_E. R_E will be that impedance in which the signal current will flow to the AC ground. We define an AC ground point as that point in a circuit at which the power level of the signal has been reduced to zero.

We normally encounter three types of an AC ground:

1. An Actual AC Ground.

This is the chassis point or the DC ground point. It is as well to remember the power supply can be placed in this category so far as the signal is concerned.

2. An Apparent AC Ground.

The apparent AC ground may be represented by any point in a circuit which acts as to represent a low impedance between that point and the actual AC ground thereby bypassing the signal to an actual AC fround. A large value capacitor is a typical example should one side be returned to an actual AC ground.

3. The Virtual AC Ground.

The virtual A.C. ground point is perhaps the most difficult to recognize. It may best be explained as that point in a circuit where we have two signals of equal amplitude and frequency but exactly opposite in phase. Figure 6 will help clarify these points.

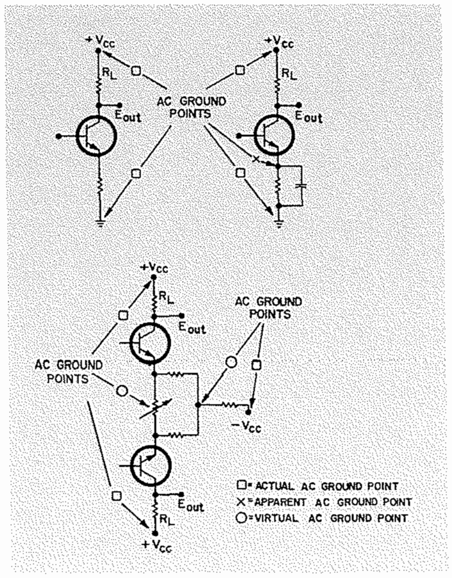


Figure 6. Illustrating the three types of AC ground normally encountered in electronic circuits.

Figure 8 summarizes the results of our DC analysis of the common emitter, common base and common collector.

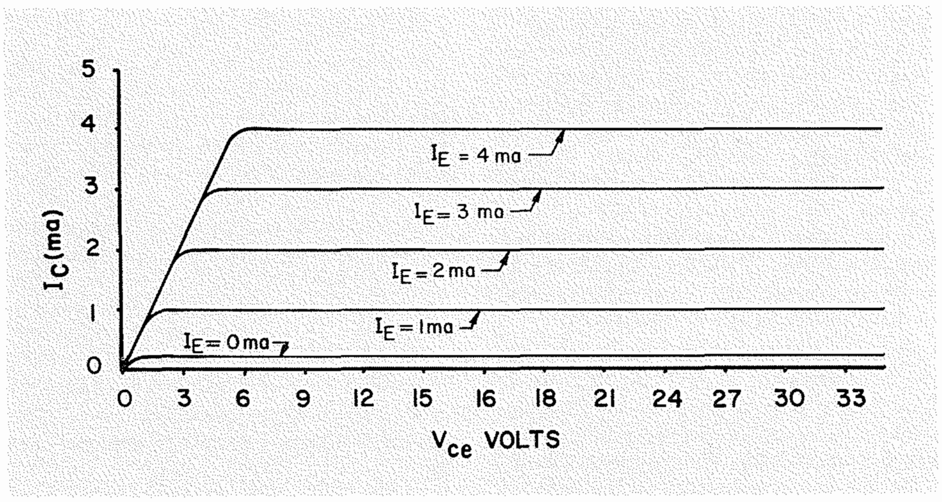


Figure 7. We define the parameter R_c in the common-base "Tee" configuration as;

$$R_c = \frac{\Delta V_{ce}}{\Delta I_c}\Bigg|_{I_E} \text{ ohms}$$

Where ΔV_{ce} is the change in the collector voltage because of the change in collector current ΔI_c, when we hold the emitter current I_E constant.

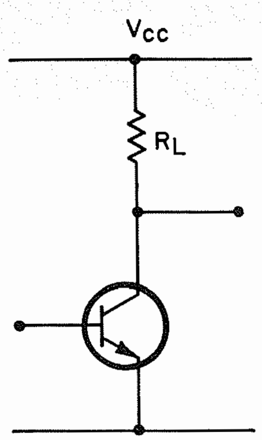
Once the collector becomes saturated, the change in I_c is very small for a large change in V_{ce}. Hence, R_c is a very large resistance and does not modify the DC equivalent circuit to any extent. For this reason it was omitted from Figure 7. Therefore; $R_{out} \cong R_L$ (Common Base).

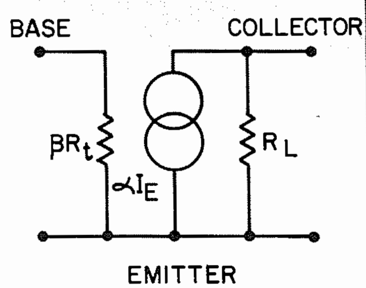
LIST OF SYMBOLS

$A_{(v)}$	Voltage gain defined as $\frac{\Delta E_{out}}{\Delta E_{in}}$
I_b	Base current
I_c	Collector current
I_E	Emitter current
R_c	Collector resistance (Tee Equivalent)
R_b	Base spreading resistance (Tee Equivalent)
R_e	Emitter resistance (Tee Equivalent)
R_E	External Emitter resistance (refer to text)
$R_{E(s)}$	The equivalent resistance between the signal source and the emitter terminal of the transistor in the common base configuration.
R_L	Load resistance
R_r	$\frac{R_b}{\beta}$
R_t	The "Transresistance" resistance ($r_e + R_r$)
re	dynamic emitter resistance
V_{bb}	Base voltage
V_{cc}	Supply voltage
V_{ce}	Collector to emitter voltage
Δ	(Delta) the change in the variable with which it is associated.

BASIC CIRCUIT	EQUIVALENT CIRCUIT	EQUATIONS	REMARKS

COMMON EMITTER





GAIN = $A(v) = -\frac{R_L}{R_t}$

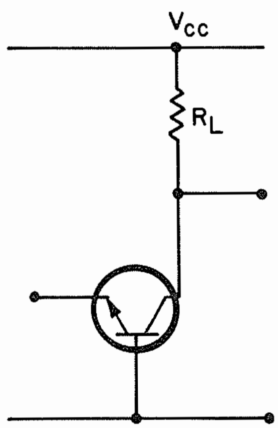
RIN = βR_t

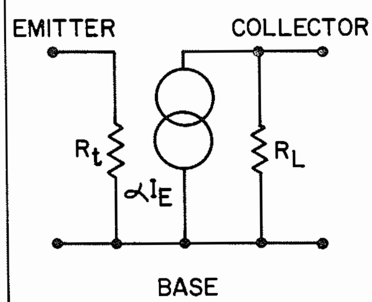
A resistance (R_E) between the emitter terminal of the transistor to the AC ground will modify the gain equation and the input impedance; then,

$A(v) = -\frac{R_L}{R_t + R_E}$ and

$R_{in} = \beta (R_E + R_t)$.

COMMON BASE





GAIN = $A(v) = +\frac{R_L}{R_t}$

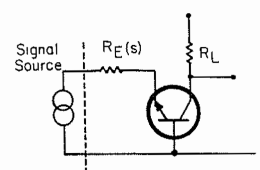
RIN = R_t

ROUT = R_L

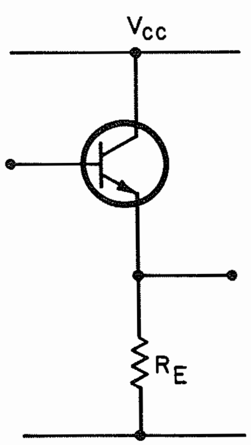
The equivalent resistance $R_{E(s)}$ between the input signal source and the emitter terminal of the transistor will modify the gain equation and the input impedance as seen from the signal source; then,

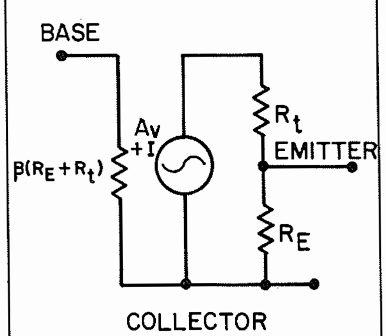
$A(v) = +\frac{R_L}{R_t + R_{E(s)}}$ and

$R_{in} = R_t + R_{E(s)}$.



COMMON COLLECTOR





GAIN = $A(v) = \frac{R_E}{R_E + R_t}$

RIN = $\beta (R_E + R_t)$

ROUT = $(R_t + \frac{I}{\beta})$ in parallel with R_E

The actual value of R_{out} will depend on what resistance is connected to the base. Let us assume the base is directly coupled to the preceding stage. The equivalent output impedance of the preceding stage becomes the numerator over beta in the second term in the parenthesis and the output impedonce of the stage under consideration R_{out} is modified accordingly; eg., if the output impedance of the previous stage is 100 Ω, then

$R_{out} = (R_t + \frac{100}{\beta})$ in parallel with R_E.

Figure 8.

SERVICE NOTES

SILVER-BEARING SOLDER AND SILVER SOLDER: TWO DIFFERENT THINGS

Many components in Tektronix instruments are mounted on ceramic strips. The notches in these strips are lined with a silver alloy and repeated use of ordinary tin-lead solder will breakdown the silver-to-ceramic bond. For this reason, we recommend the use of a silver-*bearing* solder containing 3% silver when performing service or maintenance work that requires soldering on these ceramic strips. This type of solder is used frequently in printed circuits and should be readily available from radio-supply houses.*

Silver-*bearing* solder should not be confused with silver solder. They are two different things!

The use of silver-*bearing* solder in the construction and maintenance and repair of electronic circuits is a safe and accepted practice. The silver-*bearing* solder used and recommended by Tektronix for ceramic strip soldering, melts at about 365 degrees Fahrenheit, and is applied with an ordinary soldering iron. It is composed of 60% tin, 37% lead, and 3% silver. It contains absolutely no cadmium! It produces no toxic or lethal fumes!

Silver solder, on the other hand, is a brazing alloy and is most commonly used by welders. It is composed essentially of silver, copper, zinc, and sometimes cadmium. When the alloy is composed of 45% silver, 30% copper and 25% zinc it requires approximately 1340 degrees Fahrenheit to melt it and it is usually applied with an acetylene torch. Should either the silver solder or the metals to which it is being applied contain cadmium, this high temperature will cause the cadmium to vaporize and release fumes. These fumes will be toxic and they can be lethal.

In summary, let us repeat; Silver-*bearing* solder and silver solder are two different things:

Silver-*bearing* solder is used primarily in the soldering of electronic circuits. Silver solder is an alloy used in the brazing and welding of metals.

Silver-*bearing* solder is applied with a soldering iron and requires only relatively low temperature to melt it. Silver solder is applied with an acetylene torch and requires a high temperature to melt it.

Silver-*bearing* solder absolutely does not produce toxic fumes. Silver solder, if it contains cadmium or is used on metal containing cadmium, does produce fumes that are toxic and can be lethal.

Positively no silver solder is used in any instrument produced by Tektronix, Inc.

*If you prefer you can order this solder directly through your local Tektronix Field Office, Field Engineer, Field Representative, or Distributor. Order Tektronix part number 251-0515-00.

OOPS! WRONG PART NUMBER

In the December 1966 issue of Service Scope, we transposed two figures in the Tektronix part numbers for the probe identification tags. The part number for the identification tags for use on the smaller (0.125" diameter) cables is 334-0798-00, and the number for the larger (0.178 to 0.185" diameter) cables is 334-0798-01.

COMPONENT LUBRICATION KIT FOR TEKTRONIX INSTRUMENTS

We have available a component lubrication kit for Tektronix instruments. The kit contains: a detent lubricant in a container-applicator; a switch-contact lubricant in a container-applicator; a pot lubricant in a container-applicator; 12 each detent-ball replacements (for lost or worn detent balls) in the following sizes—5/32", 3/16", and 7/32"; a #3 brush, and an instruction book.

The instruction book contains information on the cleaning and washing of Tektronix instruments and when an instrument needs lubrication. It also contains illustrations showing the different types of switches used in Tektronix instruments and tells how to lubricate them and replace worn or lost detent balls. The lubrication of potentiometers and fan motors and the care of air filters are also covered. Suggestions for the lubrication of rackmount tracks are given.

You may order the kit through your local Tektronix Field Office, Field Engineer, Field Representative, or Distributor. Specify Tektronix part number 003-0342-00.

TYPE 1L5, TYPE 1L10, TYPE 1L20, AND TYPE 1L30 PLUG-IN SPECTRUM ANALYZERS WITH A TYPE 132 POWER SUPPLY

These spectrum analyzers can be used in conjunction with a Type 132 Plug-In Unit Power Supply and the output displayed on any Tektronix oscilloscope that has a Sawtooth-Out sweep voltage available on the front panel.

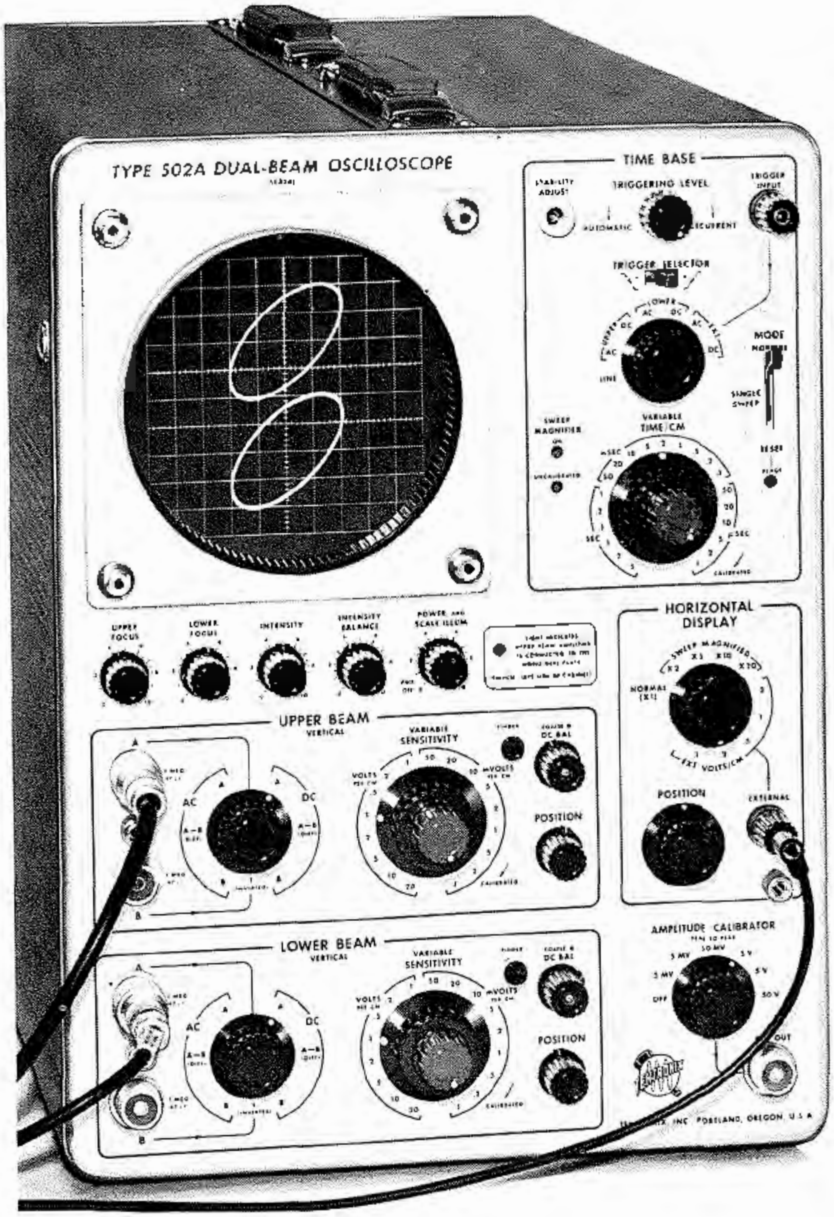
Positive output-polarity voltage from the Type 132 can be applied to the DC-coupled input of the oscilloscope. Centering of the oscilloscope sweep is performed with the oscilloscope vertical-position control prior to RF signal application to the analyzer. The analyzer vertical-position control can then be used for trace positioning.

The Sawtooth-Out sweep voltage from the oscilloscope is applied to the Sweep-Input connector.

TYPE 1L10, TYPE 1L20, AND TYPE 1L30 PLUG-IN SPECTRUM ANALYZERS—VERTICAL TRACE SHIFT

If a vertical trace shift is encountered when a Type 1L10, Type 1L20, or Type 1L30 Plug-In Spectrum Analyzer is switched between linear and log mode, suspect a gassy input tube in the indicator (oscilloscope) vertical amplifier. The output impedance of the analyzer unit is much higher in the log mode than it is in the linear mode. If grid current is present in the input tube, this current will give a different voltage drop across the input resistance (analyzer output impedance); consequently, a DC shift of the trace will result.

simplify waveform measurements



Tektronix Type 502A

100 μV/cm dual-beam oscilloscope

☐ **Measure stimulus and reaction on the same time base.**

☐ **Measure transducer outputs, such as pressure vs. volume.**

☐ **Measure phase angles and frequency differences.**

☐ **Measure characteristics of low-level signals.**

The Type 502A combines the performance capabilities *unique to dual-beam* oscilloscopes with operational features designed to simplify and speed up your measurements.

You can examine two waveforms simultaneously by applying input signals to both of the identical vertical amplifiers. You can use each vertical amplifier in a differential display mode to examine the difference between two signals. You can also use the Type 502A as a single-beam X-Y oscilloscope or as a dual-beam X-Y oscilloscope with both traces plotted on the same X scale.

This performance is combined with operating conveniences which include pushbutton beam finders for quick location of off-screen signals, vertical signal outputs, intensity balance for identification of upper and lower beams, single-sweep operation, Z-axis input, variable control of vertical and horizontal deflection factors, electronically-regulated power supplies for stable operation, and other refinements.

performance characteristics include:

Bandwidth from DC to 100 kHz at 100 μV/cm, increasing to DC to 1 MHz from 5 mV/cm to 20 V/cm • Calibrated deflection factors from 100 μV/cm to 20 V/cm in 17 steps; continuously variable between steps, uncalibrated, and to 50 V/cm • Common-mode rejection of at least 50,000:1 from DC to 50 kHz ••Phase difference between amplifiers less than 1 degree from DC to 100 kHz • Calibrated sweep rates from 1 μs/cm to 5 s/cm in 21 steps • 2X, 5X, 10X, 20X sweep magnification • Flexible trigger facilities • Amplitude Calibrator • 10 cm by 10 cm display area.

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