Cathode Ray Tubes:

Getting Down to Basics

FORWARD

This book was written to serve three major purposes:

1. To understand the interaction and interdependence between the CRT and electronic circuitry in measurement devices having CRTs. The cathode-ray tube (CRT), as the output or display section of oscilloscopes, graphics terminals and other measurement devices, requires understanding in isolating a malfunctioning electronic circuit, the design of circuitry that interfaces with the CRT is dependent upon the requirements of the CRT and before these circuits can be fully analyzed the requirements of the CRT must be known. The proper operation of the various controls and adjustments directly associated with the display requires an understanding of the probable effect upon the CRT.

2. To understand the basic theory or principles of CRT design and operation. In today's world of solid-state devices the principles of operation of vacuum devices is relatively unknown. This book is an attempt to give the engineer, technician or other reader a basic understanding of CRT operation.

3. To consolidate previous CRT-technical documents under one cover. Over the past 30 years there have been a number of CRT theory booklets and technical reports written by Tektronix covering CRT design and theory of operation; some were published and now are out-of-date and no longer in print, others were never published.

I wish to acknowledge those whose publications have been used in this book and whose efforts continue to advance the performance of cathode-ray tubes.

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CRT Product Assurance Manager
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The Transfer Storage Tube

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

The transfer storage tube Figure 26-1 will operate in a conventional (non-store) mode, a halftone storage mode, a bistable storage mode, or an enhanced (fast) bistable mode. The halftone mode offers a high contrast display of slower speed signals for viewing times of a few minutes. Operation in variable persistence is possible in the halftone mode. The bistable mode is also for slow speed signals but the display can be viewed for longer times; in fact, typically the storage can be viewed for hours. The transfer mode is essentially an enhanced mode of bistable operation with an enhance factor of around 3000. Typical writing speeds are 100×10^6 div/sec.

The halftone mode will be discussed first. The same principles of operation of the storage mesh in the halftone mode are applied to the high speed mesh in the transfer mode. The transfer mode will be discussed next. The final step in a transfer sequence is to store the information onto the storage mesh which is being operated in the bistable mode. Hence, the bistable mode is a fallout from the transfer mode and will be discussed last. The instrument may be considered as a classic halftone storage scope with an ultra fast enhance mode and a permanent storage bistable mode.

HALFTONE MODE:

The storage section includes everything from the floodguns forward. This includes a collimation system comprised of two floodguns, three wallbands (collimation electrodes) and a collector (ion repellor) mesh. This collector mesh is particularly required for collimation since the targets operate at low potentials and it is important that the flood electrons approach normally to the plane of the target mesh. The next mesh forward is the high speed target mesh which in the halftone mode is operated at the same potential as the collector. The storage mesh modulates the flood current and the differences in current are displayed on the phosphor screen which is at 7 kilovolts with respect to the floodgun cathode. This operation can be treated as a classic halftone tube.

The flood electrons approach the storage target. Electrons which pass through the mesh openings are accelerated by the 7 kV field to the phosphor and excite a visible display. The transmission of electrons through the mesh openings is described in the curve of Figure 26-2. The storage mesh potential on this curve actually is a potential determined by both the support wire potential and the dielectric surface potential. Controlling the storage potential along this curve is what the halftone mode is all about.

An operating point for the storage mesh is found by lowering the potential of this target until some section of the view screen begins to go dim. This indicates that this area has dropped off the flat upper part of the curve such as to point A of Figure 26-2. The operating point is selected 3 volts above this point to ensure that the entire target is at saturation.

The following waveform Figure 26-3 is then applied to the mesh to move the dielectric down the curve and prepare for writing:

TRANSFER STORAGE TUBE

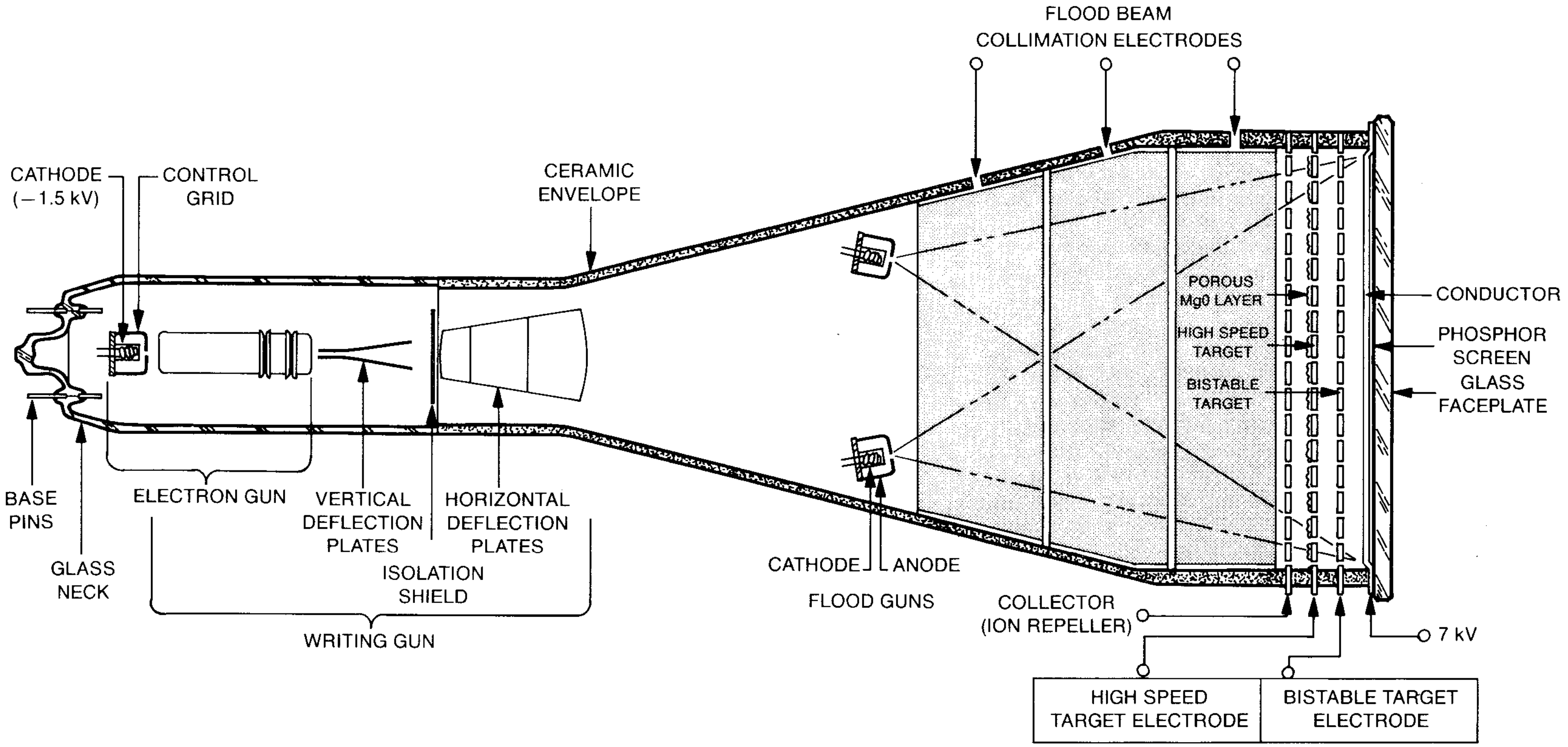

Figure 26-1

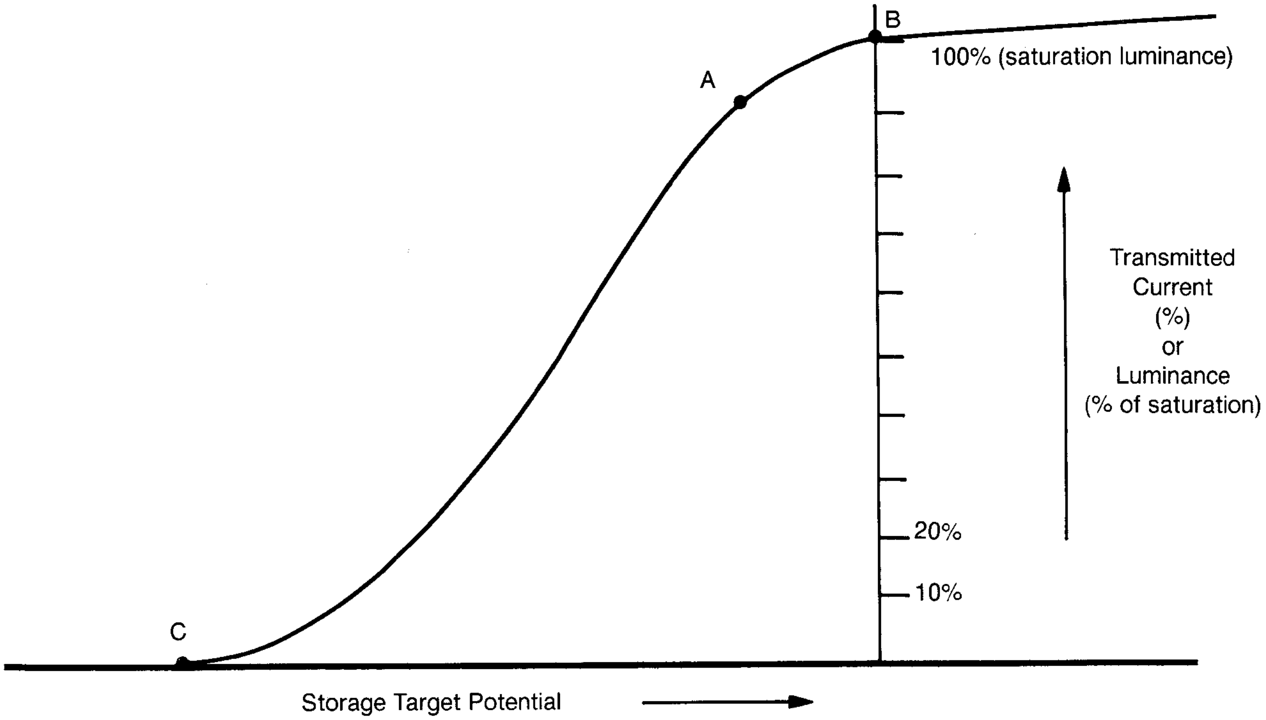

Figure 26-2

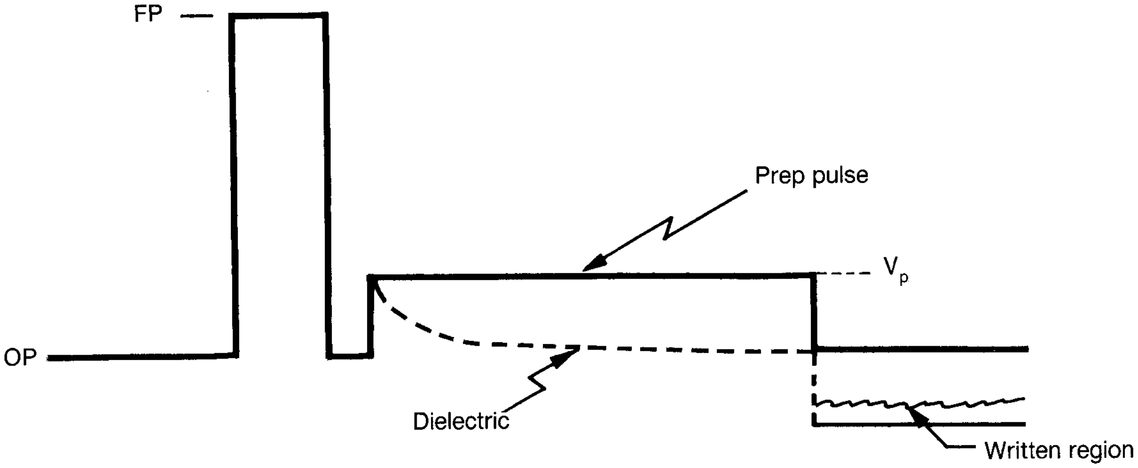

Figure 26-3

This discussion will follow the test set technique for achieving the above waveform rather than what is done in the instrument. The difference is that the test set adds a prep pulse to the operating point. The instrument has a pre-set voltage at the top of the prep pulse and the operating point will be varied to change the pulse height. The advantage of the latter is in versatility to the scope user and does not affect the way the tube operates.

The fade positive pulse breaks down the dielectric and establishes a uniform potential across the target. The dielectric surface changes positive with respect to the mesh wire during the fade positive pulse, but between the FP and prep pulse moves to approximately floodgun cathode potential.

The prep pulse height is below the first crossover potential. The dielectric charges down toward floodgun cathode. This moves the storage target potential negative approximately Vp volts. As Vp is increased and the cycle repeated, some area of the target goes dark. On our transmission curve this corresponds to Point C or cut-off. Due to a combination of target non-uniformities and collimation imperfections, different areas of the storage target have different transmission curves (Figure 26-4). Thus, to prep the entire target below cut-off, the prep pulse height must be increased until the last area goes dark, (Point D of Figure 26-4).

The difference in volts between that required to get the first area to go dark and what is required for the last area to go dark is a measure of uniformity and is called the differential cut-off (DCO).

The writing beam charges the dielectric positive by secondary emission. Halftones are achieved by charging the dielectric to any point along the transmission curve. For the writing speed measurement of the 7623A/7633, the slowest area is charged to 10% of saturation luminance. This corresponds to Point E of Figure 26-4 and represents enough charge deposited to move the surface potential from Point D to Point E. Writing speed is inversely proportional to the voltage from D to E and the DCO is a major part of this voltage.

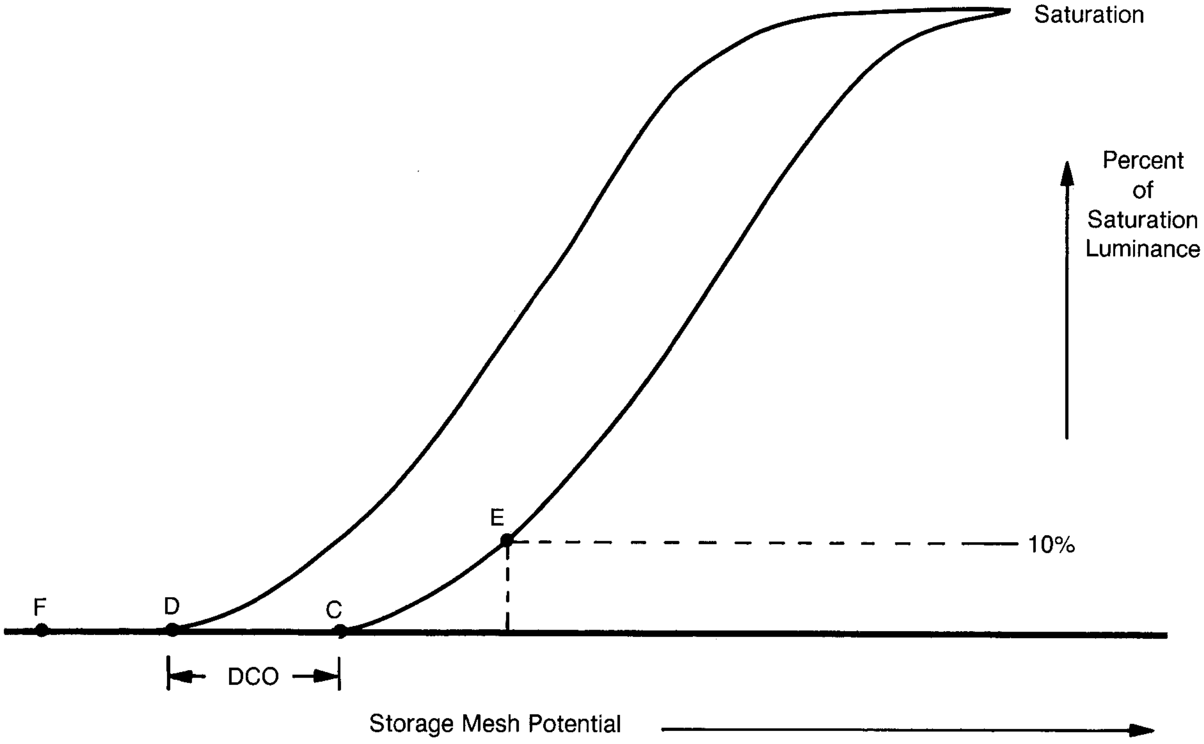

Figure 26-4

Following the prep pulse, the dielectric surface is below floodgun cathode and the most negative element in the storage system. Positive ions created by the flood beam preferentially strike this surface and drive it positive along the transmission curve. This decreases the contrast ratio which approaches 1:1 as the unwritten area approaches saturation. By erasing the target more negative (increasing the prep height) such as to Point F of Curve B, the dielectric has farther to charge to saturation and the view time is lengthened. However, now to write the target to 10% saturation requires enough charge to move the dielectric from Point $\acute{F}$ to Point E.

A writing speed versus viewtime curve is shown in Figure 26-5.

The equation for writing speed can be derived from the basic equation for charge storage on a dielectric: (1) $Q = CV$

$$\Delta Q = I_b(\delta - 1)\Delta T$$

$$C = \frac{EA}{d}$$

A = area = $\Delta L \times TW$
d = dielectric thickness
E = dielectric constant

ΔV = voltage shift required for writing

$$v = \text{writing speed} = \frac{\Delta L}{\Delta T}$$

$$\therefore \; A = v\,(TW\Delta T)$$

$$(2)\; I^b(\delta\text{-}1)\Delta T = \left(\frac{EvTW\Delta T}{d}\Delta V\right)$$

$$v = \frac{Ib(\delta - 1)d}{TW\,\Delta V\,E}$$

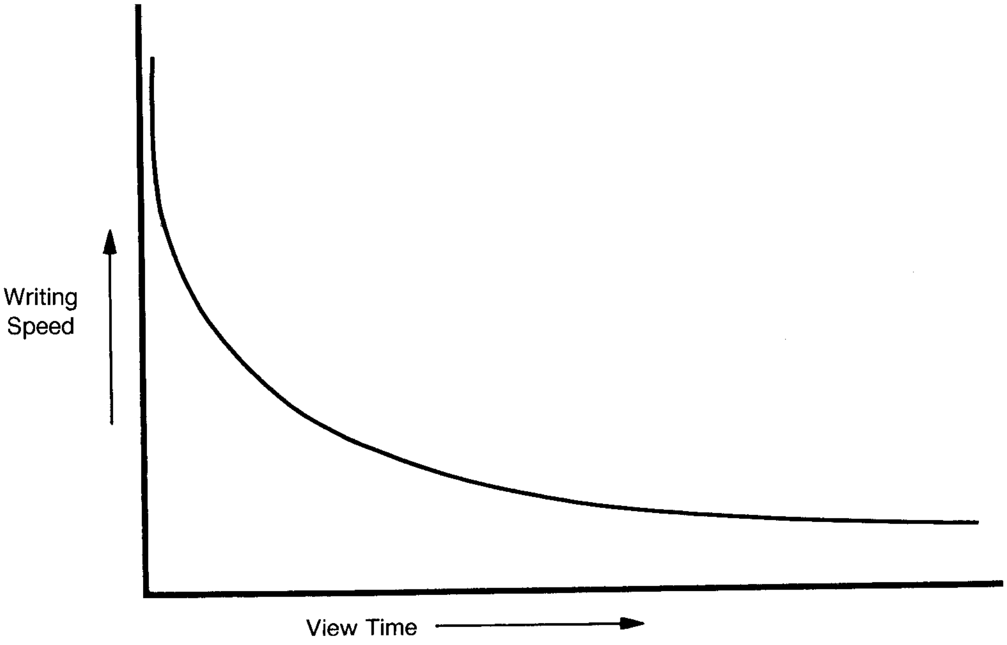

Figure 26-5

The value of this equation is that it becomes apparent what can be done to improve writing speed. The I_b/TW is a gun parameter. It is primarily limited by instrument requirements of bandpass and deflection voltages. The $(\delta-1)$ is the secondary emission gain in the target and is a material property. MgO has a high secondary emission gain and good stability through target processing. The last two parameters are dielectric structure properties. The dielectric thickness is obvious. The dielectric constant can be varied by changing the density of the structure.

Target deposition methods attempt to optimize writing speed by achieving a thick deposition (20 microns typically) and a low density (about 5% of bulk density) with a material which has a high secondary emission ratio (Mg0). However, it turns out that these structure changes also increase the speed at which ions write up the target; thus, we move up on the view time curve to high writing speeds and short view times (Figure 26-5). The transfer mode provides a way to extend the view time and use the fast writing speeds that normally would be viewable only for a fraction of a second.

TRANSFER MODE:

In the transfer mode, the high speed target performs in the same manner that the storage mesh did in the halftone mode. One difference is that the target is at fade positive while the display is viewed and only drops into the halftone condition when the transfer cycle is initiated.

The classic bistable erase pulse is applied to the storage target while the high speed target is at fade positive (Figure 26-6). This ensures a maximum amount of transmitted current which is required for erasure. This erasure leaves the storage target dielectric at rest potential (Figure 26-7).

A prep voltage, Vp, is selected so that all areas of the high speed target are well above floodgun cathode and below first crossover. As in halftone, the dielectric charges down toward floodgun cathode. However, due to the low fields on either side of the high speed target (rest potential on the storage target and 125 volts on the collector), the charging has a self-leveling effect. That is, the areas of higher potential initially receive more flood current and consequently charge down more rapidly. The areas of low potential charge slowly. The net effect is that all areas approach a condition of uniform flood current density which implies uniform transmission of electrons over all of the target, or low DCO. The DCO is typically reduced to a few tenths of a volt. A considerable amount of writing speed of the transfer tube depends on this reduction of the DCO.

To establish V, we operate the tube with no writing beam. V moves the target along the transmission curves (Figure 26-8).

As before, the two curves correspond to the extreme areas of the target or the DCO. If the ΔV is set for a transmission at Point A of Figure 26-8, which was the last area of the target to cut-off, it establishes a charging rate on the corresponding area of the storage mesh of : $Qa = Ia (\delta-1) T$. Ia is the current transmitted through the high speed mesh in Area A. Note in Figure 26-6 that the storage mesh during ΔV is pulsed to 600 volts to ensure a good secondary emission gain $(\delta-1)$. ΔT is the pulse width. This corresponds to view time in Figure 26-5 for the high speed target and is kept narrow. However, a lower limit exists that allows operation in the lower portion of the transmission curve where the slope is steeper (higher u). A typical value is 100 milliseconds.

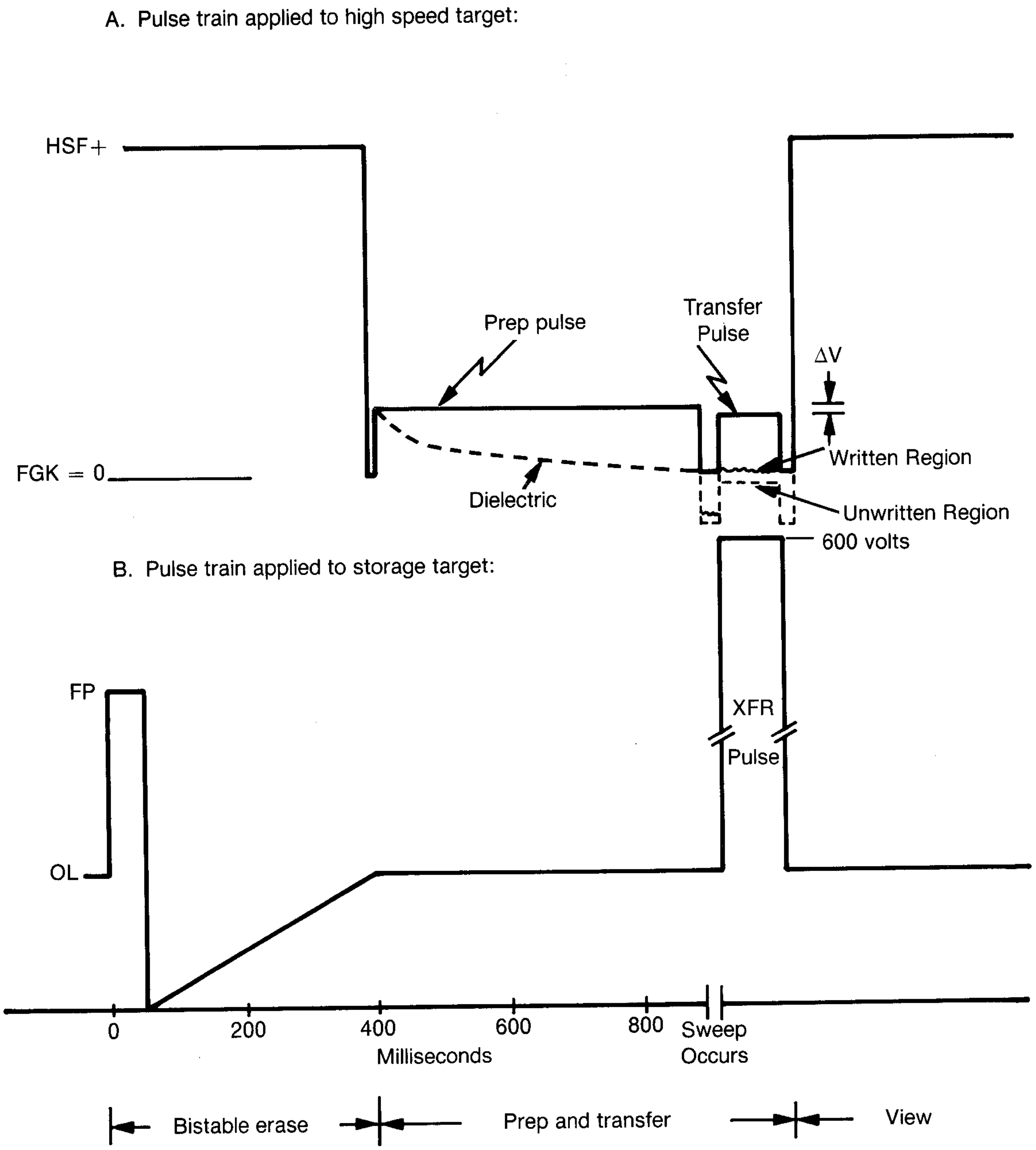

Figure 26-6

For any value of ΔV, $\Delta V5$, Qa is the area which charges most positive on the storage mesh. Any other area would have a charging rate less than Qa but greater than Qb. Qb is the slowest charging area. ΔV is established so in the area on the storage target corresponding to A, 5% of the target is written above first crossover (Point A on Figure 26-7). This ensures that a minimum of increase in the charging rate (potential on high speed dielectric) will cause the storage mesh in this area to charge above first crossover. All other areas are charged to a point between A and B on Figure 26-7 and floodgun current will subsequently charge them to rest potentials.

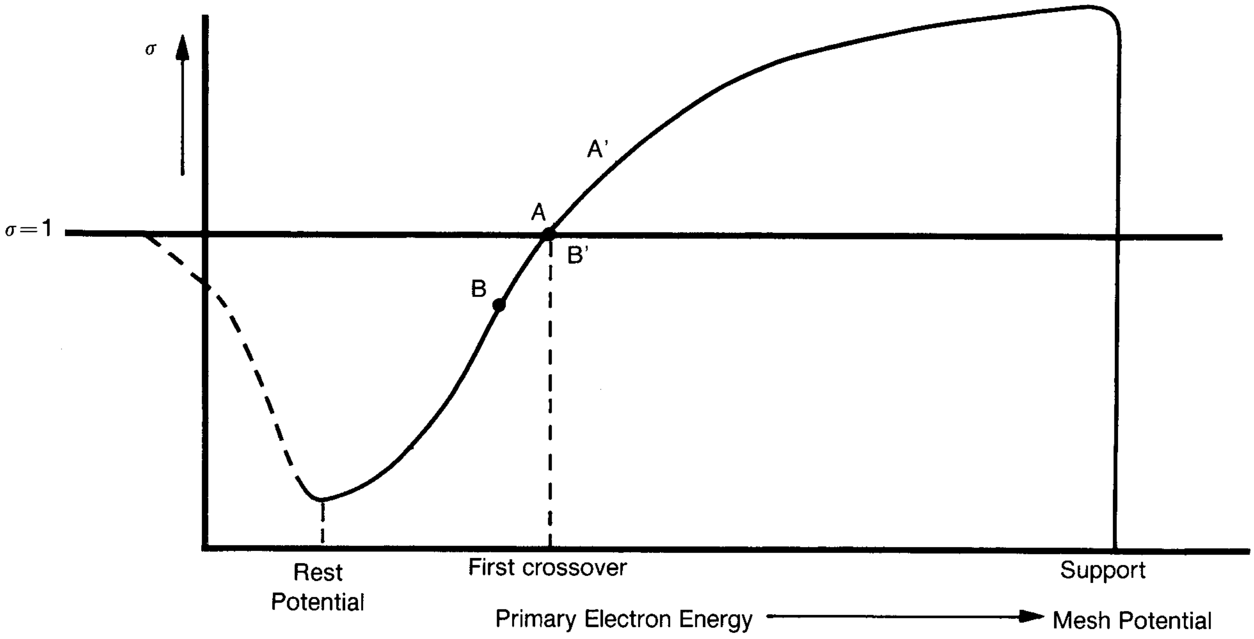

Figure 26-7

While the writing gun is off, DCO can be easily measured. If ΔV is decreased (transfer pulse on high speed target is raised), the charging rates of all areas of the target increase. At ΔV95 the charging rate of the slowest area, Area B, is great enough to charge a corresponding area of the storage mesh above first crossover (Point B on Figure 26-7). Now the fastest charging area, Area A, is well above first crossover, Point A on Figure 26-7, and all areas of the target are above first crossover. The floodguns subsequently charge all areas of the target toward the stable point at the storage mesh potential. Actually, ΔV95 is defined when 95% of the quality area is written. The DCO is the difference between. ΔV95 and ΔV5.

For writing, the ΔV is set at ΔV5. To write the slowest area of the target, the writing beam must charge the dielectric enough to move the transmission of this area from Point B to Point C on Figure 26-8. The charging rate of the slowest area is now sufficient to move the storage target in the corresponding area above first crossover (Point A on Figure 26-7) since this charging rate is now equal to the initial charging rate of Area A.

The same equation used for halftone writing speed can be applied to the high speed target.

$$V = \frac{Ih}{TW}$$

$$\frac{I}{\Delta V}$$

$$\frac{(\delta\text{-}1)d}{E}$$

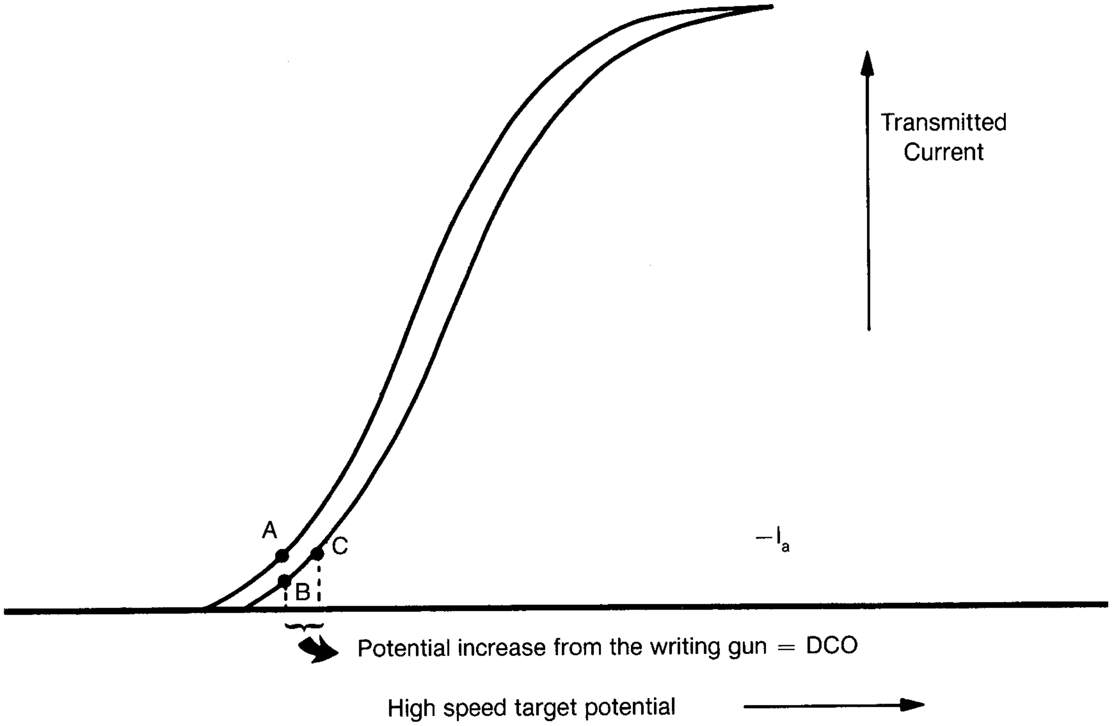

Figure 26-8

A sensitivity measurement is possible which measures (δ-1) (d/E.) Typical value is 3×10^6 volts/coulomb.nm^2. ΔV in this equation corresponds to the DCO. Ib/TW equal to 1 μa/mil is typical with the 7633 CRT. Plugging these values into the equation yields about 100×10^6 cm/sec per 120 millivolts of DCO. This is good agreement with measured writing speeds. The correlation improves if a factor is included for the density distribution of the writing beam.

Oscilloscope application revealed a basic problem. The problem is that the target must wait in the prep mode until the sweep is triggered. The dielectric is charging on a curve assymptotic to the floodgun cathode. There is no way to know when the sweep will trigger. Therefore, there is no way to know in advance to what potential the dielectric will prep. It is essential to know this so V5 can be established in advance. The solution to this is to stop the prepping of the dielectric at a certain level and hold it there. This is done with a holding pulse train as seen in Figure 26-9.

Each positive pulse (about 2 μsec pulse width at 100 Hz) pushes the dielectric above first crossover and a small, fixed amount of positive charge is added. (see inset of Figure 26-9). Between pulses, the dielectric is below first crossover and charges negatively toward floodgun cathode. The rate of negative charging is dependent on the dielectric potential (the lower the potential the slower the charging). When the prep pulse is initiated, the negative charging between pulses is greater than the positive charging during pulses. The net negative charge lowers the dielectric potential until the negative and positive charging is equal, equilibrium is established. The small potential shifts during each cycle of the holding pulses is small with respect to the DCO and have a minimum effect. Thus, the potential on the dielectric is stable and ΔV is set for this established potential. The cost of this stability in terms of performance is that the high speed target does not prep completely so the minimum DCO/maximum writing speed is not achieved. However, the writing speed loss without the pulses in the first minute is typically several orders of magnitude greater than that due to the increased DCO with the holding pulses.

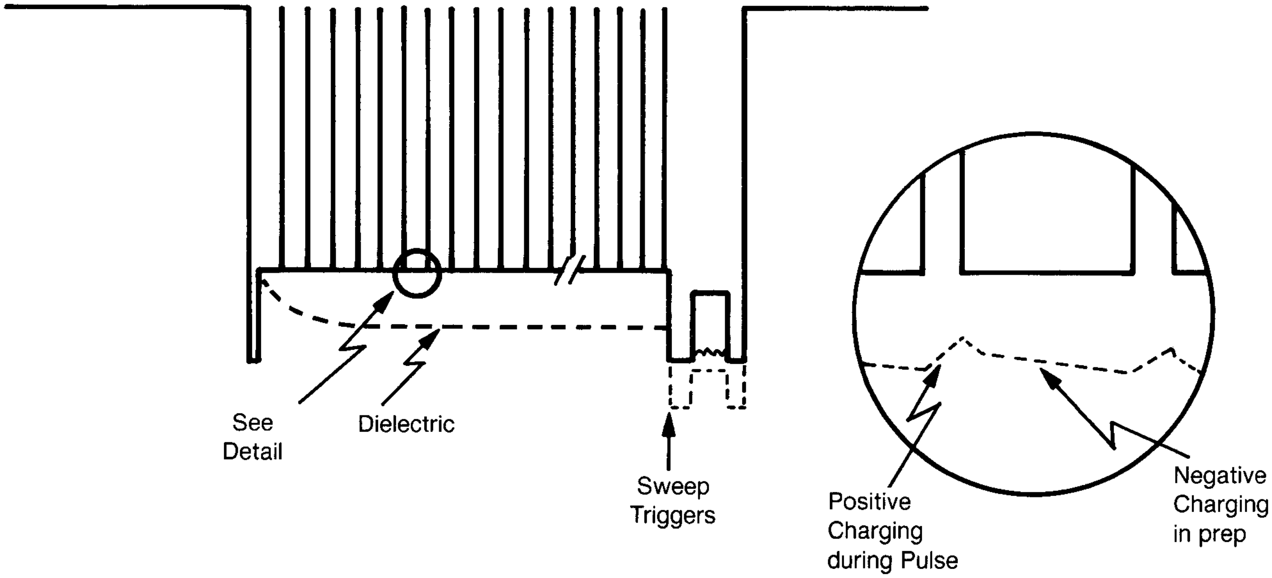

Figure 26-9

BISTABLE MODE:

The bistable mode is essentially the same as our classic bistable storage tubes. To write the storage target requires the writing beam to charge the dielectric from rest potential to first crossover (Figure 26-7). The writing speed is limited since the beam must pass through both the collector mesh and the high speed target.

VIEWING:

When a signal is written onto the storage target (either directly by the writing beam or transferred from the high speed mesh), the image is viewed on the phosphor screen as a bright area (high current density) with a dark border. Unlike the halftone mode in which the background is near cut-off (Figure 26-4, Point D) and the written area is the only area transmitting a significant current, the background in the bistable mode is transmitting near saturation. (Figure 26-10, Point A).

The bright area of the written information is viewable because it scavenges electrons from surrounding areas and focuses these on the phosphor. This is possible because of the relatively large difference in dielectric potential between written and unwritten area (Points A and B of Figure 26-10). The trace profile is shown in Figure 26-11. The dips adjacent to the trace reflect scavenged electrons.

One disconcerting effect of the lack of contrast when this scavenging cannot occur is that it is difficult to detect the difference between the unwritten and the fully written condition. The differences in transmission (Points A and B of Figure 26-10) are insignificant. However, with the focusing of the scavenged electrons, the trace is a brilliant several hundred footlamberts at a contrast ratio near 3:1

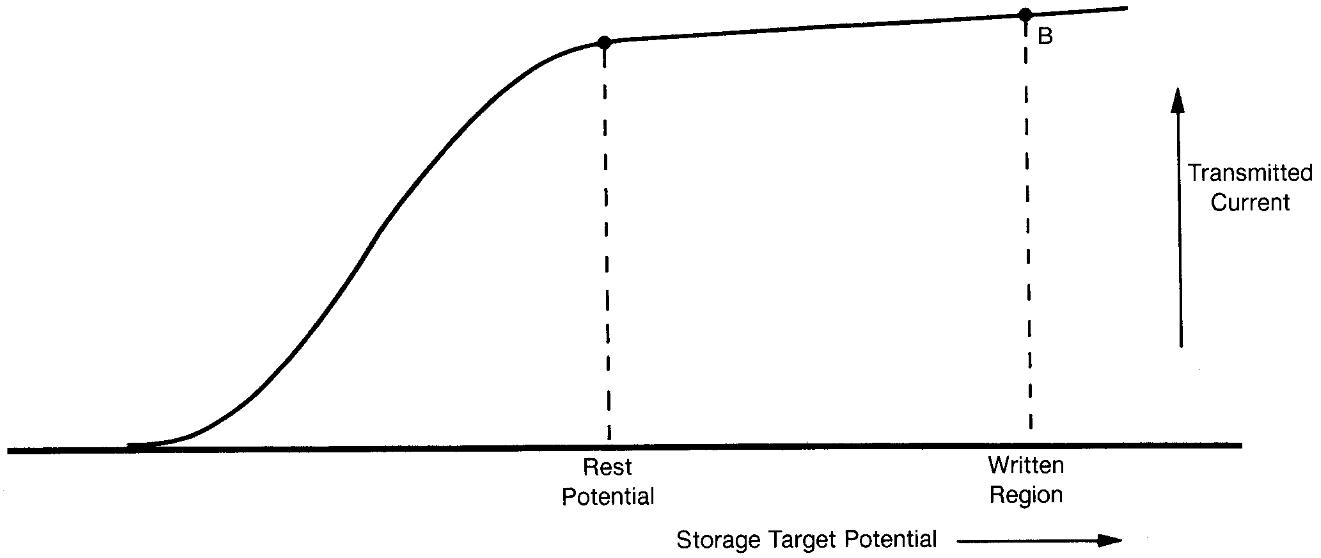

Figure 26-10

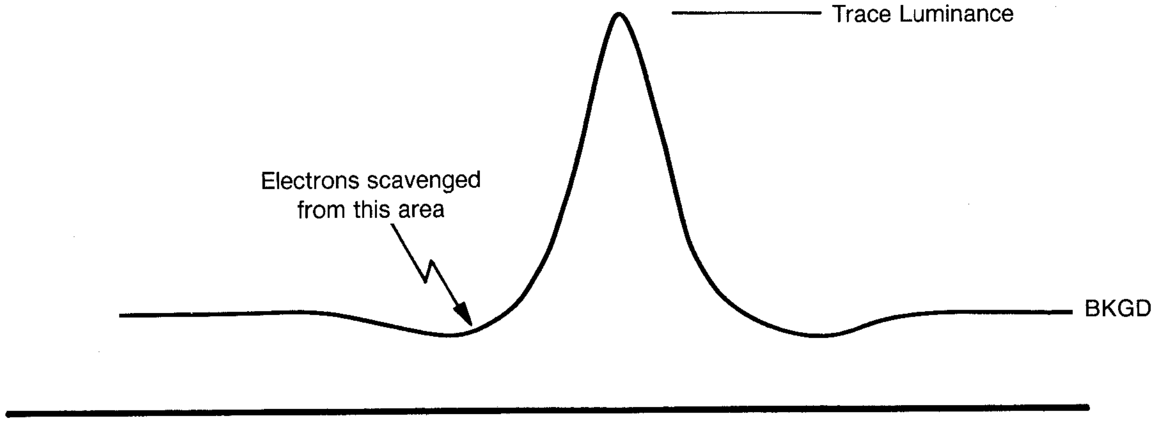

Figure 26-11

FEATURES OF THE TRANSFER STORAGE OSCILLOSCOPE

A few Tektronix 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. Here we shall discuss the features of the type 7633 and mention some of the innovations of the more recent 7834. For details of the controls available on other transfer instruments you should refer to their respective operating manuals.

Many of the facilites of the 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 allows 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 when viewing very fast, faint traces, or moving the background well below cutoff for good contrast and long viewing times 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 carefully. A vernier screwdriver control marked FAST LEVEL CENTER, 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 recent instruments 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 27-1.

Turning now to the reduced-scan feature, you may recall that we mentioned the difficulty of achieving uniform storage target performance in transmission tubes. But the writing speed and thus the usefulness of an instrument is limited by the performance in the least sensitive part of the screen. During manufacturing we try to make the target as uniformly sensitive as possible but there are still areas on the target less sensitive than other areas. When the first transfer tube instrument, the 7623, was introduced, the writing speed specification was limited to the center 4 × 5 division area. This is inconvenient for users who generally prefer to have an 8 × 10 div graticule. To make measurement more convenient additional graticule markings were added to the face of the CRT, outlining 8 × 10 half-sized divisions within the center 4 × 5 standard divisions. When the REDUCED-SCAN mode is entered by pulling the appropriate knob, the deflection sensitivity of the instrument 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 negative cathode potential on the writing gun is doubled for a more intense writing beam. The combined effect of these changes is a six to eight times increase in writing speed.

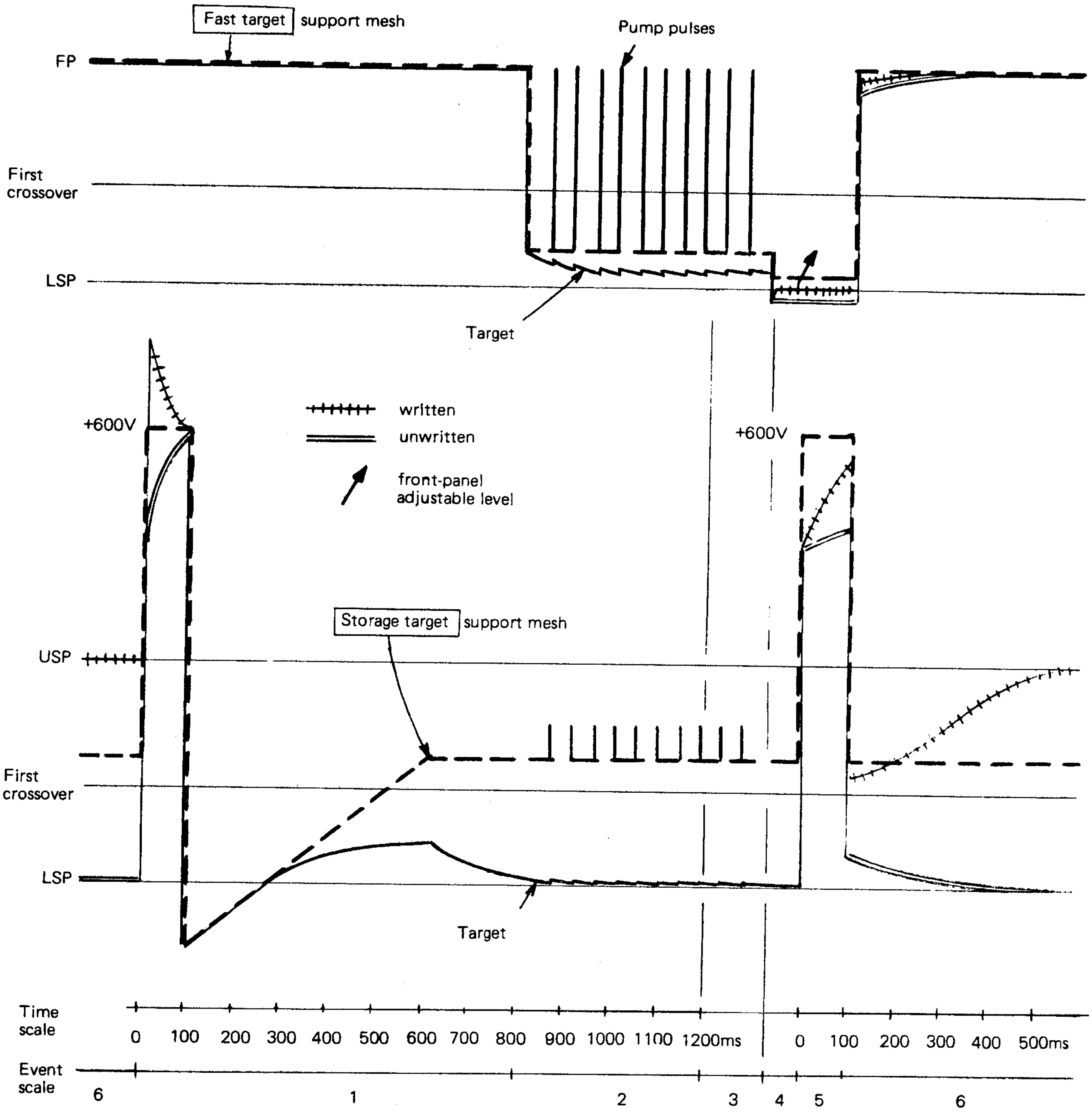
Fast target support mesh
Pump pulses
FP
First crossover
LSP
Target
+600V
written
unwritten
front-panel adjustable level
+600V
Storage target support mesh
USP
First crossover
LSP
Target
Time scale
0 100 200 300 400 500 600 700 800 900 1000 1100 1200ms
0 100 200 300 400 500ms
Event scale
6
1
2
3
4
5
6

Figure 27-1

A further effect of the reduced-scan operation is that the writing beam spot size is decreased by a factor of about 1.5 and to this extent the resolution 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 application 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 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. In storing slow signals 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 then you will notice that the background of the storage target brightens and each new trace adds to that background brightness. As a result it may not be possible to repetitively store more than one or two times before the target is fully written.

Such a mode of operation is referred to as the "multi" mode. To make multiple sweeps 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 using the periodic erase feature it might be wise to disable this before beginning multiple repetitive storage.

One of the innovations of the 7834 allows traces to be added in the "multi" mode on an 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 occuring at specific intervals. In principle this is similar to the variable trigger holdoff feature offered by many oscilloscopes, 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 minimum. 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 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 smaller tracewidth 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 nearly 20 years ago the writing speed as 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.