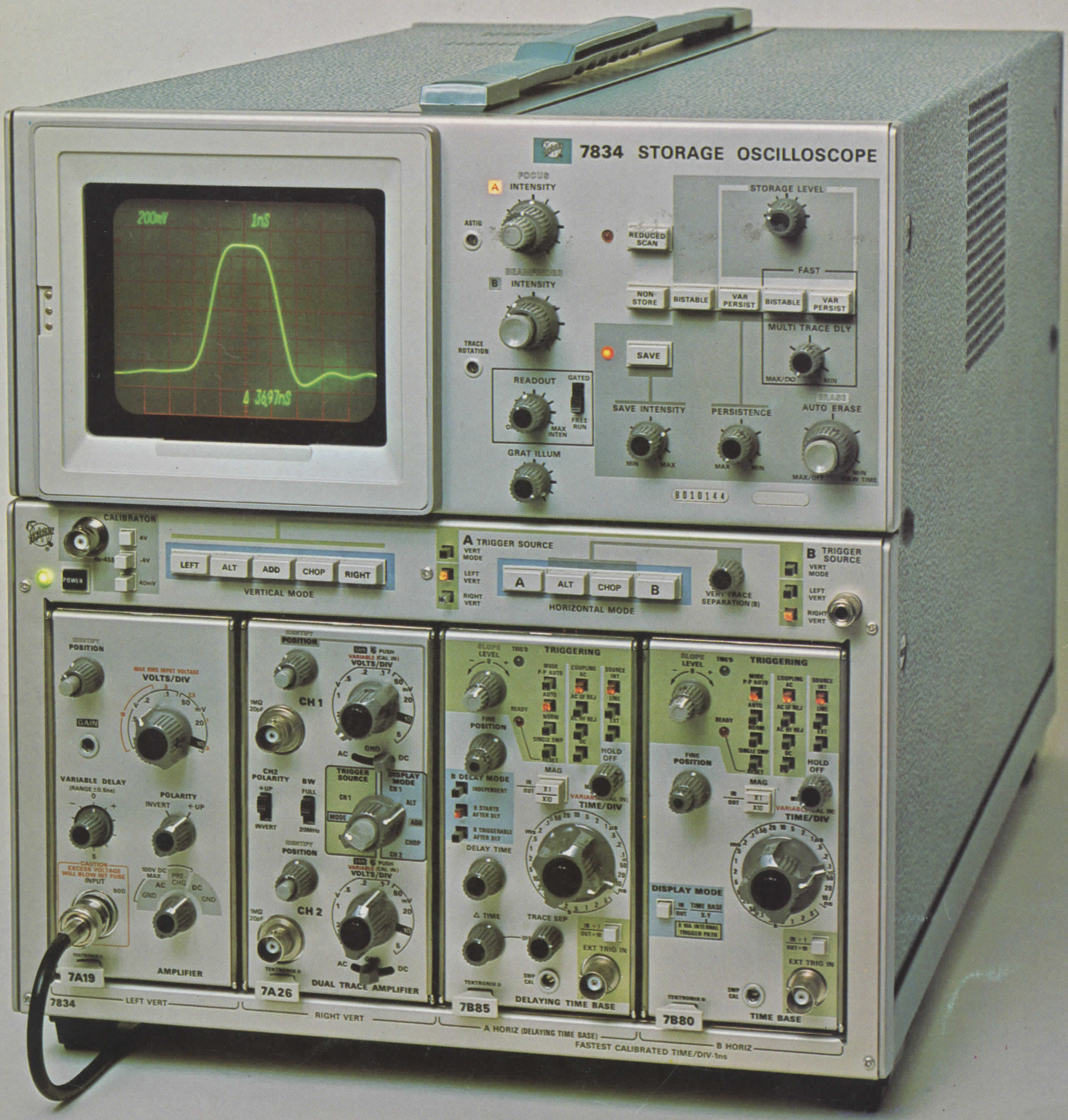
PRINCIPLES OF

STORAGE TUBES and OSCILLOSCOPES



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PRINCIPLES OF STORAGE TUBES AND OSCILLOSCOPES

by John Schmid

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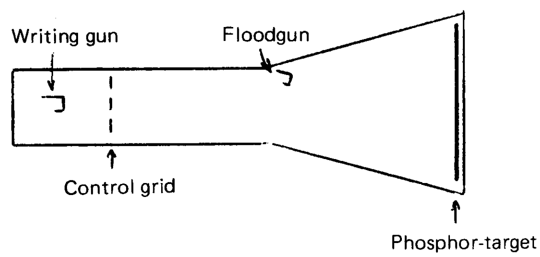
* from "Storage Cathode-Ray Tubes and Circuits", published by Tektronix, Inc. (Publication No. 062-0861-01, now out of print).

INTRODUCTION

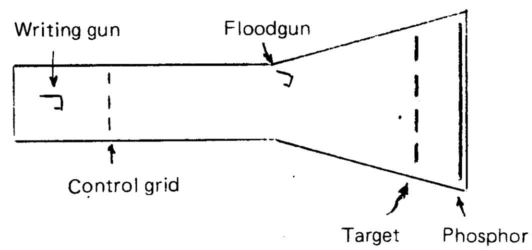
The purpose of this little booklet is to acquaint you with the principles and some of the characteristics of storage cathode-ray tubes and the instruments in which they are used. It does not deal with any circuit or application details. Readers should be familiar with conventional oscilloscope terms and know how ordinary CRTs work.

Storage tubes fall into two categories, depending on the location of the storage target. These are the phosphor-target tube and the transmission tube.

Phosphor-target tube



Transmission tube



As you can see, storage tubes also contain two separate cathodes or guns from which a writing and a flood beam are directed towards the target.

Some of the basic principles are common to both tube types and are treated in chapter 1. The next two chapters deal with phosphor-target tubes in particular, and chapter 4 describes oscilloscopes using these. The transmission tubes (of which there are three versions: bistable, halftone and transfer) are covered in the remaining chapters. Two appendices deal with specifications. The summary (pp. 48-49) and the index (p. 50) should assist in locating details quickly.

The terms used in this booklet reflect current practice at Tektronix. For phosphor P1 the European designation letters are GJ, and for P31 they are GH. Trace brightness is generally shown in foot lamberts (fL) because these are the units in which our factory specifies them at present, but for tables 1 and 2 in this booklet the SI unit candela/square metre (cd/m^2) is used as fractional numbers can thereby be avoided. The conversion factors are 1 fL = 3.43 cd/m^2 and 1 cd/m^2 = 0.292 fL.

Apart from their use in oscilloscopes, storage tubes are frequently found in information display devices, where they provide stored readouts of alpha-numeric characters or graphics without the need for display refreshment from a computer memory. In this application, different tube characteristics are of interest, such as for example the resolution (expressed by the number of paired lines which can be written in the screen area) and the dot writing time. Except for the briefest reference to dot writing time, these factors are not discussed in this text. A suitable introduction can be found in chapter 9 of "Information Display Concepts" by Nick Stadtfeld and Bob LeBrun, published by Tektronix, Inc. (Publication No. 062-1005-00, now out of print), and the specifications of Tektronix Information Display Monitors are included in Appendix B.

Chapter 1
STORAGE TUBE BASICS

All storage tubes rely on the mechanism of secondary emission from a dielectric surface. In this first chapter we shall study the principles of this mechanism.

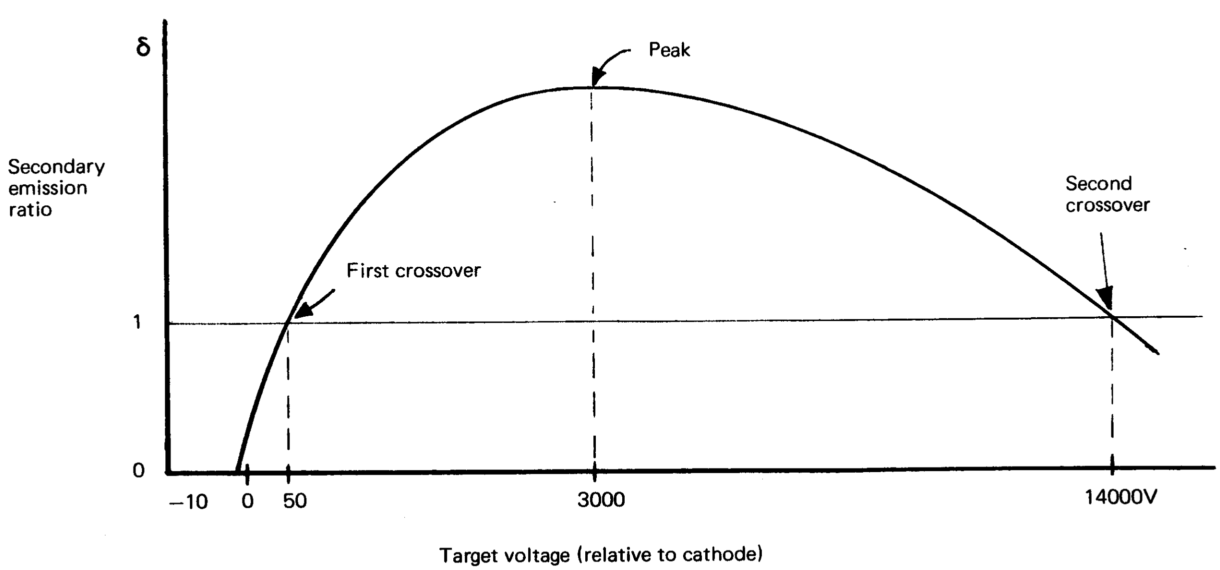
The purpose of storage tubes is to record the movement (and in some cases the intensity) of an electron beam over a target area. In order to make the various parts of the target separately addressable, the target must be made of a dielectric material of such composition and construction that lateral leakage is kept to a minimum. The target should therefore be thought of as a collection of separate insulated points, and since it is insulated it can be described as "floating".

When a beam hits such a dielectric target, secondary emission can occur: due to the landing energy of the electrons, other electrons are knocked out of the target surface and collected by a nearby collector. In order to do its job as a collector, its voltage has to be more positive than that of the target itself, but not so positive as to appreciably attract the primary beam electrons.

It stands to reason that when the electron beam lands with very little energy on the target it will knock out few, if any, secondary electrons. As the landing energy is increased, secondary emission will increase until, beyond a certain limit, the landing electrons hit the surface with such force and penetrate the material so deeply that more and more of the secondary electrons produced by the impact are trapped within the material instead of escaping. The landing energy of the electrons is determined solely by the potential difference between the cathode from which they originate and the target on which they land; it is not affected by intermediate accelerating and decelerating potentials.

If the landing speed is varied and the amount of secondary emission plotted, a curve with the general appearance shown in figure 1 results. This is true of all dielectrics, but the exact voltages at which the crossovers and peak occur depend on the material. The figures shown are typical for the dielectrics used in the tubes discussed in this text. (The slightly negative starting point of the curve is due to the thermal energy with which electrons are leaving the cathode.)

Figure 1



Secondary emission curves are generally shown in terms of the ratio δ of secondary emission to primary (or incident) beam. Such a presentation is valid and useful because, for a given target material and construction, the ratio does not change with the intensity of the primary beam, and plotting the curve in these terms brings out the essential points about secondary emission.

The line on the graph representing $\delta = 1$ is of great significance. Portions of the curve above it represent conditions under which the target loses more electrons by way of secondary emission than it gains, and conversely at points below this line the target gains more electrons from the primary stream than it loses. Since the target is in fact a dielectric, which is electrically floating, its surface voltage will drift up or down whenever there is an imbalance between the number of electrons landing and leaving. But before we go to the trouble of studying the effect of this voltage drift in detail we must look at two factors which will lead us to modify the shape of this curve.

First, we assumed that the collector was always slightly more positive than the target, so that any electrons liberated from the target would be attracted and collected by it. But since "the target" is in fact an array of insulated and independent points, what constitutes "the target"? How could we measure it? And how could we make the collector "always sit at a level slightly higher than the target"? As a practical solution the nearby collector is simply held at a reasonable fixed positive voltage, typically 150 V. This will be sufficient to collect secondary electrons - as long as the target voltage does not exceed +150 V. But if, for any reason, a point on the target does exceed +150 V, then, although secondary emission will still occur, the liberated electrons will tend to return to the target as the most positive element in the neighbourhood. This does not in any way affect the basic secondary emission curve shown in figure 1, but if our interest centers not so much on the electrons knocked out of the surface but on the net gain or loss to the target, then we have to redraw the curve at and above 150 V to show that at such voltages the target does not in fact lose any electrons because of secondary emission. The curve drops to a secondary emission ratio of zero. This can be seen in figure 2.

The second modification of figure 1 occurs at the opposite end of the curve. Once the target voltage is below that of the cathode, the primary stream of electrons will not land on it any more but will go straight to the collector. Again this does not affect the validity of figure 1. It is a fact that if any electrons did land they would land with zero energy and would be incapable of knocking off secondary electrons. But if we are concerned with the balance sheet of the target we will interpret the situation differently and say that since the target neither receives nor loses electrons and since therefore, in this trivial sense, the gains and losses exactly balance, we are dealing with a δ of 1. The way in which the new curve deviates from figure 1 is again shown in figure 2.

Figure 2, then, is not a curve representing the secondary emission ratio but one which plots the secondary emission yield (in other words the net gain or loss of the target) against the landing voltage of the primary beam. For simplicity, and to conform with literature, we will continue to label the ordinate δ.

A small point still remains to be explained: why the curve to the left of point B is shown slightly above the $\delta = 1$ line. If no electrons can land on the target because it is more negative than the cathode from which they originate, one would have expected the curve to remain at $\delta = 1$, representing neither gain nor loss. In fact, within the stream of particles coming towards the target are occasional positive ions, and these will be attracted by the negative target and land on it. Since a gain of positive ions is equivalent to a loss of electrons,

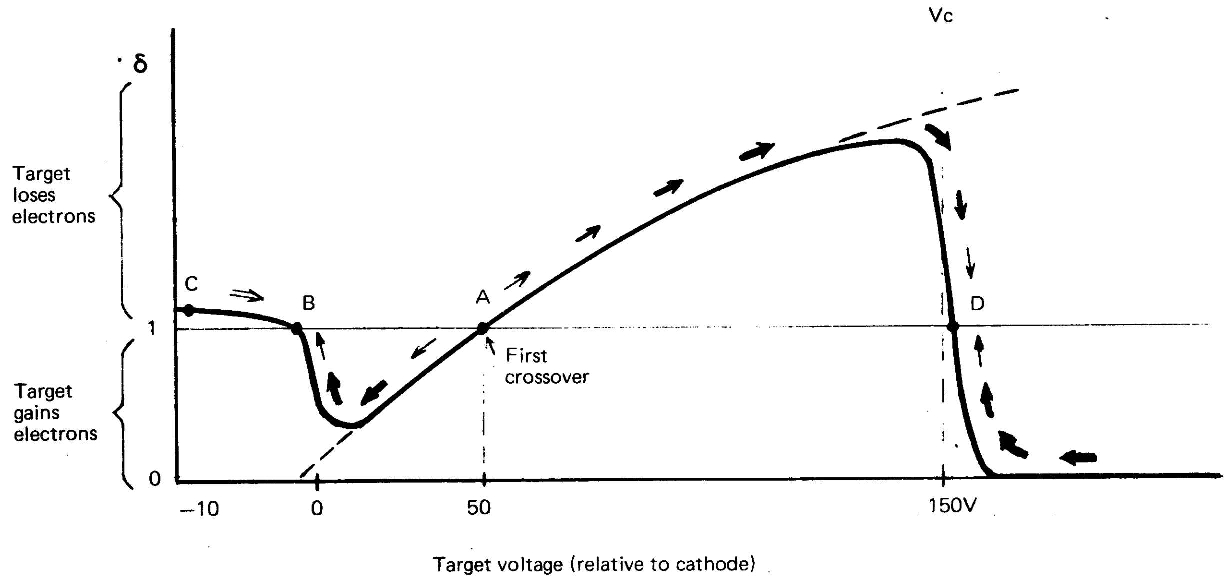


Figure 2

it must be shown on the balance sheet the same way as a loss of electrons - in other words, as if the secondary emission ratio were greater than one.

We can now return to the study of the voltage drift. The target is a collection of separate addressable points. As long as electrons arrive and leave in unequal numbers, these points will move up or down in voltage. A net loss of electrons, and therefore a drift in a positive direction, happens whenever the target voltage is in regions where the curve is above $\delta = 1$, and a net gain and negative drift in regions where it is below $\delta = 1$. This is shown by the arrows in figure 2. Therefore, as long as the beam continues to hit a given target area, that area will charge in the direction of the arrows. If you study these directions for a moment, you will see that they converge on two points, B and D. These are the only two points at which the target can stabilize. (The target cannot rest at A since the unexpected gain or loss of a single electron due to noise will bring it under the influence of one or the other divergent trend.) B and D are called, appropriately enough, the lower and upper stable points.

The speed of the voltage drift is obviously a function of the amount of discrepancy between landing and leaving electrons. Whenever the curve approaches $\delta = 1$, the movement will slow down, whereas in regions of large gains or losses the voltage will change more quickly. In figure 2 we tried to make this point by varying the fatness of the arrows. The region between B and C is a special case. Drift in that part is due to the landing of positive ions rather than electrons, and since these are fewer in a ratio of perhaps 1 to a million, the drift from C towards B is measured in minutes, compared with tens or hundreds of microseconds on other parts of the curve.

We said that this drift towards the stable states occurs in any part of the target, as long as that part has an electron beam directed towards it. Therefore, if the whole target were to be flooded with a defocussed electron beam, all those portions of it whose surface voltage happened to sit above A would move towards the upper stable point and the remainder towards the lower stable point, and under the influence of this floodbeam the target would be maintained at these points. This would give us a device capable of bistable storage of information in the form of a voltage pattern.

In order to be useful, we must of course have means of entering and deleting information - in other words, of writing and erasing - and we must make this voltage pattern visible. If the pattern becomes visible because of light emission from the storage tube itself, we speak of a direct-view storage tube. These form the sole topic of the present text. (The other method of making the pattern visible is by scan conversion: scanning the target with a reading beam which is then used to modulate some other light-emitting device such as a TV picture monitor.)

We will not discuss in this chapter how the pattern stored on the target is made visible in a direct-view storage tube. There are, as you know, two entirely different methods of doing this, which will be explained in later chapters. But with both methods it is convenient to use a higher target voltage for the written information and a lower one for the unwritten background. "Writing" therefore means lifting the target surface by means of a focussed writing beam from a lower to a higher voltage - in the case of the bistable system, from the lower to the upper stable point.

How could this be done? Well, the target consists of a dielectric, and in order to increase the voltage of a given point on it we must cause that point to lose electrons. The only mechanism we have available is the one just studied: secondary emission. Writing beam electrons must arrive with enough energy to cause a secondary emission ratio of more than unity. The writing beam can only have so much energy if it originates from a cathode sitting at a considerably more negative voltage than the target. One could, in principle, stop the floodbeam, move its cathode sufficiently negative and focus it, then start writing on the target. Afterwards the flood condition could be re-established. (We shall see that in both types of storage tubes the floodbeam is the source of electrons which produce the visible stored display. In bistable tubes it also has the vital function of maintaining the written and unwritten parts of the target at their respective stable points as explained at the bottom of page 3.)

In practice it is found simpler to use two separate guns in the same CRT envelope: a permanently defocussed floodgun, which maintains a floodbeam at all times, and a separate focussed writing gun, operating at a much more negative voltage, whose electron beam is controlled by a control grid in the normal manner.

When writing the target area, the writing beam action is initially opposed by the continuing floodbeam action. The target voltage will only move positive if the number of electrons lost due to greater-than-unity secondary emission of the writing beam exceeds the number of electrons gained from the lower-velocity floodbeam. This will be considered in more detail in chapter 3. Once the target has moved above the first crossover, the floodbeam will of course assist the writing beam in moving the target further positive.

Finally in this chapter, let us consider how this information could be erased again. This involves moving all those areas of the target which are written back to the unwritten level. The target itself is, as we keep saying, floating. But the dielectric is in fact mounted on some kind of conducting surface, and if a negative pulse is applied to this surface, capacitive coupling will also move the target as a whole negative by the same amount. Once all points of it have been lowered below the first crossover, the continuing floodbeam will see to it that the target is then maintained at the lower stable point. This description of the erase process is only a preliminary one. The erase pulse is in fact more complex to take care of additional problems, and we shall look at these when discussing the two tube types in detail.

Chapter 2
BISTABLE PHOSPHOR-TARGET TUBE CONSTRUCTION

We mentioned in the introduction that direct-view storage tubes fall neatly into two types, depending on the means adopted to make the stored pattern visible. These types are the phosphor-target tube and the transmission tube. In the first case the target dielectric is made of phosphor which will light up in the written areas and be looked at directly by the eye. In transmission tubes, on the other hand, the target forms a mesh which controls the flow of the CRT beam on its way to a conventional phosphor screen, acting much like the grid in a valve.

The earliest phosphor-target tubes had poor definition and an extremely dim display. This led designers to concentrate on transmission tubes. They on their part suffered from lack of robustness and were rather expensive to make. Then Tektronix engineers returned to the phosphor-target idea and managed to refine it into a practical proposition. Their phosphor-target tubes represented a breakthrough in price and simplicity. They first entered the market in the type 564 oscilloscope in 1963 and are the subject of Tektronix patents.

The basic idea is simple enough: if phosphor is used as the dielectric in a bistable system such as we described, then the stream of flood electrons hitting the written areas with an impact speed equivalent to the 150 volts or so of the upper stable point will produce a light output, whereas the unwritten areas at the lower stable point receive no floodbeam electrons, or if they did the landing energy would be virtually zero, causing no light emission. This phosphor target will therefore continue to emit light from the written area as long as the floodbeam is present.

But there are of course problems. First, the phosphor must be suitable as a dielectric, which means it must offer a high secondary emission ratio and possess good insulating properties. The most efficient phosphor, P31, does not have these qualities; we generally use a modified form of P1 with about half the efficiency of P31, which means a dimmer trace. Furthermore, with the phosphor target at about 150 V, compared with the more usual several kilovolts, the trace brightness is again appreciably reduced. Nevertheless, under subdued lighting conditions it is still a usable display.

Then there was the problem of poor definition in early tubes. This was traced to the lateral spreading of the written area after the passage of the writing beam, due probably to inadequate lateral insulating properties of the phosphor. Our solution was to deposit the phosphor either as a pattern of finely spaced dots or to lay it down as a layer of randomly arranged semicontinuous particles with the aim of preventing lateral leakage between adjacent areas.

Figure 3A

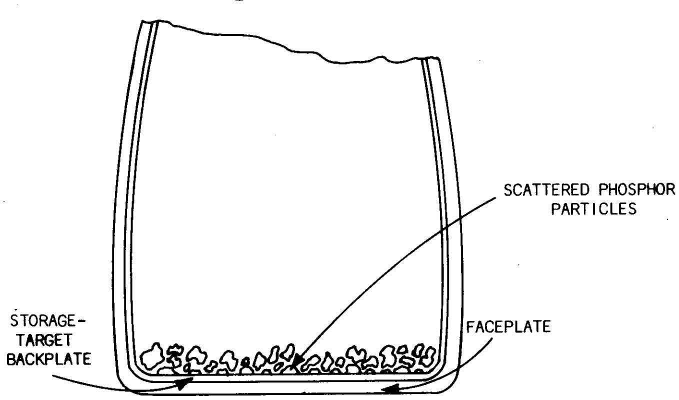
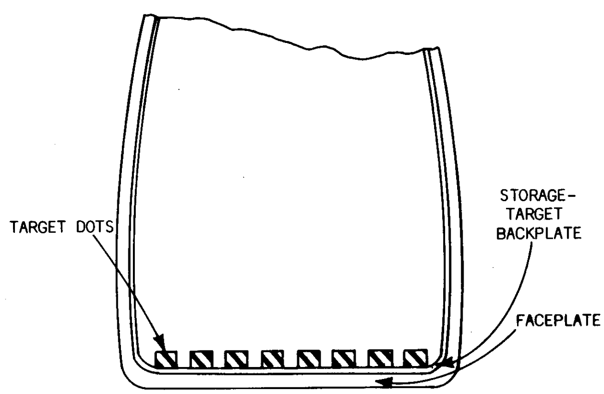


Figure 3B



The particles, whether regular dots or of random shape, must of course form a pattern so fine that the width of the focussed writing beam will cover several of these target elements. In this way the limits of definition are dictated by the fineness of the writing beam only.

You will remember that bistable target operation depends on a nearby collector to collect secondary electrons. The discontinuous nature of the phosphor deposition allows us to use the conducting foil on which the target is deposited ("Storage Target Backplate" in figure 3) as a collector. This foil is so extremely thin as to be transparent, so that light emitted from the phosphor can be seen through it by the observer. Secondary electrons knocked off the target will therefore be attracted through the gaps in the phosphor to the higher potential collector.

Perhaps we should consider briefly why the primary stream of flood electrons does not itself go directly through these gaps to the collector, thus defeating the whole purpose of the arrangement. The reason is that the flood electrons arrive with a fair amount of kinetic energy and are not easily diverted at the last moment to the minute gaps between phosphor particles. By contrast, secondary-emission electrons have much lower energy and therefore move at much slower speed, which makes them more manoeuvrable. It is incidentally the difference between the high energy of the landing electrons and the lower energy of the secondaries which gets converted into heat and light emission from the phosphor.

Let us pause at this point to summarize briefly what we have learnt of phospor-target storage tube construction and operation. These tubes have a target composed of phosphor which can be written - that is, lifted by a writing beam to a higher potential - and will then attract electrons from a floodbeam whose landing energy is partly converted to light and partly used to dislodge secondary electrons. The secondary electrons find their way through gaps in the target to the storage-target backplate which acts as collector. The floodbeam is therefore used in the first place to make the written areas visible, but it also has the effect of shifting the target from whatever voltage it may have been left at by the writing beam or erase pulse to the upper or lower stable point, making this storage tube a bistable one. The beam originates from a floodgun and is deliberately dispersed to cover the whole target area. The writing beam comes from the writing gun which is so negative with respect to the target that when the writing beam lands it causes much secondary emission, thus lifting the target voltage. The writing beam is intensity-controlled, focussed and deflected in the usual way.

With this basic picture in mind we must now go a little more deeply into the problems of target construction, since this will considerably increase our understanding of storage tube behaviour. These are problems which are of concern at the design stage, but also have important effects on operating characteristics.

A suitable target material must be chosen. Then it must be decided whether to deposit particles according to figure 3A or 3B. Nowadays the semicontinuous method shown in figure 3A is so predominant that we will base our further discussion on this, although very similar problems would be encountered with the other method. Having made both these decisions we can then also vary the thickness of this target layer, and this has a surprising number of repercussions which we must present at length in the remainder of this chapter. If your main interest is transmission tubes and you are reading this chapter merely to understand bistable principles we suggest you now turn to page 11.

As target thickness increases a number of factors are affected in a beneficial way. Luminance increases fairly linearly, since the presence of additional material (and the higher operating voltage that this permits) generates additional light. Resolution increases rapidly at first: when the target is only molecules thick, wide spaces exist between particles and these fill in as thickness increases. Predictably, once a certain thickness has been reached, the increase in resolution

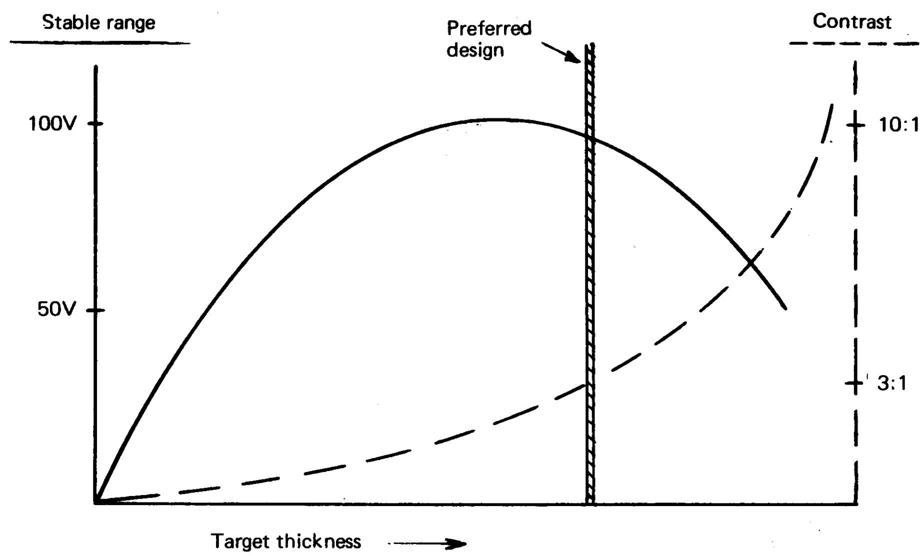


Figure 4

levels off. But perhaps the most significant improvement resulting from greater target thickness is the increase in contrast, as shown in figure 4.

Against this catalogue of benefits resulting from increased target thickness we must set one factor which, after reaching a peak, decreases again. This is the stable range of collector operating voltages, and to understand what it is, and why it is so important to us that we sacrifice a great deal of contrast to it, we must consider one aspect of this storage tube which has hitherto been ignored: the possibility of leakage from the target surface to the backplate on which it is deposited.

In unwritten screen areas there is in fact some leakage through the target, to the collector, which sits at a high positive voltage, lifting the phosphor surface above the lower stable point (LSP) and causing a slight amount of light emission because of the increased landing energy of the floodbeam. It might seem to contradict basic theory that the target can rest at a point above LSP, since the secondary emission ratio is then less than unity and it ought to gain electrons, but this effect is balanced by the migration of electrons through the target to the collector.

The amount of leakage will vary from point to point across the screen, since the phosphor layer is randomly semicontinuous, but some leakage will be observed almost everywhere and we can surmise that the rest potential might look something like the solid line RP in figure 5. This will cause light emission varying across the screen in a correlated manner. From normal viewing distances these variations average out and we simply observe an average background light level, corresponding to the average rest potential (ARP).

The solid line RP is no more than an artist's impression, but given such wide variations across the target, some points will inevitably exceed the first crossover level, and these points will therefore move to the upper stable point (USP), a process which is often called "fading positive". Being individual, randomly distributed bright dots on a microscopic scale we can again see only their contribution to the average background light level.

Although on theoretical grounds one might wish to exclude these written dots from the calculation of the average *rest* potential, in practice this is not possible. The ARP is a purely theoretical value which cannot be measured directly since the target is floating. We assess the average rest potential on the basis of average light emission, and when making such light measurements we are bound to include the written dots as well as those in various unwritten states.

The full picture, then, is that dot by dot across the screen the rest potential varies in a random manner, causing a corresponding slight light output, with the exception that all those dots which happen to exceed the first cross-over level will fade positive and emit the written light level. Only the average of all these light contributions can be perceived on a macroscopic scale, and from this average light level we can deduce the average rest potential.

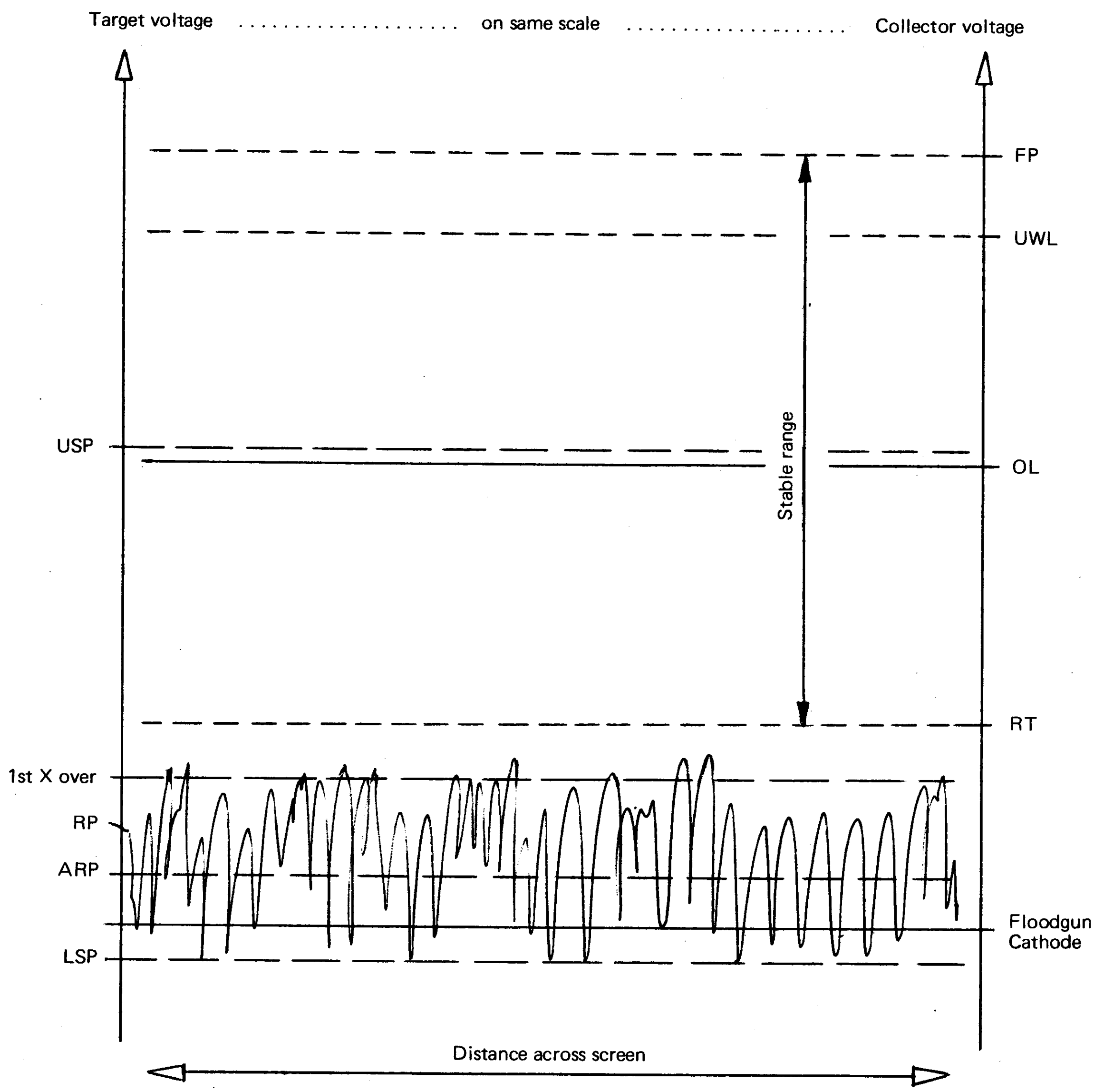


Figure 5

USP	upper stable point	FP	fade positive level
RP	rest potential	UWL	upper writing limit
ARP	average rest potential	OL	operating level
LSP	lower stable point	RT	retention threshold

The situation is illustrated in figure 5, in a purely qualitative way, for the condition where the collector voltage is set to a typical operating level OL. Naturally, as the collector voltage is varied up and down, the amount of leakage also varies and the RP curve will shift up and down to some extent.

If we set the collector to increasingly positive levels, a point will be reached where spreading of the written trace occurs because areas adjacent to it are so near the crossover that capacitive effects or local dielectric breakdown are sufficient to make them fade positive. This collector voltage level is known as the upper writing limit, UWL. At some still higher level, so much of the RP curve lies so near the first crossover that the whole screen will spontaneously fade positive. Both these collector voltage levels are shown in figure 5.

Turning now to the consequences of decreasing the collector voltage below OL, we must recall that the upper stable point of the target always occurs at a voltage in the vicinity of the collector voltage, since it is the failure of the collector to collect which cause the abrupt drop in the target "balance sheet" curve of figure 2. Now if the collector is lowered to the vicinity of the first crossover voltage, this will result in a curve as shown in figure 6, and it

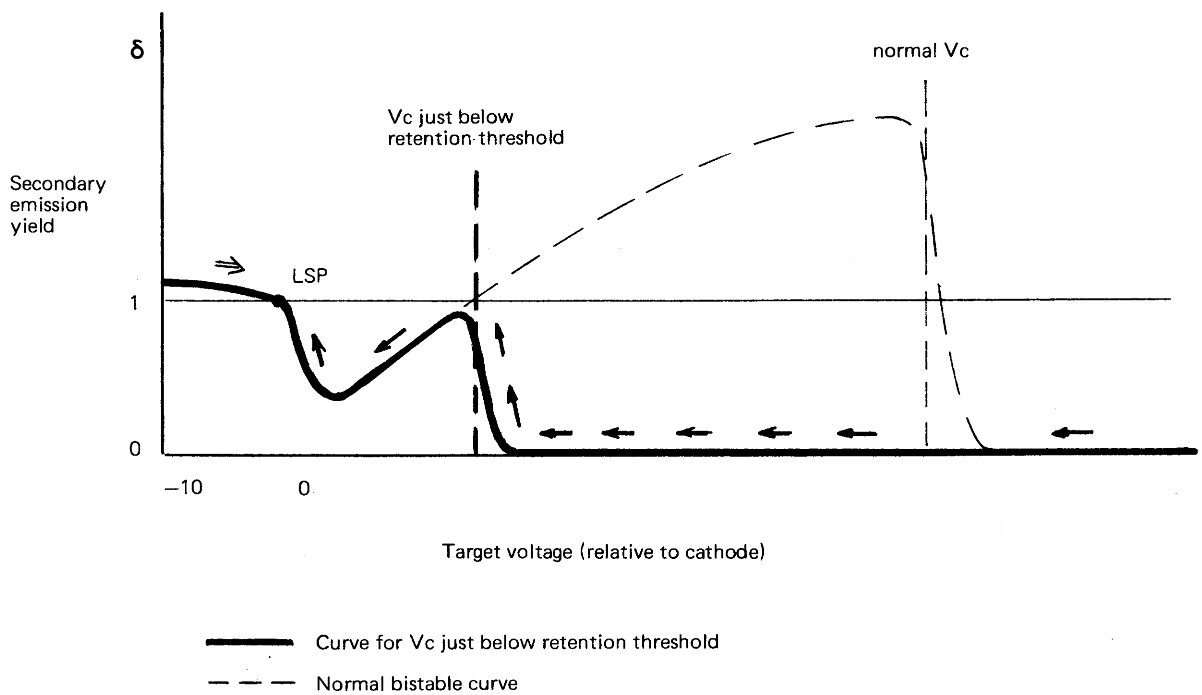


Figure 6

is clear that under these conditions there is only one stable point, the lower stable point. The floodbeam will return all target areas to the lower stable point; written information is no longer retained. This collector voltage is therefore called the retention threshold (RT).

Now we can define the stable range: it is the range of collector operating voltages between retention threshold and fade-positive. And it is this stable range which is affected by the thickness of the target in the manner shown in figure 4. In itself it will not concern us operationally, since we would be unwise to operate the collector near either of these extreme limits. But a large stable range will obviously provide a greater operating margin for the collector voltage. This margin is important to us for several reasons:

i. setting the collector voltage operationally to the centre of this range is a subjective procedure which will yield a certain spread from operator to operator;

ii. in many instances the CRT heater is unregulated, and varying mains voltages can cause performance changes;

iii. storage CRTs are subject to ageing effects which might, if the operating margin is too small, require frequent recalibrations;

iv. even with best manufacturing techniques there is usually some non-uniformity across the target, calling for different optimum collector voltage settings, and in the presence of a large operating margin the choice of a suitable compromise setting is much easier.

For all these reasons we consider a large stable range so important that we sacrifice much contrast to obtain it, as suggested by figure 4.

When contrast was first mentioned as a significant factor in connection with figure 4 you may have been puzzled since it is normally taken for granted in oscilloscopes that unwritten areas of the screen are practically black and the contrast therefore practically infinite. The discussion of the average rest potential will have explained why, on phosphor-target storage tubes, the contrast is on the contrary quite limited. But although figure 4 shows a typical contrast figure of only 3 : 1, some improvement can in fact be expected after a hundred operating hours or so. The reason is that much background light is contributed by those dots which have faded positive, and as these phosphor dots operate continually at full light output they will be the first to age and eventually burn out, leaving the unwritten part of the screen darker. On most tubes the contrast ratio will reach 20 : 1 after about 300 hours.

Chapter 3
OPERATING CHARACTERISTICS OF THE PHOSPHOR-TARGET TUBE

One of the main limitations of a storage tube is its inability to store traces if the beam is moving too fast - if it exceeds the maximum writing speed. The bulk of this chapter will be concerned with the definition of writing speed, what factors influence it and how it can be improved. Then we shall return to the topic of erasing and see in detail how it is done.

In a bistable tube, writing, as we know, is the process of raising the voltage of those points on the target which are scanned by the writing beam above the first crossover despite the continuing attempts of the floodbeam to return them to the rest potential. (Once the critical first crossover level has been passed, the floodbeam will carry them to the written level even without any further contribution from the writing beam.) The effect of the floodbeam is to add a given number of electrons to unit target area in unit time. But this number depends on the secondary emission ratio and is highest where the "balance sheet" curve of figure 2 departs most from the $\delta = 1$ level, trailing off to zero as the first crossover is approached. Since we can neither measure the secondary emission in an actual CRT, nor even be sure from what rest potential the target must be lifted, it is impossible to quantify the demands made on the writing beam if it is to achieve storage.

But the effect of the writing beam itself is also far from straightforward. Consider first the situation of a stationary beam. Even though it is focussed, the spatial distribution of beam intensity follows the normal Gaussian distribution curve shown in figure 7. At the point on the target where it peaks, the beam

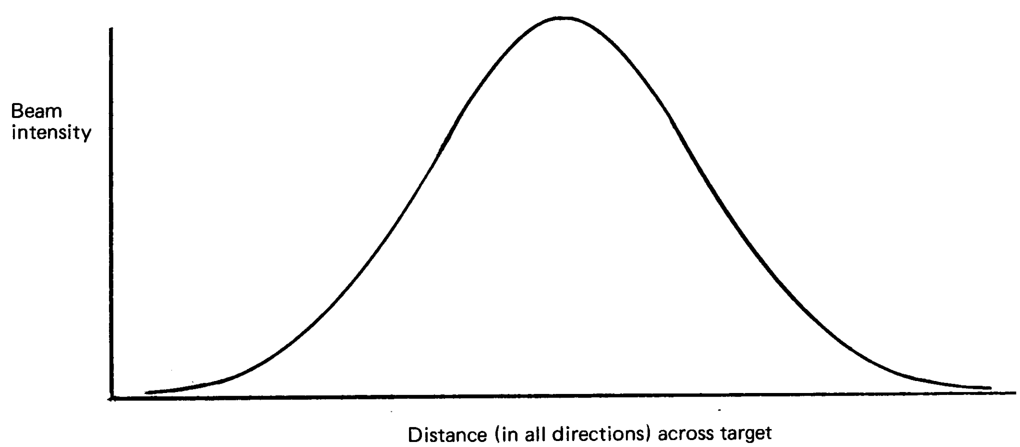


Figure 7

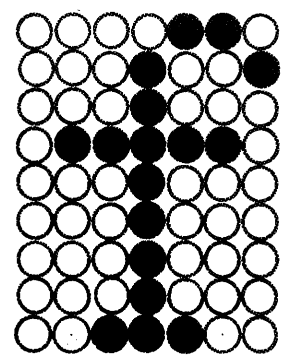
density per unit target area is greatest, hence the number of secondary electrons lost in unit time is highest. If this number exceeds the number gained from the floodbeam action the target will begin to charge up. However, the charging process takes time and relies on the continuing presence of the writing beam if it is to reach a successful conclusion, namely that the target voltage passes the first crossover. With *greater* beam density, the disparity between electron loss due to writing beam and gain due to floodbeam increases and a *shorter* beam dwell time is enough to achieve storage.

Away from the centre of the writing beam, since the beam intensity decreases, the number of electrons lost per unit time by the target will also decrease. As long as it is still greater than the gains made from floodbeam action, the target will still move positive, but it will require a longer beam dwell time to reach a successful conclusion.

Let us review the picture given in the last three paragraphs, and assume for simplicity that the target rest potential is at point B of figure 2. To achieve storage, the requirement is that the centre of the writing beam (where its intensity is greatest) should cause the target to lose more electrons per unit time than it gains from the floodbeam, and that the writing beam should dwell long enough at that spot to cause the resulting positive target drift to reach the first crossover. We can instinctively feel that something like the product of dwell time and beam intensity is significant here, but there is a certain minimum intensity below which no amount of dwell time will achieve storage because the target gains more electrons from the floodbeam than it loses from the writing beam. It would be misleading to try to quantify this complicated situation in a formula, but we will refer to the dwell time-intensity product in this loose sense later in the text.

One last consideration: if we start with the minimum dwell time and beam intensity which will just achieve storage at the beam centre, and then increase either factor, areas away from the centre of the beam will also manage to reach the first crossover. As dwell time or intensity are increased we therefore obtain a stored dot of increasing diameter.

A stationary beam such as we have discussed is typical of information display devices. For instance, a computer readout monitor might display alphanumeric characters, each of which is made up of selected written dots in a 7 x 9 dot matrix. Figure 8 shows an example. If we want to specify the minimum requirement to achieve storage, we generally adjust the beam intensity to the maximum value before defocussing occurs, and then measure and quote the necessary dwell time. This specification is called "dot writing time", and a typical value is 5 µs. You will appreciate that the beam intensity setting is a somewhat subjective adjustment.



Lower-case f in a dot matrix

Figure 8

In oscilloscopes, the beam is normally moving and we must now study this new situation. If a given spot on the target lies in the path of this beam, then as the beam approaches, its intensity will increase in a manner which corresponds to the slopes of the distribution curve. It will reach a peak when the beam is centered on the spot, and then decrease in a similar manner. But whether storage will take place depends on the same considerations which we enumerated previously: whether the maximum beam intensity is great enough and the dwell time long enough. In this situation quantitative analysis is even more futile. Specifications are verified by again selecting the highest beam intensity before defocussing occurs, and increasing the beam velocity until the beam moves so fast that there is insufficient dwell time for storage to occur. This specification is called "writing speed" and is typically, for phosphor-target tubes, 0.1 cm/µs.*

* See appendix A for more details of how writing speed can be measured.

For the moving beam again we can say that if the dwell time is made longer by moving the beam more slowly, areas to the side of the central path of the beam will receive a sufficient dwell time-intensity product to become written. As the beam is slowed down we therefore get a progressively wider stored trace.

At the end of this discussion we hope that you will have an instinctive feeling for the principal factors affecting dot writing time and writing speed. We will now consider in what way the writing speed, and also the brightness and contrast of the stored display, are affected by the collector operating voltage. Those interested only in basic principles should continue on page 15, para 2.

The published specifications assume that the collector operating level (OL) is set normally, let us say to the centre of the stable range in figure 5. As we increase the collector voltage, leakage increases, the average rest potential increases, and consequently the target rests nearer to the first crossover. This means that a lesser dwell time-intensity product will suffice to achieve writing; holding the intensity constant we can increase the beam velocity and still store. The writing speed specification has been improved. But the improvement is not spectacular and the change of collector voltage has other side effects which are more important and which we will look at shortly.

If the collector voltage is decreased the opposite effect takes place. The ARP drops and the writing beam must linger longer to achieve writing. In fact, for a specified beam velocity, if the collector voltage is decreased sufficiently, a level will be reached at which the dwell time-intensity product is no longer enough to achieve writing. This collector voltage limit is called "writing threshold" (WT). Unlike all other collector voltage limits (FP,UWL,RT), this one is not a limit due to basic constructional features of the tube; it is dependent on the beam velocity which we specified.

For such a specified velocity, the writing threshold represents the lower limit of the collector voltage operating margin to which we referred at the foot of page 9. Neither can we operate successfully above the upper writing limit since trace spreading occurs. This defines the collector operating range and is shown in figure 9 on the next page. A writing speed specification is only realistic if it puts the writing threshold in approximately the position shown in figure 9, giving a usefully large operating range.

Now to the other effects of departing from the normal collector operating level. We said that as the collector voltage is raised, the ARP goes up. Therefore the light level of the unwritten area will increase. But also, since the upper stable point follows the collector voltage up, the brightness of the written trace increases. The converse is true when the collector voltage is decreased. We must now consider whether, on balance, these effects produce traces with more or less contrast, and whether, if we have a choice, it is more important to get the maximum possible contrast or the maximum possible absolute light output. (Contrast, as defined here, means the brightness ratio of written to unwritten areas.)

The simplest way to study this matter is by way of a numerical example. The figures in table 1, page 15, have been chosen for convenient mental arithmetic, but they are typical for the actual performance of phosphor-target tubes. The set of figures headed "in total darkness" shows the actual light output of the CRT. As you see, the brightness of the unwritten areas increases more rapidly with increased collector voltage than the brightness of the written trace, so the contrast gets poorer. In the next two sets of figures, 6 and 100 candela/m^2 respectively have been added to the CRT light output figures to show what happens when these amounts of ambient light are reflected from the CRT. The contrast

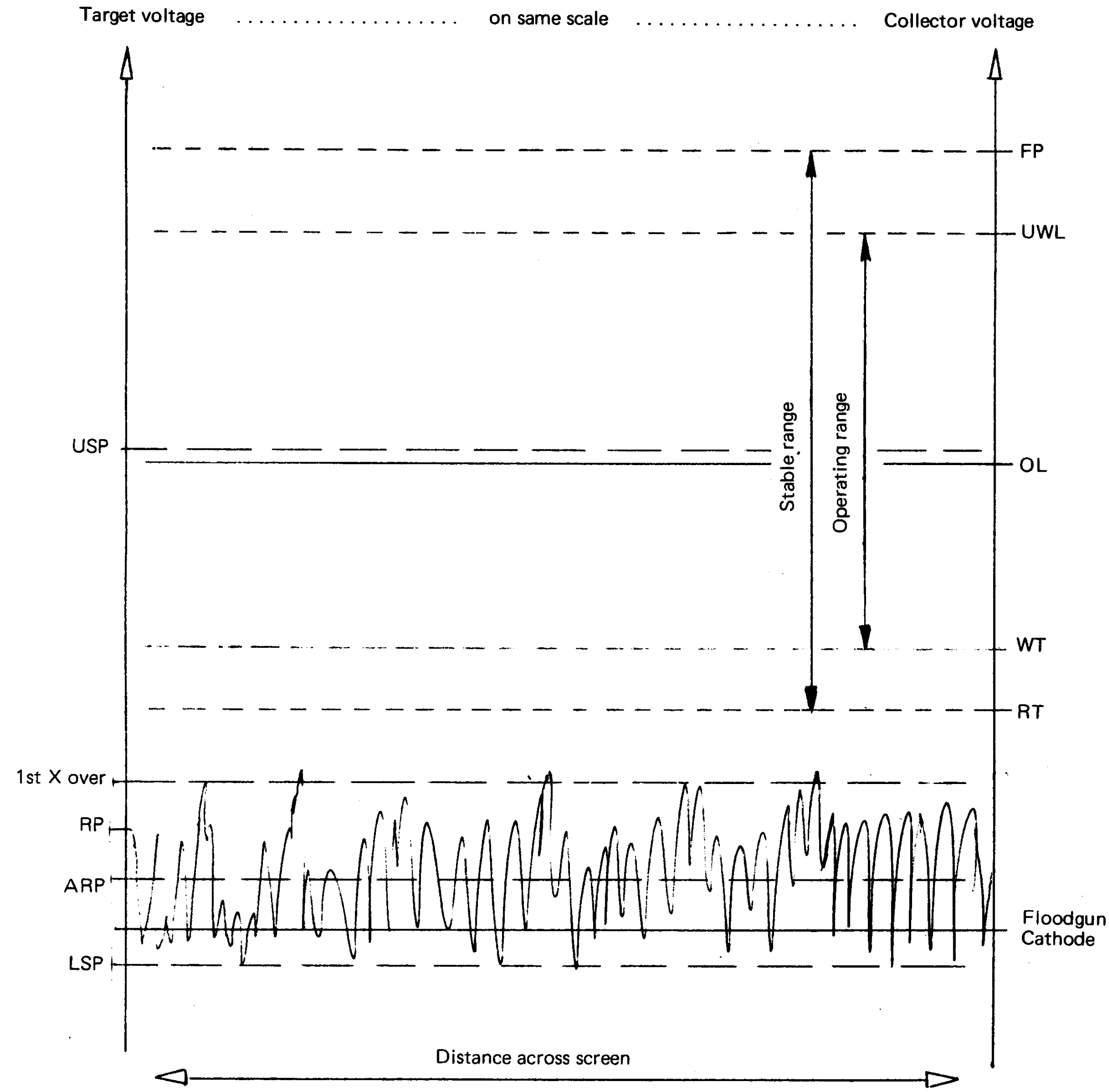


Figure 9

USP upper stable point
RP rest potential
ARP average rest potential
LSP lower stable point

FP fade-positive level
UWL upper writing limit
OL operating level
WT writing threshold
RT retention threshold

decreases, but it decreases least if the CRT light output is high, because the ambient light cannot then swamp the tube light as easily.

Which is preferable? To see the trace at all, we need contrast - and the more we have, the better. But it turns out that for different ambient lighting conditions different collector voltages will give best contrast, so no hard-and-fast rule is possible. Photography, of course, takes place in total darkness as the camera shuts out all ambient light, and would therefore benefit from a low collector voltage.

Changes in collector voltage, as we have seen, affect writing speed, absolute light output and contrast. They also affect tube life. We can summarize

Collector Voltage	in total darkness			with 6 cd/m² ambient light			with 100 cd/m² ambient light		
	written trace cd/m²	unwritten areas cd/m²	Contrast	written trace cd/m²	unwritten areas cd/m²	Contrast	written trace cd/m²	unwritten areas cd/m²	Contrast
100 V	24	4	6 : 1	30	10	3.0 : 1	124	104	1.2 : 1
140 V	50	10	5 : 1	56	16	3.5 : 1	150	110	1.4 : 1
180 V	80	20	4 : 1	86	26	3.3 : 1	180	120	1.5 : 1

Table 1

by saying that *increased* collector voltage will *increase* writing speed and absolute light output, and will *decrease* contrast and tube life expectancy - and vice versa. If you wish to favour one of these factors you can adjust the collector accordingly. But remember that whenever you depart from the normal OL voltage in either direction you are moving away from the centre of the operating range which we tried to make large to give long trouble-free periods between recalibrations.

It has already been said that the improvement in writing speed which can be achieved with higher collector voltage is only marginal. There are two other techniques, however, which are capable of increasing the writing speed by a factor of 10 or more. These will now be discussed.

To understand how they work, we must first visualize what happens when the beam moves faster than the maximum writing speed and fails to store. In such a case, the dwell time-intensity product is not enough to raise the target voltage above the first crossover, and as soon as the writing beam has passed, the floodbeam begins the destructive process of moving the target back to the rest potential. Nevertheless, the writing beam did raise the target above its rest potential. The secret of the two techniques is to make use of this charge pattern before the floodbeam can destroy it.

The first technique is useful on repetitive sweeps, and is called the "integrate" mode. By stopping the floodbeam altogether, the destructive process can be halted. Any charges laid down by the writing beam will remain on the target, if not indefinitely, at any rate for minutes. If the signal is repetitive, successive beam passages will scan the same target areas and will add to the charge pattern. This is a cumulative process which must eventually lead to the point where the written target areas cross the first crossover. If the floodbeam is then restored it will move these areas to the written state and the trace can be seen.

For a given beam velocity it will take a given number of beam passages to build up this charge. We have already seen that these factors are not amenable to numerical analysis. In practice it is a matter of trial and error to find out how long the integrate mode has to be applied before a trace gets stored. There is unfortunately no way of knowing, while the mode operates, whether storage will be achieved, since without floodbeam we cannot see a stored trace. When integration *is* stopped, and by the time we have inspected the display and perhaps decided we didn't integrate quite long enough, the portions of the trace which failed to write will have been moved back to rest potential. Any second attempt at integration will therefore be starting again from square one.

But imagine now that we wish to store a single transient, some unique event, at a speed exceeding the normal writing speed. Since we cannot repeat the event, the integration technique is useless. Yet even that one sweep did leave *some* charge behind. The second technique, called "enhance" mode, again attempts to salvage the situation. A positive pulse is applied to the collector, of such amplitude that capacitive coupling will lift the whole target by just the amount needed to bring the written area above the first crossover. Figure 10 makes this clear. The floodbeam will then immediately set to work separating the written and unwritten potential further. We maintain the positive pulse long enough to ensure that at its end the written areas do not drop back below the first crossover. The curvatures recall the

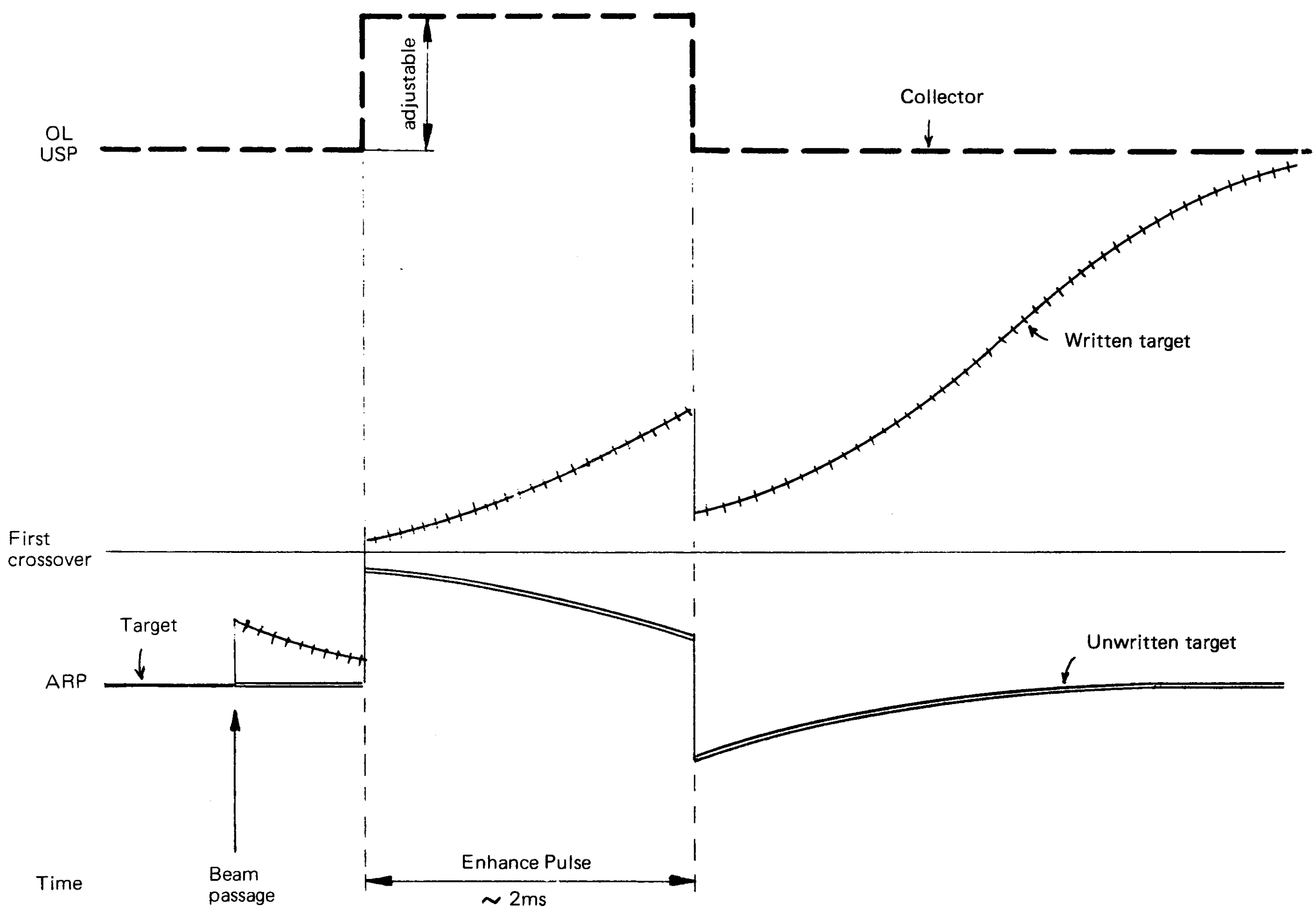


Figure 10

fact that the floodbeam is most effective at voltages where the secondary emission ratio departs most from unity, and floodbeam action slows down as a δ of 1 is approached.

Figure 10 also makes the point that immediately after the beam passage the floodbeam starts removing the laid-down charge. The enhance pulse must therefore be applied as soon as possible - in other words, as soon as the sweep is completed. But on slow sweep speeds, say 5 μs/div or slower, even this may be too late. The enhance pulse will only rescue the later portions of the trace while those near the beginning of the sweep will already have been partly or wholly destroyed by the floodbeam.

Nevertheless, if enhancing were that simple one would have to ask why the technique is not made a permanent feature of fast-sweep storage, giving at a stroke a tenfold improvement in writing speed. But figure 10 is oversimplified in an important respect. The average rest potential is a fictitious level, and the actual target rests over a broad range of levels. When the writing beam adds a charge to this, the written areas, too, will end up over a broad range of levels. There will therefore be no one correct amplitude of enhance pulse which can raise all the written, and none of the unwritten, areas above the first crossover.

In fact, the smaller the charge left behind by the writing beam, the more likely it will be that even with optimum enhance pulse amplitude some written parts will remain unstored, and some unwritten parts will become stored. The exact amplitude then becomes a matter of experimentation until the user subjectively feels that he has achieved the best compromise, making for clearest visibility.

When we said that the enhance technique allowed a tenfold increase in writing speed, this was meant as a guide line only. In any given situation it depends on the kind of compromise the user still finds acceptable. (Luckily, the interpretative powers of eye and brain far exceed that of any computer.) By contrast, the integrate technique really has no upper speed limit; it just depends on whether you can afford enough time to integrate long enough to accumulate enough charges to reach the first crossover. In cases where the signal repetition rate is 1 Hz or so and the required sweep speed very fast, this can become a question of operator patience.

The next topic in this section is the erase process used in phosphor-target tubes. Basically, the erase pulse is a negative pulse applied to the collector, which capacitively moves the whole target negative. The aim is to move the written portions from the upper stable point to below the first crossover, after which the floodbeam can complete the erasure. But there are two problems. The first arises from the fact that sooner or later we will have to return the collector back to its normal operating level, and if we do this too fast we will capacitively move the target back up. This is true even if the negative pulse was long enough to give the floodbeam a chance to stabilize the target at the rest potential, because the voltage separating rest potential and first crossover is much smaller than that between first crossover and operating level through which the collector must move. The solution is to make the trailing edge of the erase pulse so slow than any capacitive coupling effects on the target can be countered by floodbeam action.

The other problem with erasing is that when small written areas are surrounded by large unwritten areas, and the target is capacitively lowered, the unwritten areas will move to a potential which is so greatly negative that the floodbeam is totally repelled from the target. The small written areas are in effect then shielded from the floodbeam and not returned to rest potential. At the end of the erase pulse they can easily become written again. Since small written areas amidst large unwritten ones are typical in normal storage tube use, this cannot be tolerated. Shielding effects of this kind can be avoided if the *whole* target is first written and then the erase pulse applied. So the erase pulse proper is preceded by a so-called fade-positive pulse large enough to lift the unwritten areas above the first crossover (ΔV in figure 11). Figure 11 shows the complete sequence.

It sometimes happens that after the prolonged stored display of a trace it resists erasure. During such periods the charge pattern becomes buried deep inside the target, rather than just on its surface. This is *not* to be confused with a phosphor burn-in in a conventional tube, where the phosphor is permanently damaged due to excessive heat dissipation during the passage of an intense writing beam.

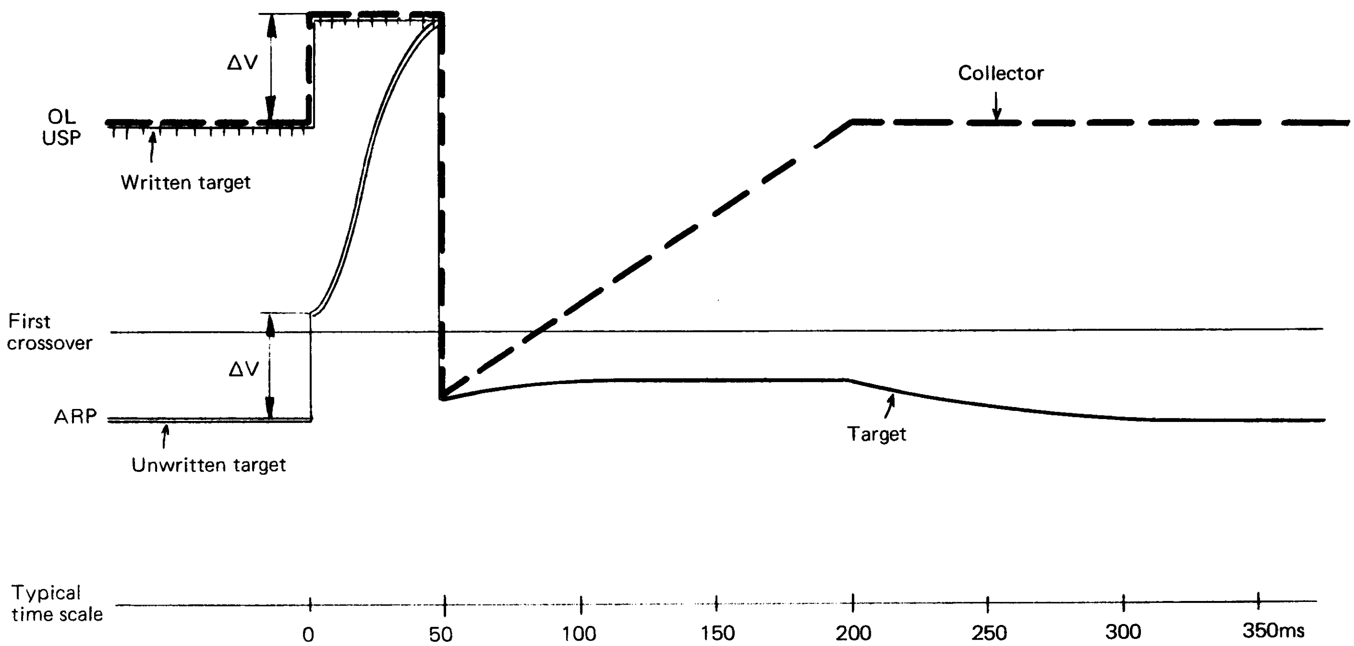


Figure 11

But though the phosphor is undamaged, unless the buried charge can be removed, an irritating residual image will remain. In the first place, to avoid buried charges, most instruction manuals give a time limit for storage, typically 1 hour. But if a buried charge does appear, and cannot be cleared by repeated erasure, the whole target should be written (faded positive) and left in this state for about 10 minutes, after which erasure should be successful.

The storage time limit just mentioned serves another purpose. As we said on page 10, dots which sit at fade-positive for prolonged periods will obviously be the first ones to burn out. Parts of the screen which are frequently written will become dimmer and the tube will eventually have to be retired. One should, in the first instance, avoid displaying the same waveform in the same position day after day. Secondly, it would be prudent for this reason (as well as to avoid buried charges) to limit viewing time.

An alternative solution is to reduce the floodbeam. This will result in a dimmer display and reduce the ageing process and the charge-burying effect, but may still be sufficiently bright to be useful. Some oscilloscopes have a storage brightness control with which the floodbeam can be adjusted between 100% and 10%. (At the lower end, the floodbeam is so weak that it allows the target to accumulate charges from successive sweeps as in the "integrate" mode, provided the sweeps follow one another at intervals not much longer than 1 ms.) On information-display monitors, viewing at full brightness is often limited to 90 seconds, after which the display goes into a low-brightness standby condition until the operator requests another viewing period.

This completes our description of the storage characteristics of the phosphor-target tube. But a word is in order about using it in the non-store mode. To stop the storage effect we simply have to set the collector below retention threshold. The tube then behaves like a conventional CRT. No matter how high the writing beam charges the target, in a matter of milliseconds - before the eye can see - the floodbeam returns it to rest potential. With the collector below RT, leakage will be very small and the average rest potential so low that the screen is completely black.

Chapter 4
BISTABLE STORAGE OSCILLOSCOPE FEATURES

It cannot be the purpose of this text to list in detail all the features of bistable oscilloscopes. Users of such instruments will have a manual with full details, and intending purchasers will mainly want to study specification sheets. A specification comparison chart of Tektronix storage scopes is given in appendix B. In this chapter we shall briefly look at some special techniques offered by many - but not all - bistable instruments. These are split-screen operation, write-through, locate mode, and automatic erasure.

Split-screen operation is a technique whereby the storage target back-plate, the collector, is split into two sections, covering the upper and the lower screen halves respectively. This permits the application of independent enhance and erase pulses and independent operation at non-store level. The technique is extremely useful for comparative work, where a trace can be stored in one half, and repeatedly stored and erased, or displayed without storage, in the other half. Split-screen construction is only practical in phosphor-target tubes.

The write-through technique is also useful for comparative work. In this mode of operation the beam intensity is reduced to the level where the dwell time-intensity product is insufficient to achieve storage, but not to the level where the writing beam cannot be seen on the screen. The margin between these two points depends greatly on the average rest potential. If it is too close to the first crossover, the slightest amount of writing beam will cause storage, and write-through will be tricky (if not impossible) to achieve. A very sharply focussed beam will also tend to store more readily, and it is sometimes useful to defocus the beam slightly or to wobble or dither it over a narrow area in order to achieve write-through conditions. Write-through is useful to position a trace to a desired location within an already stored display before turning on the full beam to add this new trace. In computer-terminal applications write-through is often used to provide a cursor; this is in fact a case where instrument circuitry automatically selects the correct beam intensity and adds spot dithering. In most oscilloscopes the user must achieve the write-through condition by judicious manual adjustment of the beam intensity.

Another helpful arrangement for the purpose of positioning the trace before storing it is the "locate" zone. This is a narrow vertical strip at the extreme left of the CRT which has no storage target. When the LOCATE button is pushed the sweep is disconnected and the beam appears in the locate zone where it can be positioned vertically to the desired level.

Next we turn to automatic erasure - auto erase for short. This is an extremely useful feature of bistable oscilloscopes. Usually a single sweep is allowed to be recorded, after which further sweeps are prevented and a user-selectable viewtime period starts. This is variable from the front panel between about one half and fifteen seconds. At the end of the viewtime erasure is initiated and after that a new sweep is allowed. The applications for such a system are too numerous to list and must be left to the reader's imagination.

It might be useful here to give the basic timing diagram of the scheme most frequently adopted. Figure 12 shows how, in addition to the conventional sweep holdoff which gives the sweep circuit time to reset, a lockout is introduced which prevents the recognition of new triggers until the viewtime and erasure are completed.

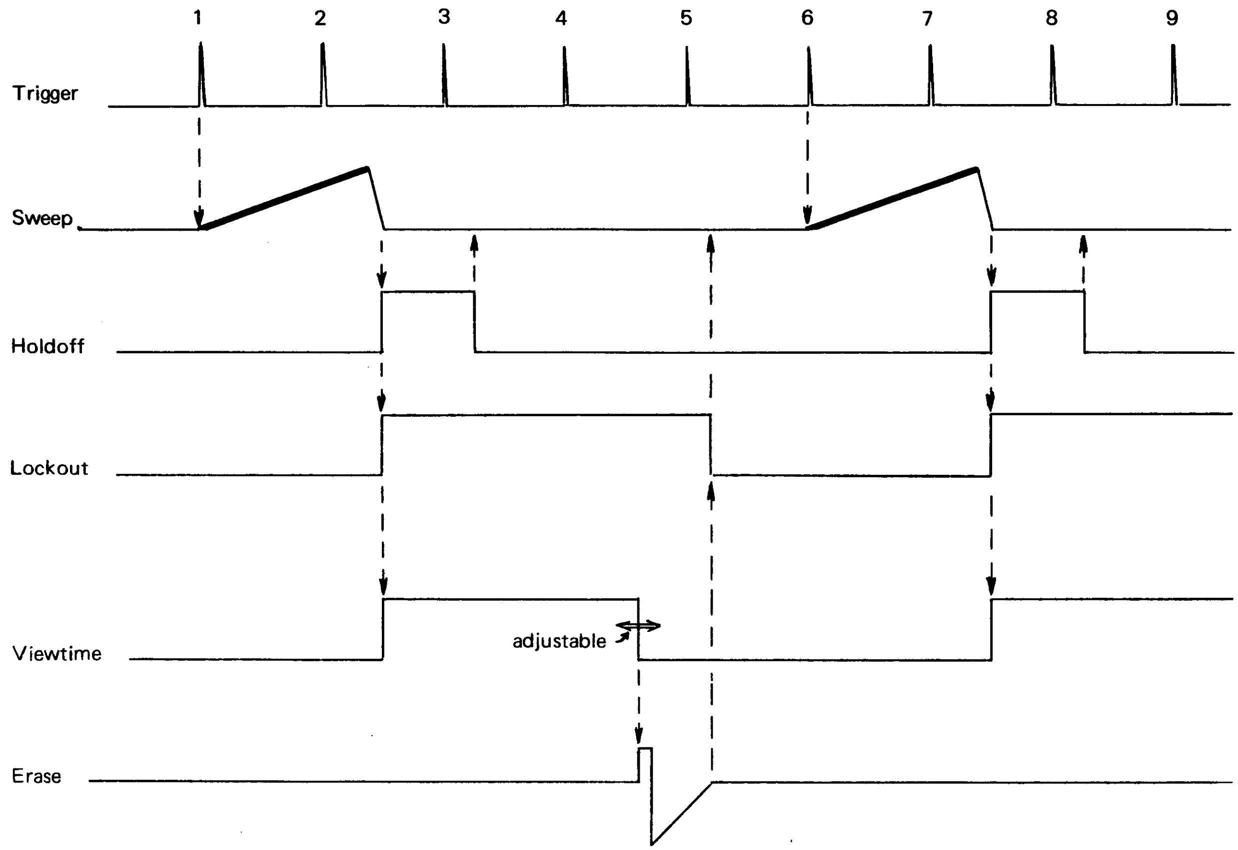


Figure 12

Trigger 1 starts sweep
Trigger 2 ignored because sweep in progress
Trigger 3 ignored because conventional sweep holdoff operates
Triggers 4, 5 ignored because viewtime/erase cycle in progress
Trigger 6 starts next sweep

Another method used occasionally is to let the sweep circuits continue to function but to blank the CRT beam during the viewtime and erase periods. Unblanking then occurs at the beginning of the next full sweep after erasure is completed. The advantage is that the timebase circuits continue to provide sweep sawtooth and sweep gate outputs during the viewtime, with which ancillary equipment could be driven. But at very slow sweep speeds this method may entail long additional waiting periods if a sweep happens to be in progress when the viewtime/erase period ends.

Several other auto erase schemes are in use in different instruments, most of them (like the ones described above) permitting only one sweep to be recorded at a time. But some instruments allow the recording of further sweeps during the viewtime, and these auto erase circuits are often call "periodic erase". If the periodic erase is interlocked with the sweep so that neither can start until the other is completed, then on slow sweeps it is still possible, by a suitable adjustment of the viewtime, to set up a "single-sweep followed by erase" sequence.

Chapter 5

THE BISTABLE TRANSMISSION TUBE

While the chief advantages of the phosphor-target tubes are their robustness and low cost, their brightness leaves much to be desired. The transmission tube principle offers the exact opposite: a very bright display at the expense of cost and robustness. But in recent years the last two factors have been brought under control, and transmission tubes are a practical proposition for many applications.

In these tubes, the target is not at the CRT faceplate but further back in the form of a mesh. The detailed construction is shown in figure 13. A metal mesh is suspended some distance away from the faceplate, with a dielectric deposit facing the writing and flood guns. The mesh is designed with a certain pitch and a certain ratio of openings to solid matter known as the transmission factor, which will allow the passage of the floodbeam under certain conditions. Floodbeam electrons which do pass find themselves accelerated towards a conventional phosphor screen operated at about +7 kV and will hit it with corresponding energy which produces the bright display.

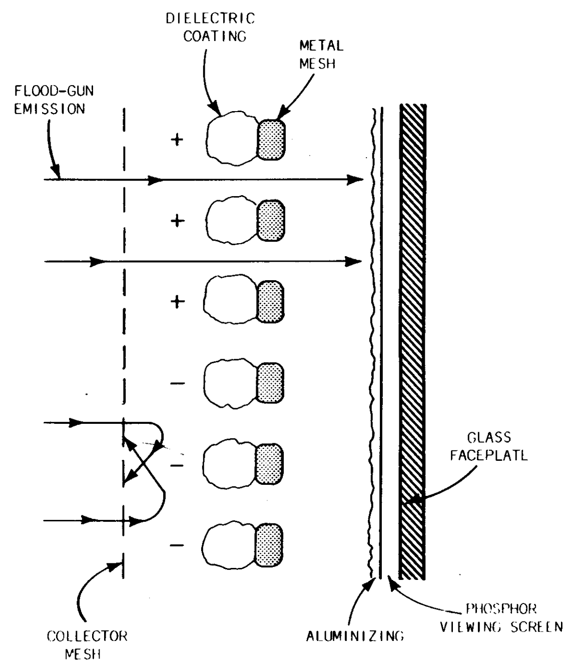


Figure 13

The target still consists of a dielectric chosen for its good secondary emission properties (but is not now made of phosphor). It still obeys the laws discussed in the first chapter and operates along the "balance sheet" curve in figure 2. Under the influence of the floodbeam it will rest at the upper or lower stable point. Since it is deposited on a separate mesh operating at about 0 V (floodgun cathode potential) rather than on the collector, there will be virtually no leakage through the target material when it is unwritten, and therefore the average rest potential is at the lower stable point.

In the bistable transmission tube, the transmission factor is chosen so that when the target is at the lower stable point practically all of the floodbeam is repelled, while the more positive potential of the upper stable point will allow it to pass through. The target mesh acts like the grid of a valve in controlling the flow of the beam towards the anode, except that we have the somewhat difficult constructional task of making sure that the floodbeam passing through the written target regions remains collimated until it reaches the phosphor and that there are no electron-optical parallax errors.

It might be useful to look at the brightness curve of this tube (figure 14). As with any valve, beam cutoff is a gradual process, and the curve relating target voltage to brightness (which is proportional to floodbeam passage) has the typical shape of a valve transfer curve, but as the target only rests at LSP and USP we are still dealing with a bistable storage tube.

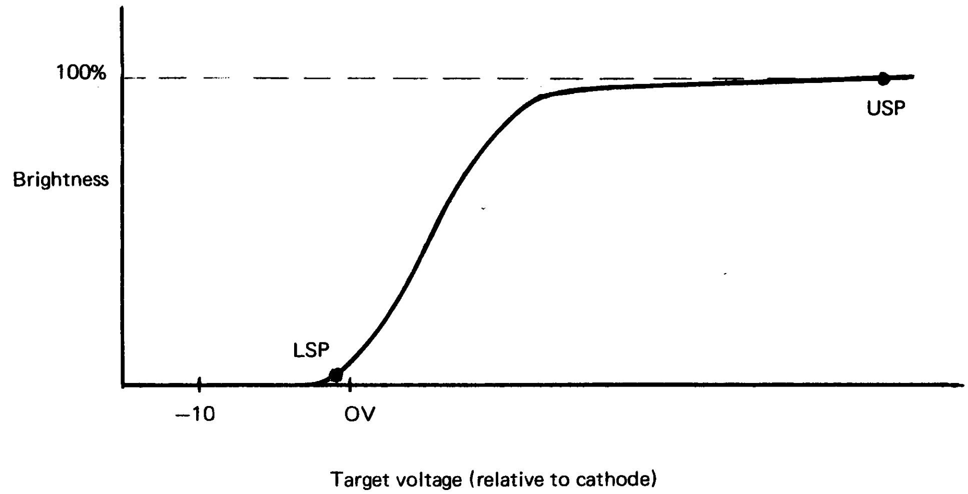


Figure 14

As shown in figure 13, a second mesh suspended near the target acts as a collector. To minimize moiré effects, its pitch and orientation must be carefully chosen. It is the presence in these tubes of two suspended meshes of intricate design which largely accounts for their cost and delicacy, and it also explains why split-screen operation is not a practical proposition in transmission tubes.

In other respects the tubes operate much like phosphor-target bistables, with the exception that erase and enhance pulses can now be applied to the target support mesh, leaving the collector undisturbed.

The writing speed and other features of an oscilloscope using this kind of bistable tube would also be largely unchanged and need not be discussed any further.

Chapter 6
THE HALFTONE TUBE AND VARIABLE PERSISTENCE

In the previous chapter we stated that in transmission tubes the effect of the target on the floodbeam could be compared with that of a grid in a valve. By altering the spacing of the target mesh - the transmission factor - it is possible to construct a different kind of transmission tube in which, even when the target rests at the lower stable point, most of the floodbeam can still pass through it and reach the phosphor. It then takes a more negative target potential to reach cutoff and the brightness curve looks as in figure 15.

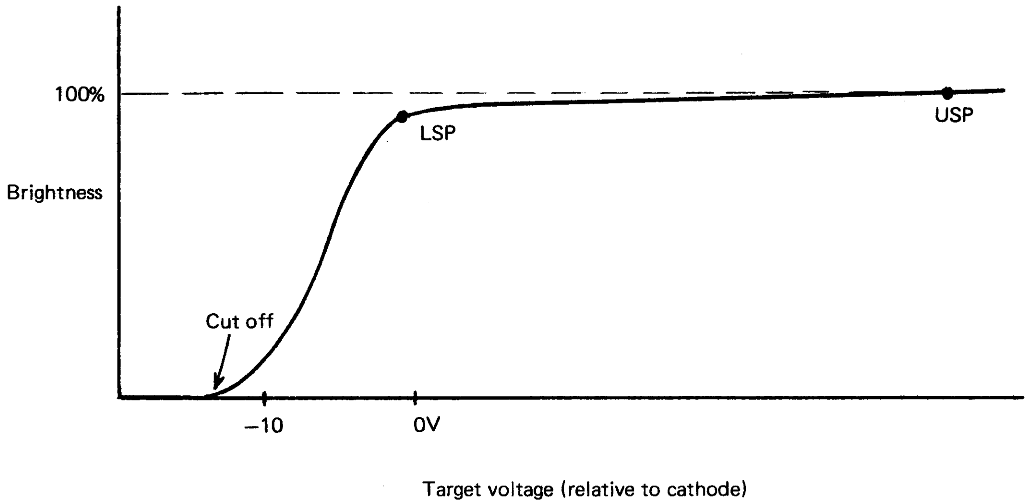


Figure 15

It would obviously be pointless to operate such a tube in the normal bistable fashion since the light output from written and unwritten areas is virtually the same and the contrast therefore extremely poor. These tubes use in fact a different mechanism. To understand it, you must recall the considerations which led us to draw the different-sized arrows in figure 2. If the floating target sits anywhere above the lower stable point, the floodbeam will quickly shift it towards one of the stable states. But if it is more negative than the lower stable state the floodbeam will not land on it and it will drift towards the LSP very slowly - in a matter of minutes - as a result of positive ion landings. If we could therefore lower the target voltage to the cutoff point, we would have a black screen in the "ready-to-write" state, and within the next few minutes the passage of a writing beam with its high secondary emission ratio could lift the written target areas above the cutoff point and result in a visible display.

This method offers two characteristics which may be advantageous. First, different writing beam dwell time-intensity products will leave different amounts of charge behind, and if these charges lift the target partially up the slope of the transfer curve they will give rise to different amounts of brightness, giving us a storage tube with halftone capability. (Halftone in this context means intermediate degrees of intensity between minimum and maximum light output.) Secondly, since the writing beam does not have to lift the target above the first crossover to achieve a stored display, since in fact any amount of charge which lifts the target above cutoff should give some sort of visible trace, greater writing speed can be achieved. A typical figure would be 5 cm/μs. (Appendix A explains how to measure the writing speed.)

Against these advantages we have to set the fact that within 10 minutes the unwritten background as well as the trace will fade up to LSP, obliterating the stored display. Even during this time the process of fading up is of course a continuous one, and a trace only lightly written may disappear into the background before the LSP is reached. This is particularly true because the background of transmission tubes tends to be non-uniformly lit in spite of the most careful manufacturing techniques and will therefore mask the presence of faint traces. One can think of the trace as a signal, often a weak one, seen against a background noise level, and during the fading-up process the signal-to-noise ratio becomes poorer until it is too small to be usable.

The question must have arisen in your mind how the target can be lowered to the cutoff point. This is achieved by applying a so-called "prep pulse" to the target support mesh after the target has been erased and rests at LSP. The prep pulse is a positive pulse as shown in figure 16. The target surface is capacitively moved by the same amount, but immediately the floodbeam will go to work shifting it back towards the lower stable point. After allowing time for this action, the prep pulse is brought to an end, and its negative-going transition is again capacitively coupled to the target surface. The prep pulse can obviously be made of such an amplitude that the negative transition will just drop the target to the cutoff point from where, as we know, it will return slowly.

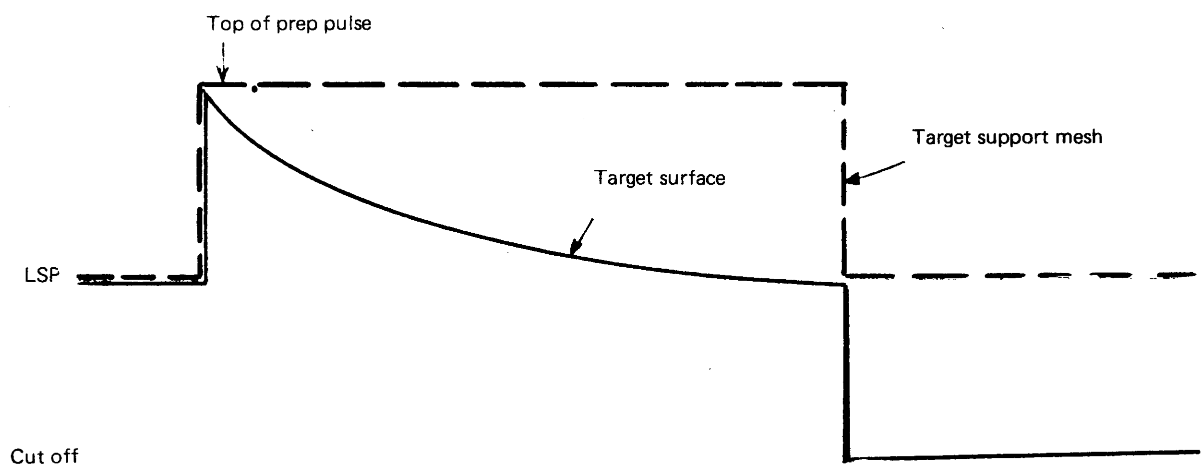


Figure 16

The study of the prep pulse leads us directly to a discussion of the erase pulse sequence in halftone tubes. The complete pulse train is shown in figure 17. For the usual reason - to avoid shielding effects - the whole target is first written by a fade-positive pulse. Then the erase pulse proper is applied, after which the target is at the lower stable point where the CRT screen will still be brightly lit. The sequence ends with a prep pulse at the end of which the target drops to the cutoff level and is "ready-to-write". Cutoff is generally about -12 V. The collector operating level (and hence the upper stable point) in these tubes is around +150 V, just as in phosphor-target tubes.

A word is in order about operating these tubes in the non-store mode. Unlike bistable tubes they emit the full light level when the target is at the lower stable point and for non-store conditions, where we want a dark screen, it is therefore not sufficient to operate the target monostably at LSP. Instead, the floodbeam has to be cut off and this is usually done by raising the floodgun cathode voltage above that of the floodgun anode. (The floodgun anode has not previously been mentioned since this text discusses principles rather than details. In fact, all storage CRTs have floodgun anodes which control the emission of flood electrons, as well as several collimating electrodes, all normally operating at carefully chosen positive voltages with respect to the cathode.)

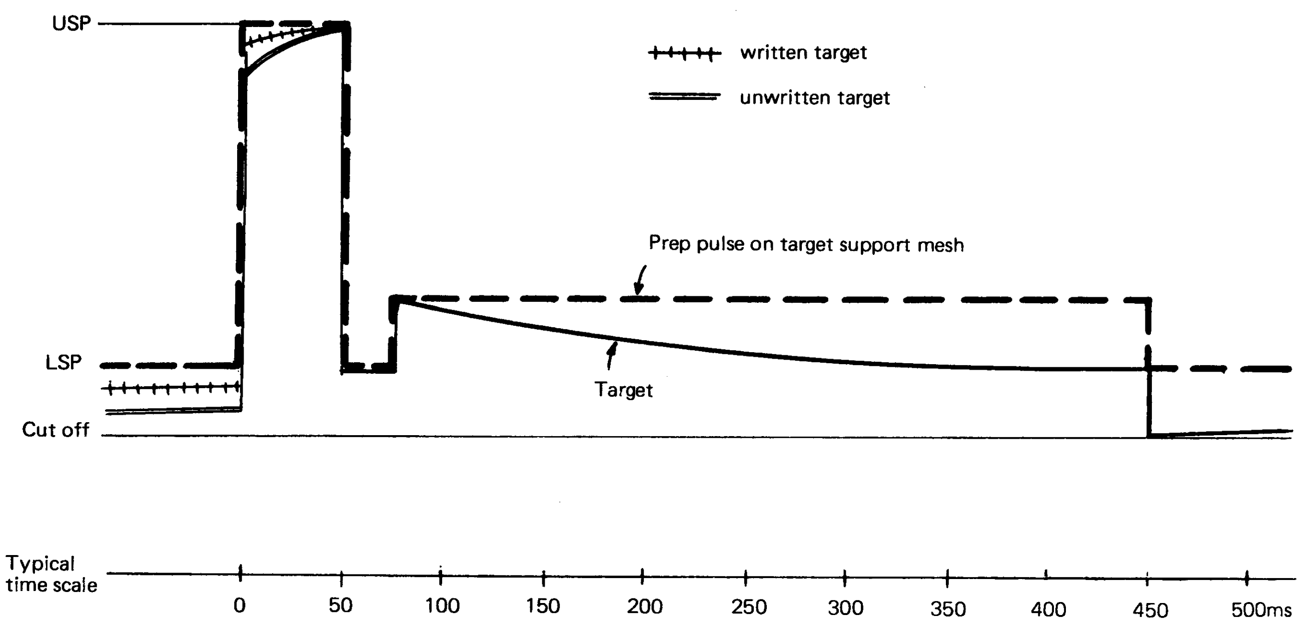


Figure 17

Two more topics need to be discussed in this chapter. The main disadvantage of this kind of tube is the short viewtime of under 10 minutes, and we will first describe a technique known as the "save" mode which allows longer viewtime. Then there is a second technique which makes a virtue of short viewtimes by making them variable from the front panel. This is known as "variable persistence" operation.

The 10-minute limit is, as we said, given by the rate at which ions land on the target and charge it in a positive direction. If the flow of ions could be reduced, this process would take longer. In the "save" technique we do this by reducing the amount of floodbeam. As it happens, we periodically turn if off (at a rate too fast for the eye to see) rather than reducing its intensity, but the effect is the same: the display gets dimmer. And to the extent that it gets dimmer, the number of ion landings is reduced and the viewtime is extended. A typical on/off ratio might be 1/6th, giving 1/6th of full brightness and extending the viewtime to an hour. Often a further operating mode is offered where the floodgun is turned off altogether. The display then disappears, and with no ions reaching the target (and no leakage effects because its support structure is at 0 V), the charge pattern can be stored for days. It will even be held if the mains power is interrupted, since the target support structure voltage remains unchanged on these occasions.

The "save" mode therefore offers the operator a means of postponing his viewing indefinitely as well as a choice of how he then wants to use up the available storage time-brightness product. He could, for example, run the tube at one-third brightness for 15 minutes, which would use up half the storage time, and then revert to full brightness for another 5 minutes' worth of viewing.

Finally, the "variable persistence" technique: this is an operating mode in which a sequence of very short prep pulses are applied which have the effect of partially erasing the stored information and also preventing the background from fading up. Figure 18 will make this clear.

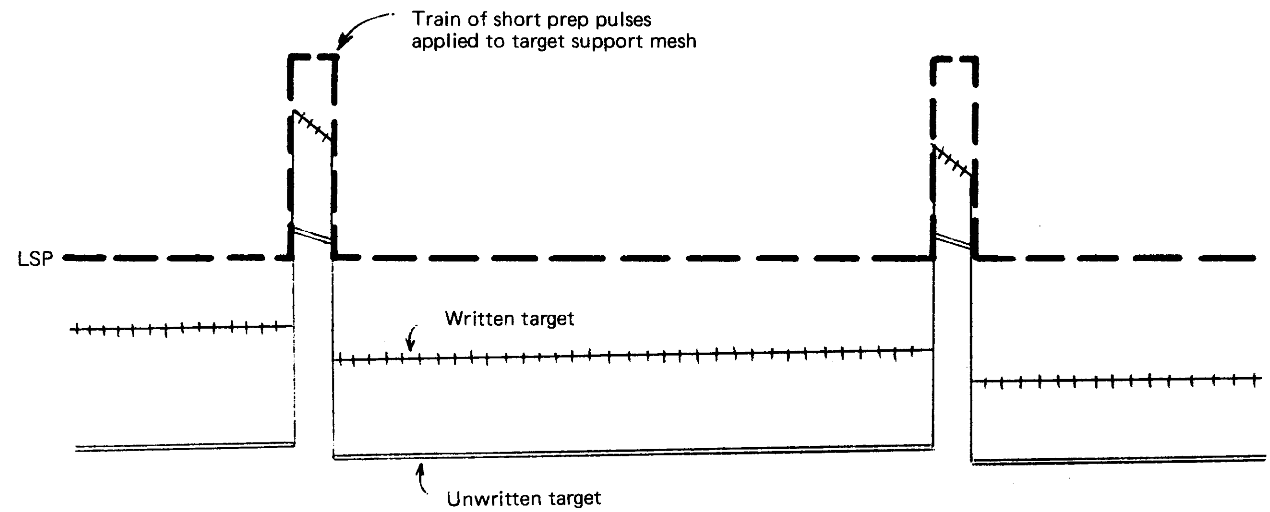


Figure 18

During each short prep pulse the target surface is lifted above the lower stable point and the floodbeam will start returning it to LSP. As always, it is more effective at voltages departing further from $\delta = 1$, and it will therefore return the written trace faster towards LSP than the unwritten background. At the end of the pulse the background is virtually at cutoff again, and the trace is a little closer to cutoff than at the end of the previous pulse. In due course the trace will reach cutoff. The effect is a gradual fading out of the written information and the maintenance of a uniform background rest potential.

As the name implies, the speed of this fading-out process can be varied from the front panel. The pulse train repetition rate is typically 100 Hz (so that the eye cannot perceive any flicker), and for slow erasure (long persistence) the pulses are made a few microseconds wide. To speed up the erase process, the pulse width is increased. Extremely short persistence can be obtained if the pulses are 1 ms wide or more.

During prep pulses, the target sits at or above the lower stable point, which means that the tube will emit the full light output. Therefore, as the pulse width is increased to obtain shorter persistence, the screen will emit this full light level during a larger proportion of time, and will appear brighter. This effect is typical and unavoidable in all variable persistence systems.

There are two main applications for variable persistence. One is the reduction of flicker on repetitive signals displayed at sweep repetition rates between about 40 Hz and 4 Hz, and the other is the continual updating of information laid down by even slower sweeps. The reduction of flicker by introducing persistence is of course bought at the cost of less rapid display response to changing conditions, and the user has it in his hand to select a suitable compromise. Together with the persistence he will have to adjust the beam intensity so that if, for instance, the persistence lasts for about 10 full sweeps the accumulation of 10 stored charges on the target does not cause undue spreading of the trace. In this respect the halftone tube acts like an integrator and the integrating properties can in fact be used to eliminate unwanted random deviations on a repetitive signal by adjusting persistence and beam intensity in the manner just described. This is analogous to improving the signal-to-noise ratio, though the results tend to be uneven due to the uneven sensitivity of the target area mentioned earlier and the relatively poor focus of such multiple-trace displays.

The other application does not involve a compromise because once the sweep runs so slowly that the eye perceives it as a travelling dot the persistence can be adjusted in such a way that just as the beam is about to write a given part of the screen the stored display from the previous beam traverse is about to fade out. In this way the screen will, at all times, display updated information across its whole width (though the information will always be most recent just behind the beam and will be one sweep old just ahead of it). Examples of slow-moving waveforms are electrocardiograms and reconstituted displays such as those from sampling or spectrum analyzer equipment.

Variable persistence is such a useful method of operating halftone tubes that it is found in practically all halftone instruments, and these instruments are in fact often known as "variable persistence oscilloscopes". The name is apt for another reason. The design of both CRT and instrument is generally optimized for fast writing rate at the expense of overall target uniformity and halftone capability, and one should not expect to be able to distinguish more than three halftone steps between full brightness and black. (At the time of going to press, Tektronix do not make any instruments optimized for halftone performance.)

It should perhaps be pointed out that the slowly varying brightness of the halftone display, as it gradually fades up towards the LSP, makes the taking of photographs somewhat difficult and demands quick decisions. With variable persistence this is even worse because the different parts of the trace will usually be at different stages of decay, and while the human eye is very tolerant of such brightness discrepancies, the camera is not.

Chapter 7
VARIABLE PERSISTENCE OSCILLOSCOPE FEATURES

In this short chapter we shall discuss the action of some of the controls found on many halftone instruments. The names of these controls will unfortunately vary from instrument to instrument, and particularly from manufacturer to manufacturer, but if their purpose is fully understood no confusion should arise.

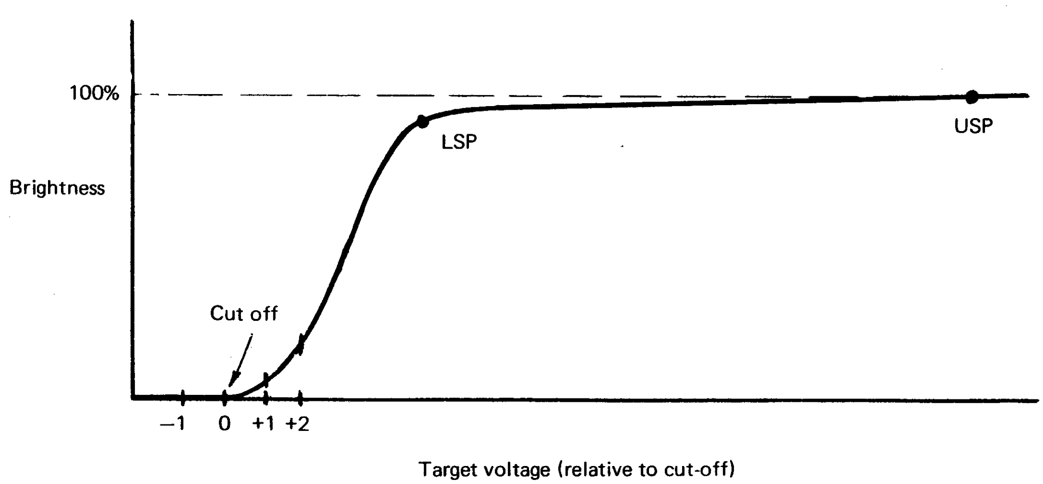
Least controversial is the control usually labelled PERSISTENCE. This is the one which varies the pulse width of the short prep pulse train to provide front-panel adjustment of the persistence time. Typically, an indent at the maximum-persistence end disables the pulse train to allow normal halftone operation with viewtime in the region of 10 minutes.

Two functions which may come under a variety of names are the SAVE switch and the associated SAVE TIME control. In halftone and variable persistence instruments with their continually fading displays, the danger is great that a precious record of an unexpected event will disappear or be overlaid with other information before the operator has taken the correct steps to save it. The SAVE switch acts as an emergency button which can be used in such instances. It blanks the writing beam or locks out the sweep, disables the erase button, stops the variable persistence and brings the SAVE TIME control into operation. With the SAVE TIME control the user is given the choice of viewing time versus brightness as discussed on page 25. An indent at the maximum viewtime end of this control may be provided which will stop the floodbeam altogether for infinite storage time. If the floodbeam can also be stopped without being in the SAVE mode (or if the SAVE mode allows one sweep before locking out further sweeps) the instrument can be left indefinitely to await, and store, a rare single event. This useful feature has been nick-named the "baby-sitting mode".

Finally, some instruments offer a control which allows the level of the unwritten target to be adjusted from the front panel. This offers the intelligent user considerable advantages which we will investigate in the remainder of this chapter. A typical name for this control is STORAGE LEVEL.

Figure 15 showed how at a certain negative voltage of the target the floodbeam is just cut off, hence the screen completely black. If a front panel control allowed us to alter the target voltage within limits, we could deliberately adjust it to some other level (such as -1, +1 or +2 shown in figure 19). Let us consider the consequences of operating the target at these points.

Figure 19



If the target is at +1, there will be some slight light emission. The background appears dim rather than black. Being nearer to the lower stable point, it will also take less time (less than the typical 10 minutes) for the background to fade up. The viewtime is therefore shorter. But as the background sits on a steeper part of the transfer curve, a given trace contrast can be achieved with a smaller increase in target voltage, hence the writing beam need only lay down a smaller dwell time-intensity product. The writing speed is therefore greater. The opposite effect takes place if the target starts from -1: fade-up takes longer, hence the viewtime is increased, but the beam needs to deposit substantially larger charges to create a visible display. By making the level of the unwritten target adjustable, the user is given the opportunity to favour the factor which is most important to him. In Tektronix instruments the manuals recommend that the control should normally be centered, giving target operation at the 0 point, and the operator would then depart from this centre setting when required.

How can the target voltage be adjusted externally when the target is a floating dielectric? This is a matter of changing the voltage of the support mesh. Refer again to figure 16. If the mesh were normally held at a voltage slightly lower than LSP, but the top of the prep pulse remained unchanged, then during the prep pulse the target would of course still be stabilized at the LSP level, but at the end of the pulse, since the support structure then drops by a larger amount, the target would also drop further negative, perhaps to the -1 level in figure 19. The opposite adjustment of the support mesh voltage would give us a smaller drop at the end of the prep pulse, leaving the target perhaps at +1 or +2.

But this is not all. With the STORAGE LEVEL control we can move the mesh voltage at any time, even after the prep pulse, and hence by capacitive coupling we can move the target voltage at any time. We can thereby adjust the background level at will. When we are looking for a very faint trace which has barely managed to lay down a charge, we can raise the target voltage *after the sweep has taken place* for optimum visibility at the steepest part of the transfer curve, or if we have an unexpectedly solid trace we can lower it for best contrast and a totally black background*.

We have now repeatedly stumbled across a basic trade-off situation between storage time and writing rate. If a trace is laid down by a very fast beam it will be faint, and will therefore merge into the background long before the normal 10-minute viewtime which a really solid trace would provide. Again when the STORAGE LEVEL control is adjusted to the optimum sensitivity at the steepest part of the transfer curve, this obviously reduces the viewing time. It might interest some readers that the same trade-off troubles the CRT design engineers: when they select dielectric materials for the target or vary its thickness or similar factors, any changes which result in increased writing speed cause a decrease in viewtime. It seems as if the laws of nature conspire to prevent us from increasing the writing speed beyond a certain limit and still have a viewtime long enough to be worthy of the name "storage".

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* On the British-designed DM63 oscilloscope this control has been named VARIABLE ENHANCE. This must not be confused with the enhance mode described on page 16. The instrument writing speed is specified on page 47 with the variable control at minimum ("normal") and at maximum.

Chapter 8
THE TRANSFER TUBE

When the laws of nature seem immutable, a trick can sometimes help. The transfer tube perfected by Tektronix uses such a trick. The highest writing speed has to be paid for by extremely short viewtime. In the transfer tube this process is carried to the point where the trace is only stored on the target for a few tens of milliseconds, and the trick is that the stored voltage pattern is then immediately transferred from this fast-decay target to a slower target within the same tube which can operate either in the bistable or in the halftone mode. The writing speed achieved by such tubes typically exceeds 100 cm/µs and can reach 2500 cm/µs with a special reduced-scan technique described in chapter 9.

The transfer tube, then, is a device containing two separate targets of the transmission type. Figure 20 shows the names given to them. As in all transmission tubes the collector consists of a mesh on the gun side of the target, and the phosphor is deposited behind the faceplate and is operated at several kilovolts to give a bright display.

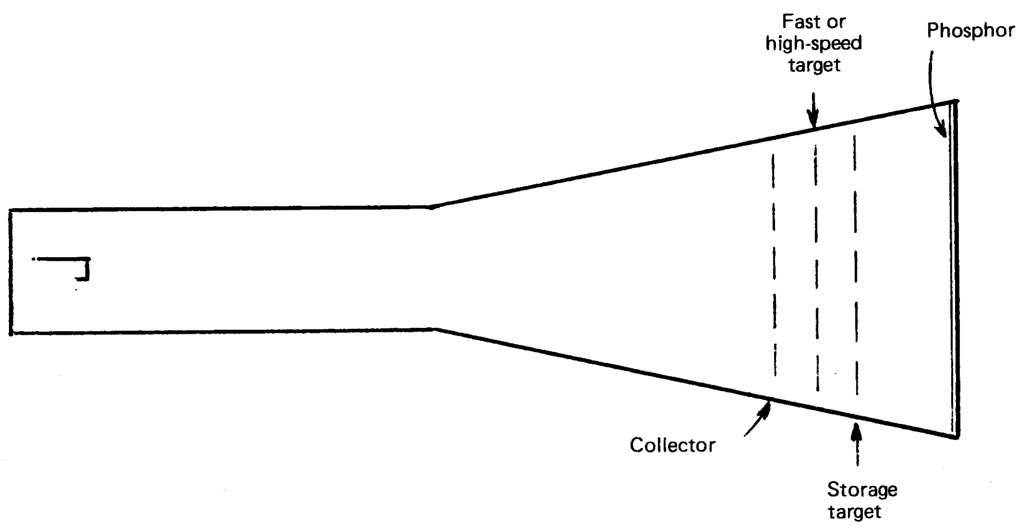


Figure 20

This tube can also be used in a conventional bistable, halftone or variable persistence mode. All these modes employ the storage target only; the fast target mesh is held at collector potential to allow unhindered beam passage. Let us start by considering how the tube operates in these conventional modes.

In earlier chapters we explained how the transmission factor of the target mesh must be chosen in a way that makes it suitable for either bistable operation (when at LSP potential the beam is cut off) or halftone operation (when at LSP potential almost the full beam still reaches the screen). So how can the storage target in this tube be used for both modes? Well, the transmission factor is made essentially the same as for a halftone tube, resulting in a curve as in figure 19. This explains its operation in the halftone mode, but what about the bistable mode?

In the first place you will note that there *is* a difference in brightness between LSP and USP, the two bistable operating points, but this is so small that it would not be useful by itself. The difference is increased, however, by an

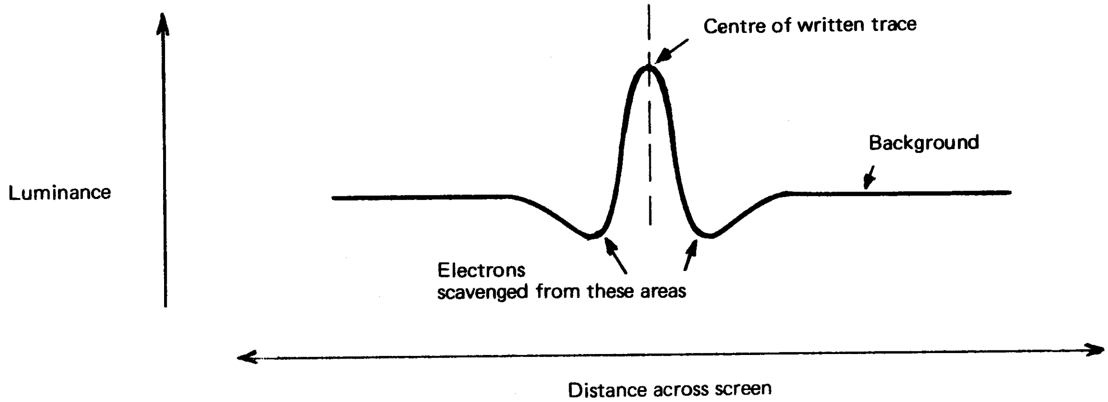


Figure 21

electron-optical phenomenon known as "electron scavenging", in which the written trace attracts flood electrons from nearby unwritten areas, thereby increasing the effective contrast between written and *adjacent* unwritten areas to a ratio in the order of 2 : 1. Figure 21 illustrates the trace profile.

Therefore, while the halftone mode performs conventionally, with a typical written trace of 800 cd/m² and dark background, in the bistable operation of this tube the background is extremely bright and the contrast rather low, but nonetheless perfectly adequate. This is the price we pay for offering both operating modes. Before we leave this topic, it might be worth putting the brightness levels produced in the bistable display into perspective. Table 2 recaps the information given earlier in table 1 and adds the approximate light output of the transfer tube for comparison. Its advantage in bright surroundings is obvious.

Phosphor-target tube

Collector Voltage	in total darkness			with 6 cd/m² ambient light			with 100 cd/m² ambient light		
	written trace cd/m²	unwritten areas cd/m²	Contrast	written trace cd/m²	unwritten areas cd/m²	Contrast	written trace cd/m²	unwritten areas cd/m²	Contrast
100 V	24	4	6 : 1	30	10	3.0 : 1	124	104	1.2 : 1
140 V	50	10	5 : 1	56	16	3.5 : 1	150	110	1.4 : 1
180 V	80	20	4 : 1	86	26	3.3 : 1	180	120	1.5 : 1

Transfer tube in bistable mode

	800	400	2 : 1	806	406	2 : 1	900	500	1.8 : 1

Table 2

Photography presents a slight difficulty. It takes place in total darkness, since the camera shuts out all ambient light. Under this condition, table 2 shows that the contrast ratio of the transfer tube is less than that of conventional bistable tubes. The resulting pictures will therefore have rather less contrast than you may be used to, but with correct exposure they will be perfectly legible. For 3000 ASA film typical settings are f16 and 1/25 s.

Switching the storage target to the bistable or halftone mode is simply a matter of preparing it correctly during erasure. After the fade-positive and normal erase pulse it rests at LSP and is ready for bistable writing. If this is followed by a prep pulse the target will be moved to cutoff and be ready for halftone writing. The writing speed of the transfer tube in these modes is similar to that of separate bistable or halftone transmission tubes.

The remainder of this chapter will be concerned with the operation of the tube in the transfer mode. In this mode, as we know, the trace is first written on the fast target and is then quickly transferred to the normal storage target. When the transfer is completed the fast target is returned to the fade-positive level to allow unhindered floodbeam passage to the storage target and phosphor so that the stored trace can be seen at full brightness.

Before studying this technique in more detail, let us consider some of the design aims. The transfer tube is more complicated and more expensive than other tubes and may have marginally poorer focus because of the presence of three separate meshes. In the face of these disadvantages we would be foolish not to optimize its performance for the fastest possible speed. The fastest speed is achieved by operating both targets in the halftone mode. The fact that the fast target only stores for about 100 milliseconds is immaterial as long as we can successfully transfer the stored trace in that time, but we then still have to choose a suitable compromise for the halftone performance of the normal storage target, and in an effort to achieve the fastest writing speed it has been made relatively fast-decaying. Typically the viewtime at the fastest writing speed is about 15 to 30 seconds. This may not sound much, but it gives enough time to make comparative observations or take a photograph (and it is, apart from very sophisticated and expensive scan converting techniques, the only way of storing waveforms of this speed for direct viewing).

However, few users will want the highest possible writing rate all the time and for more modest requirements the storage target can be used bistably. The transfer process still makes this a great deal faster than any non-transfer tube, bistable or halftone.

The transfer mode of operation is essentially a single-sweep technique and is only suitable for sweeps which are completed quickly, since otherwise the beginning of the trace will have faded away on the fast target before the end of the sweep is reached and the transfer initiated. In general, the transfer mode is not suitable for sweeps slower than about 100 µs/division. This is one reason why instruments using the transfer tube also offer conventional bistable and/or variable persistence modes.

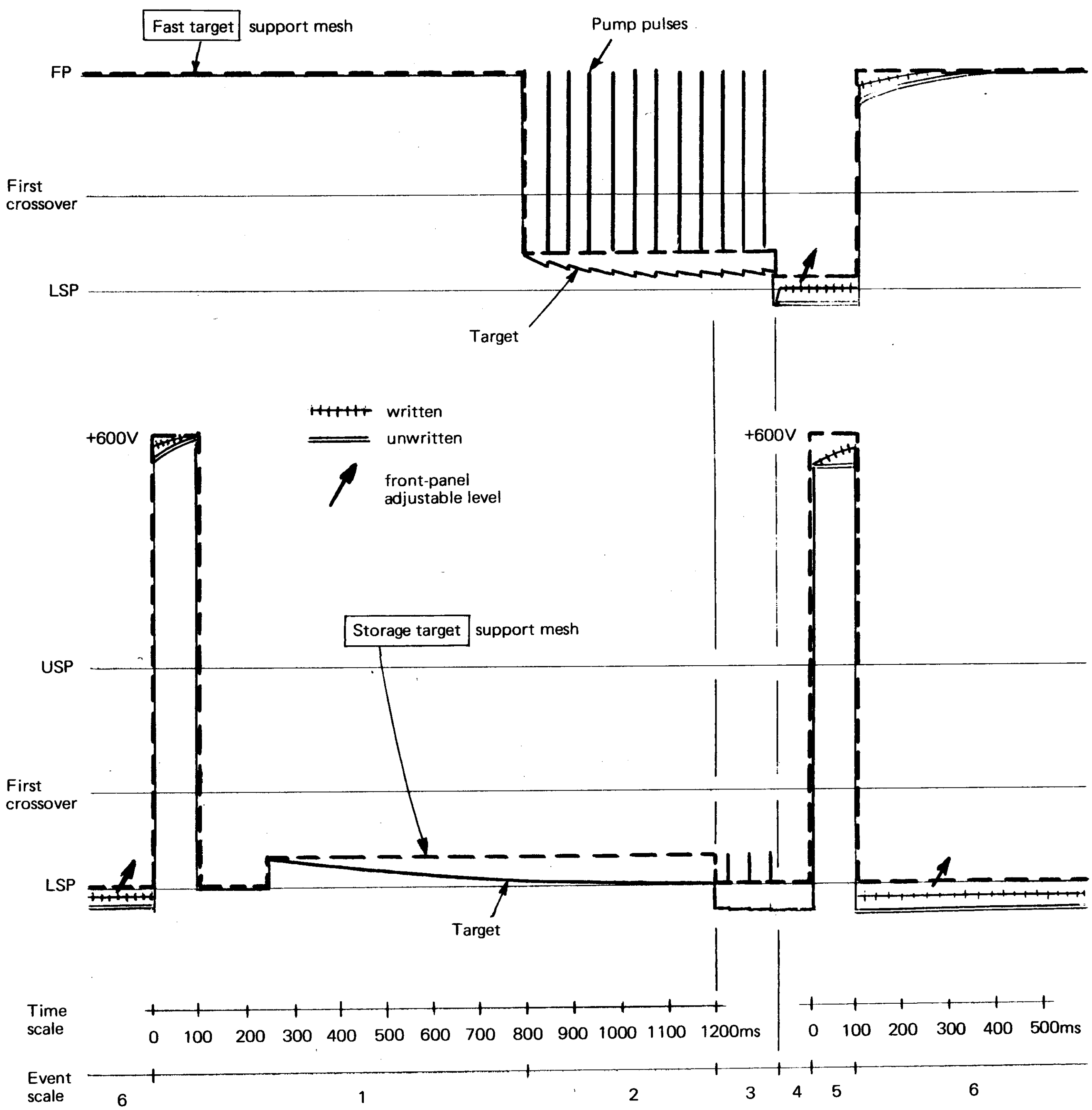
In instruments using the transfer tube, as the different modes are selected, complicated sequences of events follow during which the voltages of most CRT electrodes are adjusted at one time or another so as to obtain best overall performance. For example, although the collector is normally operating at +150 V, there are good reasons for departing from this level during the erase-write-transfer sequence. Flood gun anode and collimating electrodes are similarly adjusted. These adjustments can be of no interest to the reader of this booklet, and we will therefore confine the detailed explanation of events which follows to the *essential* voltage movements on the two target meshes. These are illustrated in figures 22 and 23 for halftone and bistable transfer mode respectively. In both cases the sequence of events is the same:

1. erasure of storage target
2. preparation of fast target
3. sweep allowed and waiting for next trigger
4. sweep takes place
5. transfer of recorded trace from fast to storage target
6. viewtime until next erasure is initiated

These events are identified on the event scale at the bottom of the illustrations. We will now look into the details of each mode.

First figure 22, which illustrates the halftone transfer mode. When the erase button is pressed (or the viewtime of the auto erase circuit has ended) the erase sequence of the storage target starts with a fade-positive pulse. It has been found useful to raise the mesh to +600 volts, high above the collector voltage, and at this level the mesh itself acts as collector for secondary emission electrons.

Figure 22



The upper stable point thus becomes +600 volts and the usual mechanism causes written and unwritten areas alike to drift towards this point. The next pulse is the prep pulse during which time is allowed for the target to drift to the lower stable point. Then the fast target mesh is dropped to prep level, and the fast target begins to drift towards the lower stable point. A series of so-called pump or equalizer pulses (about 2 µs wide) causes the target drift to stabilize fairly quickly and maintain its level during possible long waiting periods for the next sweep.

Next, the sweep circuit is unlocked and becomes triggerable, and at the same time the storage target drops to the "ready-to-write" level. It will now have to stay at this level until a trigger starts the sweep. Some floodbeam is bound to get through the fast target mesh, especially during the pump pulses, and to neutralize the effect of the resulting ion landings on the storage target, small pump pulses in synchronism with those on the fast target are applied to the storage mesh. They tend to push the storage target more negative, thus stabilizing the voltage. When the sweep circuit receives a trigger, the fast mesh drops to the "ready-to-write" level and a trace is recorded on the fast target.

Immediately after the sweep has ended the transfer pulse is applied to the storage mesh. This once again raises the upper stable point to +600 volts and capacitively couples the storage target to near this value. Now in areas of the fast target where a trace was laid down the floodbeam is permitted to pass through, and is accelerated towards the storage target where it causes secondary emission. These areas of the storage target will therefore move towards the upper stable point. But in unwritten areas of the fast target little floodbeam can get through, and so the corresponding areas of the storage target will remain almost unchanged. At the end of the transfer pulse the storage mesh returns to its normal level and we have a trace exactly as if it had been written by the writing beam in the normal halftone process, with limited viewtime and the usual options of looking at it at full brightness briefly or at reduced brightness for a longer period, and of raising or lowering the background level to favour writing speed or contrast. The fast target, meanwhile, has been returned to a fade-positive level to allow unhindered passage of the floodbeam during the viewtime.

In this transfer process an effect takes place which is known as "charge multiplication" and which is really responsible for the faster writing speed that it offers. When the trace is initially laid down by the writing beam on the fast target, an extremely fast-moving beam will deposit only minute charges at any given point on the trace (and these are likely to become obliterated extremely quickly). But in the transfer process, the presence of these charges causes a certain amount of floodbeam to be transmitted for a full 100 ms at all points along the path of the writing beam. Calculations show that the charges thus accumulated on the storage target are about 1000 times as great as those originally deposited by the writing beam. This is why, after the transfer process, the viewtime can be measured in tens of seconds, rather than tens of milliseconds.

If we now compare this with the bistable transfer mode shown in figure 23 we find that the only difference is in the way the storage mesh is prepared during erasure and operated during viewtime. The erase pulse has the usual typical shape for bistable operation: a fade-positive pulse, the negative edge, and the slow return to the normal operating level. The operating level will typically be set to a voltage a little above the first crossover. The advantage of this unusual setting can be seen clearly in the illustration: after the transfer pulse the written and unwritten areas of the target end up on opposite sides of the first crossover and will then drift respectively to the upper and lower stable points. This is the same principle as in the enhance mode of phosphor-target tubes, and it leads to the same drawbacks if the potential difference between recorded and unrecorded areas is not sufficiently clear-cut.

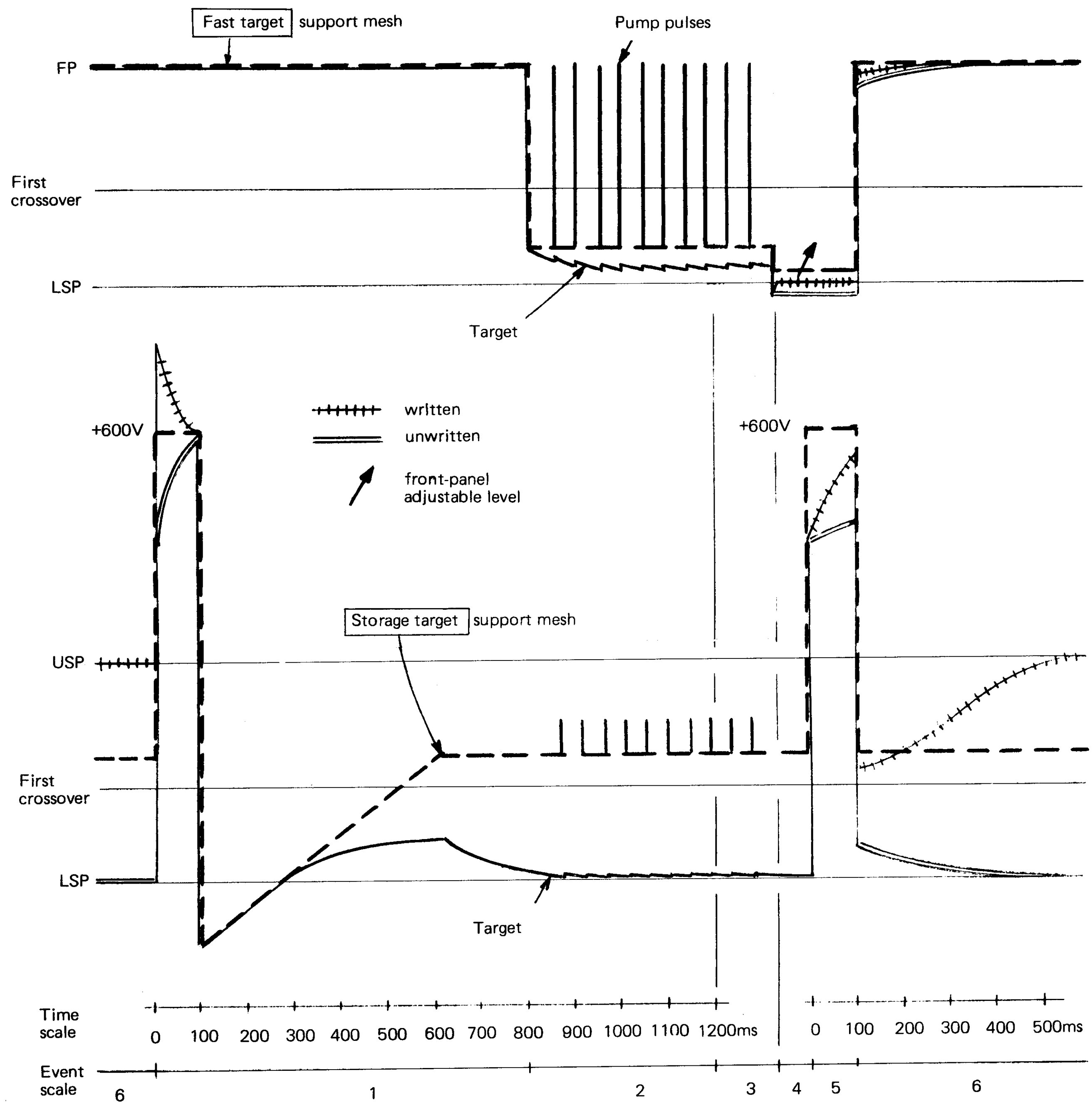


Figure 23

We can now understand why the writing speed is less fast in the bistable transfer mode. As in any other type of storage tube, this is the consequence of the way in which the *storage* target is operated. In the halftone mode, trace visibility is optimized by displaying the slightest charge laid down by the writing beam at the steepest part of the transfer curve. In bistable operation such slight charges are discarded in the interests of fixed contrast and long viewtime.

Perhaps we ought to remind you at this point that the transfer tube just discussed has a storage target with a transmission factor suitable for halftone operation, so that when it is operated bistably the screen is unusually bright even in unwritten areas. Refer again to figures 15 and 21 and table 2 for details.

Chapter 9
FEATURES OF THE TRANSFER STORAGE OSCILLOSCOPE

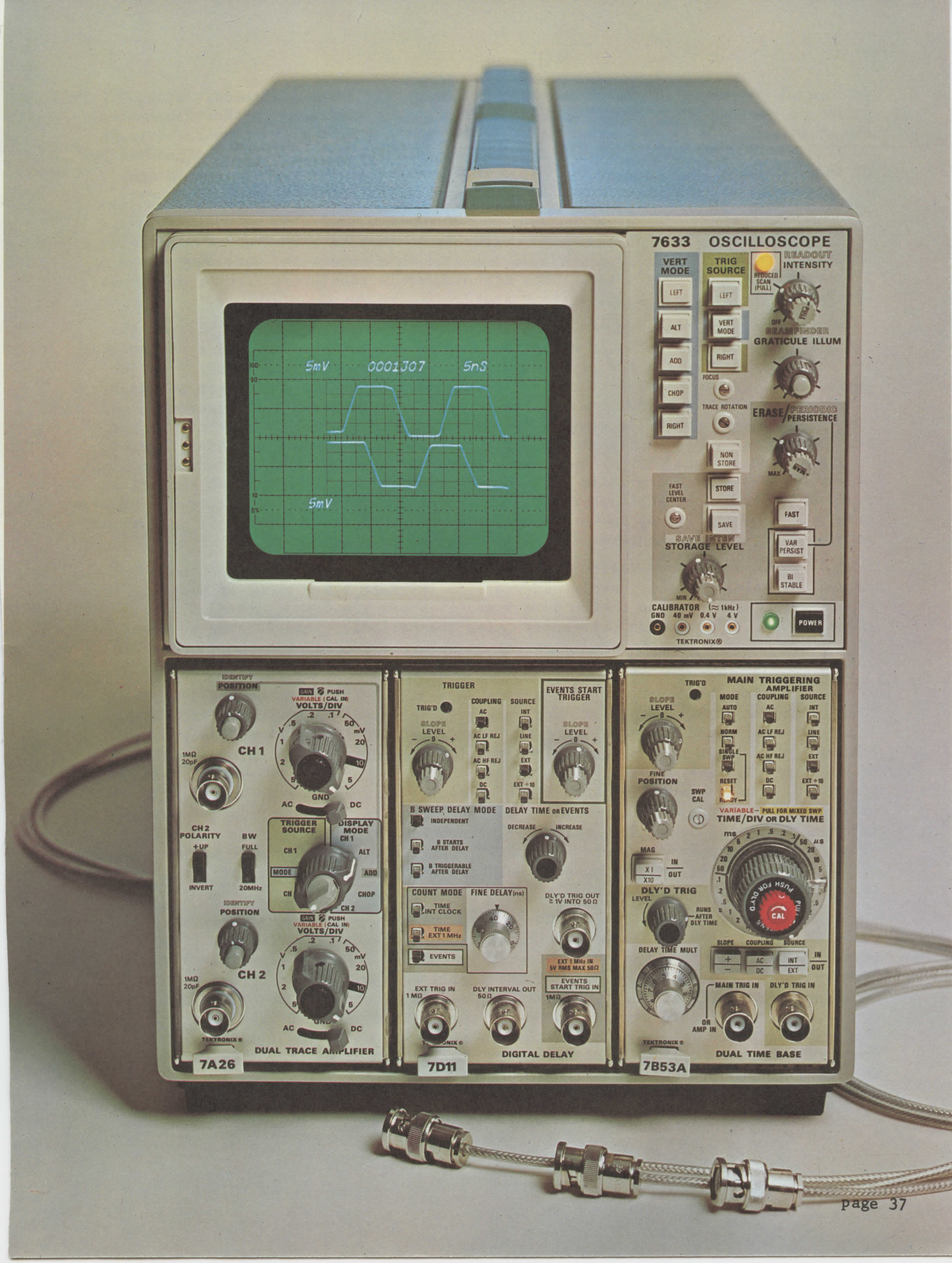
At the time of writing, only the Tektronix type 7633 and 7834 oscilloscopes offer both transfer modes discussed in the previous chapter and a "reduced-scan mode" to be described in this chapter. Other instruments using transfer tubes each lack either the reduced-scan feature or one of the transfer modes. (Details can be seen in appendix B.) Here we shall discuss the features of the type 7633 shown on the facing page and mention some of the innovations of the more recent type 7834 illustrated on the front cover. For details of the controls available on other transfer instruments you should refer to their respective operating manuals.

Many of the facilities of the type 7633 will be familiar to you from previous chapters. There is an auto erase circuit (here called PERIODIC ERASE) which operates in *all* storage modes, and there are the PERSISTENCE and STORAGE LEVEL controls. Erase and persistence are disabled when the SAVE pushbutton is selected, and the floodbeam can then be reduced or stopped with the "save time" control (here called SAVE INTENsity). To operate the instrument as a normal bistable or variable persistence scope the appropriate store mode is selected. For transfer operation the store mode button and the FAST button must be pushed.

Before going on to discuss the reduced-scan feature, let us consider briefly the effect of the STORAGE LEVEL control in the various modes. In the conventional variable persistence mode it operates exactly as described in chapter 7, allowing us to shift the target mesh voltage. We can thereby control the relative brightness of the recorded trace and the background, moving the display to the steepest part of the transfer curve (figure 19) when viewing very fast, faint traces, or moving the background well below cutoff for good contrast and long viewing time of solidly written traces.

In the fast variable persistence mode the principle mentioned in the previous paragraph obviously applies to both targets, and to optimize them for the very fastest writing speed both need to be adjusted critically. A vernier screwdriver control marked FAST LEVEL CENTER, shown in the photograph opposite, is provided so that the two targets can be made to track exactly at the desired STORAGE LEVEL setting. For details on how to adjust the FAST LEVEL CENTER control consult the calibration procedure in the 7633 instruction manual. (In later serial numbers the control is located inside the instrument.) In fast bistable operation the STORAGE LEVEL control allows us to pick a suitable fast mesh voltage as shown in figure 23.

Turning now to the reduced-scan feature, you may recall that we mentioned (on page 24) the difficulty of achieving uniform storage target performance in transmission tubes. But the writing speed and hence the usefulness of an instrument is limited by the performance in the least sensitive part of the screen. During manufacture we try to make the central screen area most sensitive at the expense of the extremities. When the first transfer tube instrument, the 7623, was introduced, the writing speed specification was limited to an inner 4 x 5 div area. This is inconvenient for users who generally prefer to have an 8 x 10 div graticule (irrespective of the size of each division). On some new instruments, therefore, additional graticule markings have been introduced, outlining 8 x 10 half-sized divisions within the inner 4 x 5 standard divisions, as can be seen in the close-up on page 40. In itself this is merely a convenience and does not alter the performance of the instrument. But when the REDUCED-SCAN mode is entered by pulling the appropriate knob, the deflection sensitivity of the instrument


7633 OSCILLOSCOPE
VERT MODE
LEFT
ALT
ADD
CHOP
RIGHT
TRIG SOURCE
LEFT
VERT MODE
RIGHT
READOUT INTENSITY
REDUCED SCAN (PULL)
BEAMFINDER
GRATICULE ILLUM
FOCUS
TRACE ROTATION
ERASE/PERIODIC PERSISTENCE
NON STORE
STORE
SAVE
FAST LEVEL CENTER
SAVE INTEN
STORAGE LEVEL
FAST
VAR PERSIST
BI STABLE
CALIBRATOR (≈ 1kHz)
GND 40 mV 0.4 V 4 V
POWER
TEKTRONIX®
5mV
0001307
5nS
5mV
IDENTIFY
POSITION
VOLTS/DIV
CH 1
CH 2
AC GND DC
TRIGGER SOURCE
DISPLAY MODE
INVERT
20MHz
DUAL TRACE AMPLIFIER
7A26
TRIGGER
TRIG'D
COUPLING
SOURCE
EVENTS START TRIGGER
B SWEEP DELAY MODE
DELAY TIME OR EVENTS
DECREASE
INCREASE
COUNT MODE
FINE DELAY(ns)
DLY'D TRIG OUT ≥ 1V INTO 50 Ω
EVENTS
EXT TRIG IN 1 MΩ
DLY INTERVAL OUT 50 Ω
EVENTS START TRIG IN
DIGITAL DELAY
7D11
MAIN TRIGGERING AMPLIFIER
MODE
COUPLING
SOURCE
FINE POSITION
SWP CAL
TIME/DIV OR DLY TIME
MAG
DLY'D TRIG
DELAY TIME MULT
MAIN TRIG IN
DLY'D TRIG IN
DUAL TIME BASE
7B53A

is exactly halved, so that the selected sweep speed and vertical sensitivity, as shown by the time/div and volts/div switch and as indicated on the CRT readout, now apply directly to the new, smaller divisions, and in addition the EHT voltage on the writing gun is doubled for a more intense writing beam. The combined effect of these changes is a six- to eightfold increase in writing speed. The changes in deflection and EHT which occur in the reduced scan mode have been nick-named "gearshift operation".

A further effect of gearshift operation is that the writing beam spot size is decreased by a factor of, typically, 1.5 and to this extent the resolving power of the display becomes greater. This improvement in resolution is over and above that gained by the additional writing speed.

One more feature remains to be explained. You may remember that when the transfer mode is used a single sweep is recorded and transferred, and a new recording normally starts with the erase sequence. Now in some applications it may be desirable to record several traces on top of one another for comparison purposes. This can be achieved by not erasing the storage target (event 1 in figures 22 and 23) while going through the rest of the transfer mode sequence. In this way the new information can be added to the trace already existing on the storage target. On slowish recordings many traces can be added in this way, but if you are looking at very fast events where it is necessary to advance the STORAGE LEVEL control in a way which brings up the background, then of course with each new trace the background is also charged up further and it may not be possible to do this more than once or twice before the target is fully written.

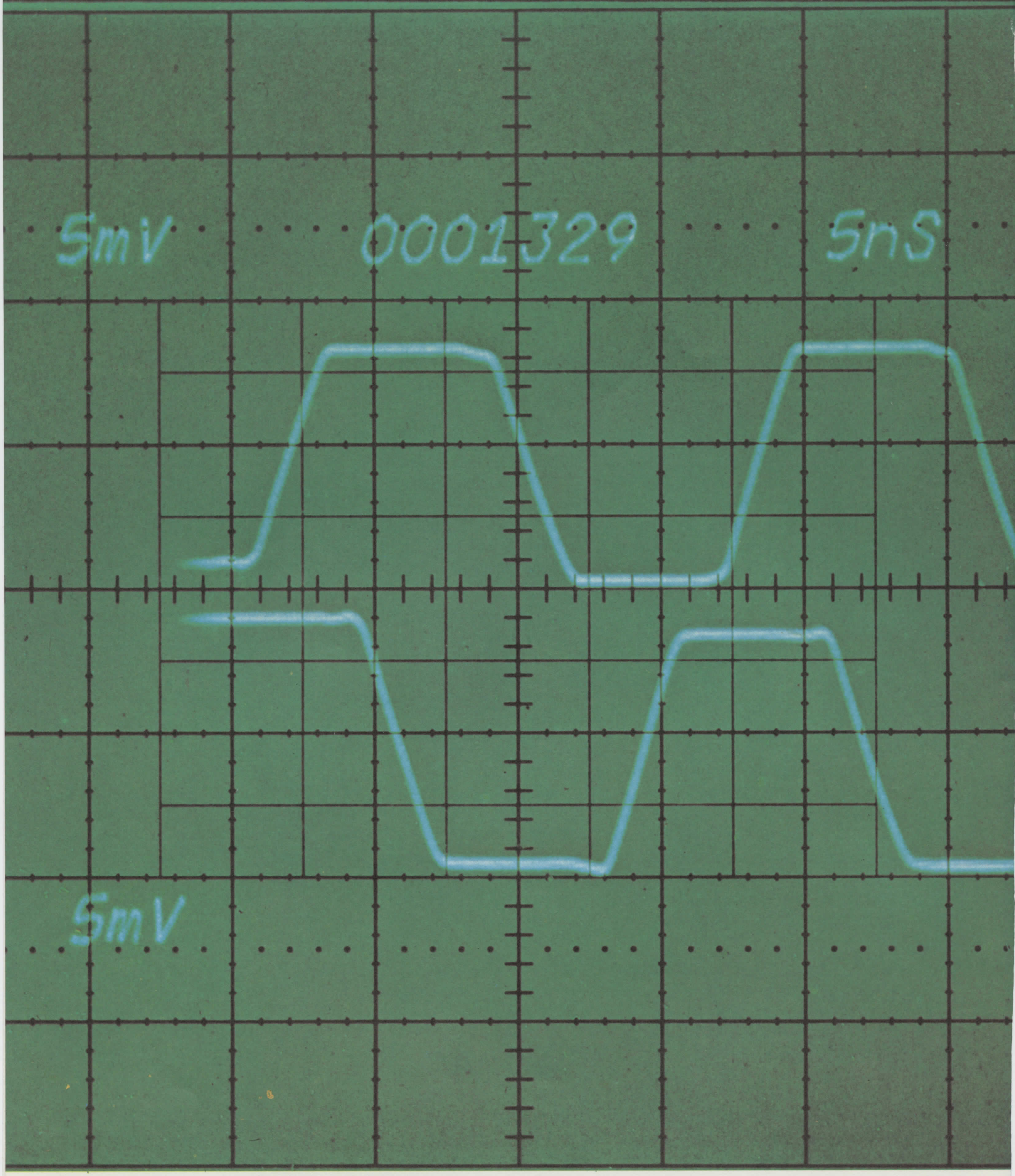
Such a mode of operation is referred to as the "multi" mode. To make multiple recordings it is merely necessary to initiate a new sweep by pressing the single sweep RESET button on the normal oscilloscope timebase instead of the erase button. If you were previously using the periodic erase feature it might be as well to disable this before embarking on multiple recordings, since otherwise your experiment may be brought to an untimely conclusion.

One of the innovations of the type 7834 allows traces to be added in the "multi" mode on a automatic basis at intervals selected by the MULTI TRACE DELAY control. This could be useful, for instance, during calibration procedures when the operator wishes to superimpose the results of each of a series of adjustments. He would merely have to set the MULTI TRACE DELAY to the time required to make and observe each adjustment and recording the results then becomes a "hands-off" operation. The control might also be used to make the instrument ignore unwanted information in a long pulse train while automatically recording data occurring at specific intervals. In principle this is similar to the variable trigger hold-off facility offered by many scopes, but here the time scale is a different one: the MULTI TRACE DELAY is adjustable between 0.6 and 4 seconds.

Baby-sitting operation of the 7633 can be had by putting the timebase into the single-sweep mode, then initiating an erase cycle (after which the timebase will automatically be armed, as indicated by the RESET button lighting up), and finally entering the SAVE mode. One sweep will then be allowed before the timebase is locked out. If the instrument is used in either variable persistence mode and you want indefinite storage after the event, then you must make sure that the SAVE INTENsity control is at the minimum position in which the floodbeam is completely turned off. When returning to the instrument to view the trace recorded in your absence, all that is necessary is to turn up the SAVE INTENsity control to the desired brightness. Baby-sitting is of course also available in the type 7834.

The 7834 achieves the fastest writing speed of any storage tube instrument (2500 cm/μs) by design improvements in the CRT gun assembly and deflection system, giving a finer writing beam and providing the target with a greater charge density. The instrument also features comprehensive remote control facilities.

If we compare the transfer tube oscilloscope with the first storage instrument introduced 14 years ago we note with amazement that the writing speed has been improved by a factor of 10 000 without employing any radically new principles, making possible the single-shot storage of a 2 cm high sinewave of 400 MHz where previously as many kilohertz were completely out of reach.



Central graticule area, showing 8 x 10 reduced-size divisions

WRITING SPEED

In this booklet the term "writing speed" was used in the sense of "maximum stored writing speed" - in other words, the maximum beam velocity at which the tube is capable of producing a satisfactory stored trace. Several questions arise from this:

i. What criteria are used to define "satisfactory"?

ii. How could the performance of a given instrument be verified?

iii. What is the maximum beam velocity produced by a signal of a given shape and with given deflection factors?

In this appendix we shall answer all these questions, starting with the last one.

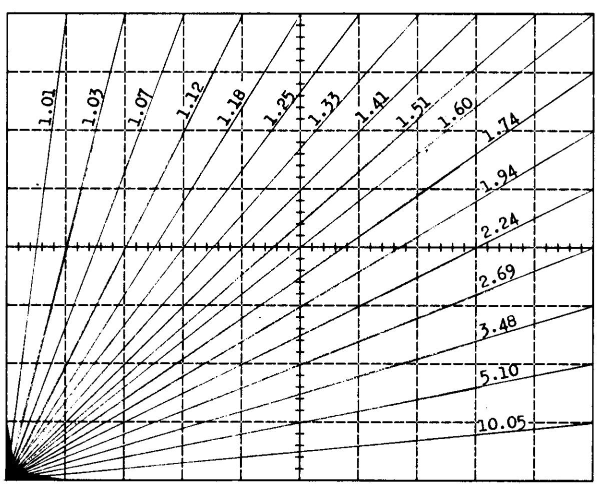
HORIZONTAL BEAM MOTION

The most trivial case is that of a straight horizontal trace, when the beam sweeps across the CRT without being deflected vertically. In this case the beam velocity is uniform and is determined by the selected deflection factor. The beam velocity is usually quoted in div/μs, so if, for example, the sweep speed is 0.1 μs/div, then the beam velocity would be its reciprocal, 10 div/μs.

COMBINED BEAM MOTION

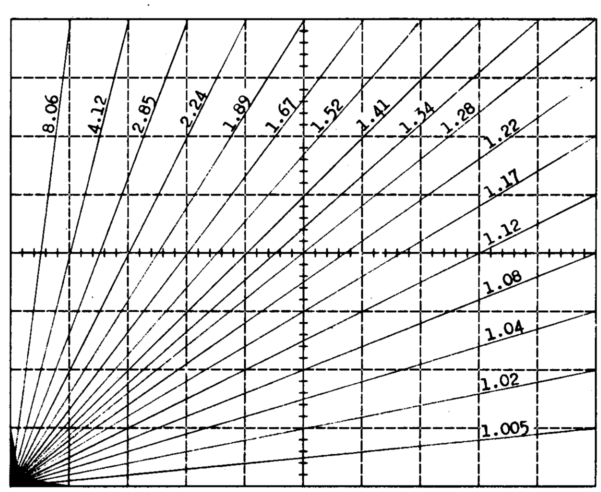
When vertical deflection is added, the beam velocity will be the vector sum of the horizontal and vertical motions. For a trace rising or falling at 45°, for instance, the beam velocity will be $\sqrt{2}$ times the horizontal component. Elementary trigonometry will allow you to calculate, for any given trace angle, the factor by which the horizontal motion must be multiplied to obtain the true beam velocity. Figure A2 gives some selected values. So if you have an actual display in front of you and want to calculate the maximum beam velocity, look for the steepest part of the curve and multiply the horizontal beam motion by the appropriate factor.

This procedure will become impractical if the vertical motion is very much greater than the horizontal motion, making the trace near-vertical, or if the horizontal sweep is uncalibrated. For some signals it may be possible to



Factors by which vertical motion must be multiplied to obtain combined motion

Figure A1



Factors by which horizontal motion must be multiplied to obtain combined motion

Figure A2

approach the problem the other way: to determine the vertical component of the beam motion from known facts about the signal, and then multiply *it* by a factor derived from trigonometry to allow for the horizontal component. Again, if the display rises at 45°, the factor will be $\sqrt{2}$. Figure A1 gives a number of values for different angles. Obviously, the most accurate results are obtained if, for near-vertical traces, you start off with a known vertical speed.

VERTICAL BEAM MOTION

Since the vertical motion depends on the signal shape, no generally valid statement can be made. Each waveshape must be treated separately. The simplest case is that of a linear ramp, where the rate of rise directly expresses the vertical motion of the beam. For instance, a ramp rising at 2 div/ns has a vertical beam motion of just that: 2 div/ns. Such a ramp is shown in figure A3, which also illustrates how the rate of rise of the ramp could be measured on an oscilloscope by selecting a sweep speed of 1 ns/div. Remember that the result of the measurement, 2 div/ns, is the *vertical* component of the beam motion only, and for the combined beam velocity you must now multiply this figure by a factor taken from figure A1, in this case 1.12.

If the ramp is the leading edge of a pulse and if the risetime t_r of that pulse is quoted, it follows that the leading edge will run through 80% of its total amplitude during time t_r. The vertical component of the beam motion can be calculated from the total pulse amplitude A and the given risetime as

$$v_{max} = \frac{k \cdot A}{t_r} = \frac{0.8 \cdot 5\ \text{div}}{2\ \text{ns}} = 2\ \text{div/ns}.$$

The formula is expressed in general terms suitable for other kinds of step responses in which the velocity is not constant but will, at some point, reach a maximum. The constant k (in this case 0.8) simply states, for a given waveshape, through what fraction of the total pulse amplitude the leading edge would run if it maintained v_{max} for the duration of t_r.

Figure A4 shows a Gaussian response for a step of the same amplitude and risetime as in figure A3. Since parts of the curve between 10% and 90% rise less steeply than the linear ramp, it follows that in other parts (near the centre) it must be steeper if the 90% level is to be reached in the same time.

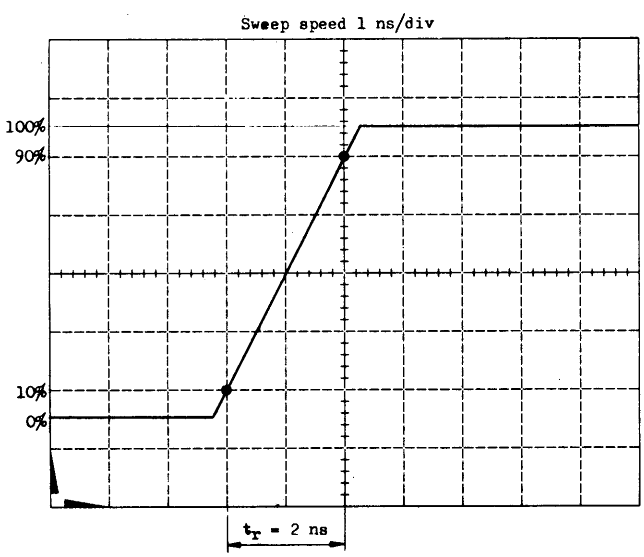


Figure A3

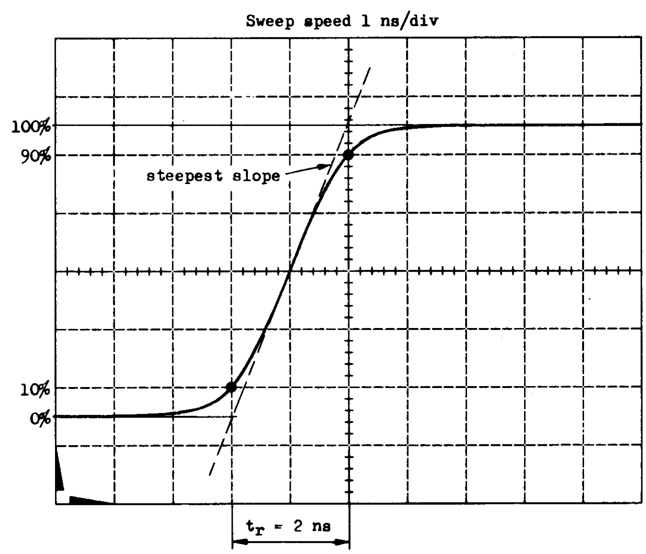


Figure A4

Not surprisingly, then, the constant k will be larger. For a true Gaussian response it is 1.023, but in practice a factor of 1 is usually employed.

Figure A5 shows the exponential response of a single RC network to a step input. In this case, obviously, the fastest vertical motion occurs at the beginning, and is such that if it were maintained, the pulse would rise to the 100% level in one time constant, and (since t_r = 2.2 time constants) to 220% during t_r. Hence the scaling factor k becomes 2.2 for this waveshape.

To sum up, the k factor in the formula is 0.8 for linear ramps, about 1 for true Gaussian response, and increases to 2.2 for single-pole RC networks. Intermediate values for networks limited by a few poles can readily be guessed. We shall have more to say about the accuracy to which such calculations should be carried when we consider how a "satisfactory" stored trace is defined.

One more waveshape will be discussed here: that of the ubiquitous sinewave. Its maximum vertical motion occurs at the centre of the sinewave and is given by the simple formula

$$v_{max} = \pi \cdot A \cdot f$$

where A is the peak-to-peak amplitude
and f is the frequency

With amplitude in div and frequency in MHz, the result will be in div/µs.

To save calculations, the nomograph on page 45 might be useful, in which, for a wide range of sinewave frequencies and amplitudes, the maximum writing speed can be read off directly.

Finally in this section we must remind you again that after determining the vertical beam velocity in this way you must then allow for the effect of the horizontal motion to obtain the actual velocity on the CRT screen.

HOW TO VERIFY THE WRITING SPEED PERFORMANCE OF AN INSTRUMENT

At its simplest one could record a vertically undeflected beam and increase the sweep speed until the stored trace became unsatisfactory. But this would only check the tube performance at that particular vertical level, and would not show up vertical non-uniformity. Further traces in other positions could be recorded, but this would be rather tedious. Also, the calibrated sweep speeds progress in a 1-2-5 sequence, making intermediate measurements difficult.

A much more satisfactory method is to use a constant-amplitude sine-wave generator as a signal source and set the amplitude for full-screen deflection. Now if at least 3 cycles of the sinewave are displayed, the waves will be steep enough in the central area for the horizontal beam motion to be neglected, and while the vertical motion is exactly $\pi \cdot A \cdot f$ at the centre only, it *will* be within 10% of that speed over a 40% band on both sides of centre, thus allowing the tube perform-

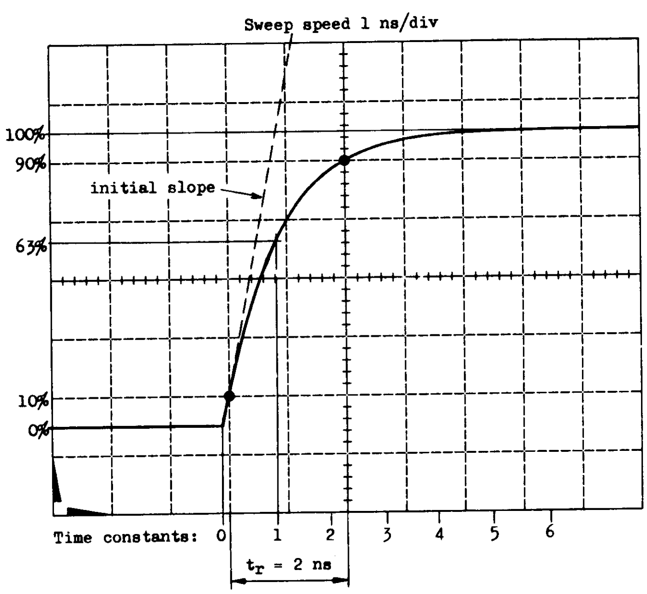


Figure A5

formance to be assessed over a reasonably wide region. The method is simply to increase the frequency of the sinewave generator, while repeatedly storing a trace, until the stored display becomes unsatisfactory, and then plugging that particular frequency and the sinewave amplitude into the formula. As the frequency is increased, the sweep speed should also be increased occasionally so that the recorded individual sinewave cycles do not run into one another.

It may then be necessary to convert the result of your measurement from div/μs to cm/μs in order to compare it with published specifications.

WHAT CONSTITUTES A SATISFACTORY STORED TRACE?

The answer depends on whether the display is bistable or halftone. For bistable displays the evidence is fairly objective: the trace is either there or it isn't. As the writing speed increases, break-up of the trace because of failure to store may start in some screen areas first. At the factory, the stored trace is checked with suitable magnifying equipment and the writing speed defined as that speed at which no breaks are greater than a certain fraction of a millimetre. For practical purposes the user can decide what, in his context, constitutes an unacceptable break. With the fairly uniform phosphor-target tubes he will find that at writing speeds not much greater than the one where such breaks first occur in one part of the screen, the whole screen area will be affected. Determining the maximum writing speed therefore becomes a reasonably repeatable experiment, giving results within 5 or 10% for different observers and different parts of the screen.

Transmission tubes, used bistably, are less uniform and will generally be optimized for best performance in the central area. Where the writing speed in appendix B is specified for the central 4 x 5 div area it would be best to ignore the tube performance outside this area.

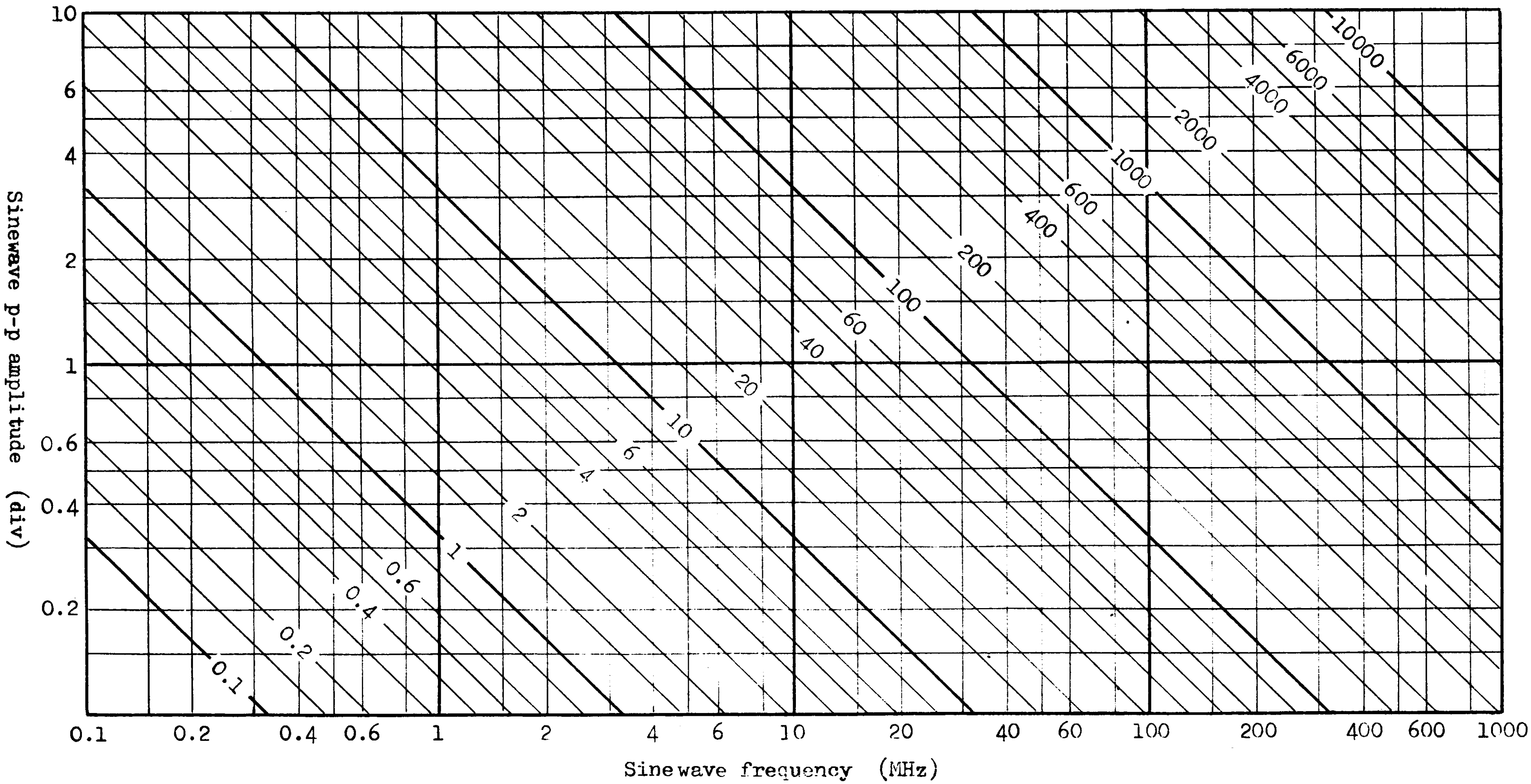
Halftone tubes present a completely different problem. The trace will not visibly break up, but rather it will become fainter and fainter until it becomes difficult to distinguish it from the background, and at the same time the storage time will become shorter and shorter. Because of tube non-uniformity this may also happen at very different writing speeds in different parts of the screen. Restrictions to the central 4 x 5 div area must obviously be observed, but even so the writing speed evaluation can yield results that differ by several factors of 2 from observer to observer, unless the conditions of the experiment are very closely defined and the observers suitably trained. For these reasons, customers should regard the quoted writing speeds of halftone instruments as guide lines only.

You can see from the above discussion why it is perfectly reasonable practice, when testing writing speed with sinewaves, to ignore the error due to horizontal beam motion and the 10% speed variation within the inner 40% band of the sinewave, or to guess the k factor for non-Gaussian step responses.

Finally a word about writing speed in the context of photography rather than storage. The method of assessment is exactly the same, the preferred technique being the use of sinewaves. As in the halftone tube a decision has to be made about the minimum acceptable contrast. But since non-store CRTs and photographic film are virtually uniform and the finished product can be measured with a densitometer or photometer, generally acceptable limits have been agreed on. A trace is considered satisfactory if the density difference in a transparency is at least 0.1, corresponding to a contrast ratio of 1.26 : 1.

MAXIMUM VERTICAL VELOCITY OF SINEWAVES

The diagonal lines are labelled in div/μs



Appendix B

STORAGE INSTRUMENT SURVEY

excluding instruments used as integral part of computer terminals only

June 1977

Types of storage

- P phosphor-target bistable
- B transmission bistable
- H halftone without variable persistence
- V variable persistence
- FB fast (transfer) and bistable
- FV fast (transfer) and variable persistence

Other abbreviations

- * optional feature
- ▽ type RM564 only
- △ central 6x8 div only
- o central 4x5 div only
- † in reduced scan mode each division is half normal size
- † integration is also a natural property of all halftone and variable persistence tubes
- – not applicable or not available

Obsolete instruments

These are listed for comparative purposes and can be identified by an entry in the "Last catalogue" column.

Last catalogue with full details	Type	Y or Z response of instrument MHz	CRT: Dual beam	CRT: Type of storage	CRT: Split screen	Usable area: cm	Usable area: div	Internal graticule illuminated or non-ill.
	D1	Y2	–	P	S	10x12.5	8x10	N
–	DM53A	Y25	D	V	–	6x10	6x10	–
	DM63	Y15	D	V	–	7.2x9	8x10	N
	DM64	Y10	–	P	–	8x10	8x10	–
	GMA-101A	Z7	–	P	–	26.6x35.5	–	–
	GMA-102A	Z7	–	P	–	26.6x35.5	–	–
	T912	Y10	–	P	–	8x10	8x10	N
	214	Y0.5	–	P	–	3x5	6x10	N
	314	Y10	–	P	–	5.1x6.3	8x10	N
	434	Y25	–	P	S	7.8x9.8	8x10	N
	434 opt 1	Y25	–	P	S	7.8x9.8	8x10	N
	464	Y100	–	FV	–	7.2x9	8x10	I
	466	Y100	–	FV	–	7.2x9	8x10	I
71	549	Y30	–	P	S	6x10	6x10	–
68	564	Y10	–	P	S	8x10	8x10	–
74	564B	Y10	–	P	S	8x10	8x10	–
74	564B Mod 08	Y10	–	P	S	8x10	8x10	–
71	601	Z1	–	P	–	8x10	–	–
	603	Z5	–	P	–	10x12.5	8x10*	N*
	603 opt 2	Z5	–	P	–	10x12.5	8x10*	N*
76	605	Z5	–	V	–	7.2x9	8x10*	N*
	607	Z5	–	V	–	7.2x9	8x10*	N*
	611	Z1.7	–	P	–	16.2x21	–	–
	613	Z1.7	–	P	–	15x20	–	–
73	4501	Z5	–	P	–	7.5x10	–	–
71	5031	Y1	D	P	S	10x12.5	8x10	I
	5111	Y2	–	P	S	10x12.5	8x10	N
	5113	Y2	D	P	S	10x12.5	8x10	N
	5113 opt 3	Y2	D	P	S	10x12.5	8x10	N
	5115	Y2	–	P	S	10x12.5	8x10	N
	5441	Y60	–	V	–	7.2x9	8x10	I
	5441 opt 5	Y60	–	V	–	7.2x9	8x10	I
	7313	Y25	–	P	S	7.8x9.8	8x10	I
71	7514	Y90	–	P	S	8x10	8x10	I
	7613	Y100	–	V	–	7.2x9	8x10	I
74	7623	Y100	–	FB V	–	7.2x9	8x10	I
74	7623 opt 12	Y100	–	FB V	–	7.2x9	8x10	I
	7623A	Y100	–	FB FV	–	7.2x9	8x10	I
	7633	Y100	–	FB FV	–	7.2x9	8x10	I
	7834	Y400	–	FB FV	–	7.2x9	8x10	I

Fastest writing speed		Stored trace brightness	Intergrate mode† (use reduced brightness)	Longest storage time of fastest recording		Longest erase cycle	Auto erase	Remote control (Erase only)	Locate zone or Write-through	Dot writing time	Resolution	Type
normal cm/µs	enhanced or reduced scan† cm/µs	fL		normal brightness min	reduced brightness min	ms				µs	paired lines	
0.025	–	15	R	60	600	250	–	–	–	–	–	D1
0.05	E0.5	100	–	10	60	500	–	R	L	–	–	DM53A
0.045	E0.9	100	–	0.5	5	250	–	–	L	–	–	DM63
0.025	E0.25	6	I	60	–	250	A	E*	L	–	–	DM64
0.01	–	5	–	15	30	1800	–	R	W	5	368x490	GMA-101A
0.015	–	5	–	15	30	1800	–	R	W	5	420x560	GMA-102A
0.025	E0.25	6	I	60	–	600	–	–	–	–	–	T912
0.04	E0.25	8	–	60	–	500	–	–	–	–	–	214
0.05	E0.25	12	I	240	–	300	A	–	–	–	–	314
0.1	E0.4	10	I	240	–	300	–	–	L	–	–	434
0.75	E5	5	I	240	–	300	–	–	L	–	–	434 opt 1
100	–	80	–	0.25	6	1350	A	–	–	–	–	464
135	R1350	80	–	0.25	6	1350	A	–	–	–	–	466
0.5	E5	3.5	I	60	–	150	A	R	L	–	–	549
0.025	E0.25	6	I	60	–	250	–	E▽	L	–	–	564
0.025	E0.25	6	I	60	–	250	A*	R	L	–	–	564B
0.1	E0.5	2	I	60	–	250	A*	R	L	–	–	564B Mod 08
0.01	–	6	–	15	–	200	–	R	–	9	100x125	601
0.025	–	15	–	60	600	250	–	R	–	4	80x100	603
0.25	–	6	–	60	600	250	–	R	–	0.5	80x100	603 opt 2
0.9	–	100	–	5	60	500	–	R	–	–	80x100	605
0.72	–	200	–	1	10	500	–	R	–	–	144x180	607
0.025	–	6	–	15	300	500	–	R	W	5	300x400	611
0.025	–	20	–	15	300	900	–	R	W	5	200x266	613
0.01	–	75	–	15	–	175	–	R	–	8	100x125	4501
0.025	E0.1	6	–	60	–	250	A	R	L	–	–	5031
0.025	–	15	R	60	600	250	A*	E*	–	–	–	5111
0.025	–	15	R	60	600	250	A*	E*	–	–	–	5113
0.25	–	6	R	60	600	250	A*	E*	–	–	–	5113 opt 3
0.25	E1	6	R	60	600	250	A*	E*	–	–	–	5115
4.5	–	100	–	5	60	500	–	–	–	–	–	5441
0.9	–	100	–	5	60	500	–	–	–	–	–	5441 opt 5
0.5	E5	10	I	240	–	300	A	E	L	–	–	7313
0.06	E1	6	I	60	–	1000	A	R	W	–	–	7514
4.5	–	100	–	5	60	500	–	E	–	–	–	7613
90° 0.45	–	100	I –	∞ 0.25	∞ 60	1000	A –	E	–	–	–	7623
200° 0.45	–	100	I –	∞ 0.25	∞ 60	1000	A –	E	–	–	–	7623 opt 12
45 △ 135 △	–	100	–	∞ 0.5	∞ 15	1300	A	E	–	–	–	7623A
45 △ 135 △	R180 R1000	100	–	∞ 0.5	∞ 15	1300	A	E	–	–	–	7633
45 △ 270 △	R350 R2500	135	–	30 0.5	∞ 15	1200	A	R	–	-	–	7834

Details
on page
↓

SUMMARY

Storage tube basics (Chapter 1)

When a target is bombarded with electrons, secondary emission can occur. The
amount depends on material and construction, and given these, on the number and speed
of primary electrons. The ratio of secondary emission to primary electrons is called
1 the secondary emission ratio, δ. This ratio depends on the speed of the primaries.
The speed is a function of the potential difference between the CRT cathode and the
target. A nearby collector can be used to attract the secondaries.

If the target is floating, it is obvious that unless the number of landings
equals the number of leavings, the target voltage will drift. Below the first cross-
over (see figure 2) the target gains electrons and drifts negative. Above the first
crossover it loses electrons and drifts positive. Higher up on the curve, where δ
2-3 is again 1, we find the upper stable point, USP. This is roughly at the collector
voltage. If the target tries to move higher still, the collector will fail to collect
secondaries, so the target keeps them and comes down again. The second, lower stable
point (LSP) is roughly at the voltage of the cathode. It occurs because the target
receives no electrons at all; they go straight to the collector. If the target tries
to move lower still, it attracts ions and comes up again, but because few ions are
produced in the tube this happens slowly.

So the floating target behaves bistably. This is basic to *all* storage tubes.
Using a dielectric as a target, we can make any part of its surface go to the upper
stable state. We do this with the writing gun (whose electrons arrive on the target
4 with great speed, causing much secondary emission) and say that those parts of the
target are written. A second gun floods the whole target continuously, moving areas
above the first crossover towards USP, those below towards LSP.

Phosphor-target tubes and instruments (Chapters 2-4)

Phosphor-target tubes use phosphor as the dielectric, with the collector as
5-6 a transparent metal film between it and the CRT faceplate. At LSP no electrons land,
so no light is emitted. At USP electrons land and leave in equal number, but landings
have more energy and the balance is converted into light.

The stable range of collector operating voltages extends from the fade-positive
level, where the whole target gets spontaneously written, to the retention threshold
7-10 level, where the target will fail to store. The range must be large enough to accom-
modate equipment drift, incorrect setting-up, CRT ageing and non-uniform target
behaviour. The main price paid for the large stable range is poor contrast.

The writing action depends on the beam depositing enough charge on each target
11-12 element to raise it above the first crossover. For a given beam intensity, this
depends on the dwell time. On stationary spots we specify the "dot writing time"
(typically 5 µs). On moving spots we specify the "writing speed" (typically 0.1 cm/µs)

If the collector operating level is raised, the writing speed can be marginally
improved. (At the same time this increases the light output, but contrast and tube
life are reduced.) Two better methods exist to store very fast traces. One is called
"integrate". On repetitive signals we can stop the floodbeam so that charges laid down
13-16 during successive sweeps are not removed from the target but accumulate until they ex-
ceed the first crossover. The other method is called "enhance". On single events
(where the integrate technique cannot be used) we add a pulse to the whole target of
such a size that the charged parts, but not the background, are lifted above the
first crossover, and we hold this pulse long enough to give the floodbeam time to in-
crease the separation betwwen the written and unwritten areas.

:ails
page

Written information is erased by applying a negative pulse to the collector, which will capacitively couple the written target areas below the first crossover,
17-18 and the collector voltage is then slowly returned to avoid coupling them back up. To prevent electro-static shielding effects, the erase pulse is preceded by a fade-positive pulse writing the whole target.

Bistable instruments typically feature a store/non-store switch and manual erase button, automatic erase with variable viewtime, integrate and enhance. In
19-20 many models split screen operation is available, allowing all these modes (except integrate) to be used in either or both screen halves, and some offer write-through or locate modes to facilitate trace positioning.

Transmission tubes and instruments (Chapters 5-7)

In transmission tubes the target is grid-like, and the phosphor beyond it sits at several kV, giving a much brighter display. The bistable transmission tube is designed to cut off the floodbeam at LSP, whereas in halftone transmission tubes it takes a more negative potential than LSP to do this. As with the grid of a valve, the cutoff characteristics are altered by changing the spacing of the grid.

Writing is done, in both cases, by the writing beam lifting the target voltage.
21-23 In bistable tubes it must be lifted above the first crossover and the floodbeam then stabilizes it at USP, giving a fixed light output. In halftone tubes the writing beam pushes the target up from cutoff towards LSP, so the amount of light depends on how far the target gets pushed up. Since almost any amount of writing beam will push the target up by some amount, this type of tube achieves a faster writing speed (typically 5 cm/μs). But ions also bring up the target towards LSP over a period of about 10 minutes, obliterating the written trace.

Erasing starts as usual with a fade-positive pulse and then a negative transition, applied in these tubes to the target support mesh. At this point,
24-25 bistable tubes are ready to write, but halftone tubes are still bright. Halftone tubes now receive a small positive pulse, the prep pulse, of such length and height that at *its* end the target just drops to the cutoff point.

Variable persistence is a kind of continual partial erasing, the result of a sequence of short prep pulses, which keeps pushing both written and unwritten
26-27 target areas towards cutoff. This maintains the background dark and causes the written trace to fade away gradually.

Instruments with bistable transmission tubes will have features similar to those using phosphor-target bistable tubes. Halftone tube instruments usually have front-panel variable persistence controls and a "save" mode allowing the floodbeam
28-29 to be reduced in order to slow down the fading-up action caused by ion landings. This gives longer viewtime at the expense of display brightness.

Transfer tubes and instruments (Chapters 8-9)

Summing up the modes of operation of these tubes, in the bistable and variable persistence mode the high-speed mesh (see figure 20) sits at fade-positive potential to allow free beam passage. Writing takes place on the storage target.
30-35 Whether this operates as a bistable or halftone target depends on the erase pulse which is either the bistable pulse only, or followed by the halftone prep pulse. In the transfer mode, writing is done on the high-speed, fast-decay target and immediately after the end of the sweep the stored pattern is transferred to the storage target, operated bistably or as halftone target.

Transfer tube oscilloscopes can operate with conventional bistable and/or variable persistence storage and will offer one or both fast (single sweep transfer)
36-40 modes. They may have provision for multiple trace recording and for reduced scan operation with greater writing beam intensity. The combination of fast halftone and reduced scan mode can achieve writing speeds of up to 2500 cm/μs.

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