BARRIER GRID STORAGE TUBE AND ITS OPERATION*†

By

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Summary—*Two versions of cathode-ray type of electron tubes to enable storage of video signals electrostatically upon an insulating target using a barrier grid or screen, have been designed and operated: the SDT using magnetic focus and deflection, and the STE using electrostatic focus and deflection. For any application, it is essential that their limitations and the functional relations between their characteristics be recognized. The inverse dependence of the fidelity with which the storage tube can reproduce a given signal, as measured by the cancellation ratio, upon the number of storage elements available on a given size target, is to be emphasized (see Equation (9) and experimental verification in Figure 17). However, there exists a maximum fidelity or a limiting cancellation ratio for which the difference between the input signal and its reproduction is just equal to the disturbance introduced by the tube. This indicates a corresponding minimum number of storage elements or amount of information to be stored, less than which no further improvement in fidelity can be realized.*

A differential method of measuring the characteristics of a storage tube is described and used. Though this method and nomenclature relating to such a subtraction or cancellation procedure is used, relationships are indicated between the characteristics described to those needed in the design of any arbitrary system involving storage of a signal.

The theory of the barrier grid target behavior is discussed. Tube data and operational limitations are presented, and it is shown that it is actually advantageous to use output amplifiers no wider in bandpass than is absolutely necessary to the overall system.

Storage times of up to 100 hours were observed with no evident distortion or decay.

INTRODUCTION

RECENTLY there has been evidenced an increasing interest in storage tubes.[1-3] In view of this fact, it seemed appropriate to describe a tube which, though still in an experimental stage

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[1] A. V. Haeff, "A Memory Tube", *Electronics*, Vol. 20, pp. 80-83; September, 1947.

[2] J. A. Rajchman, "The Selectron—A Tube for Selective Electrostatic Storage", *Math. Tab. and Aids to Comp.*, Vol. II, pp. 359-361; October, 1947. (Abstract: *Proc. I.R.E.*, Vol. 35, p. 177; February, 1947.)

[3] R. A. McConnell, "Video Storage by Secondary Emission from Simple Mosaics", *Proc. I.R.E.*, Vol. 35, pp. 1258-1264; November, 1947.

and subject to further development beyond that outlined in this paper, may be of interest to system designers in applications requiring the storage and subsequent reproduction of video signals. There are many of these applications which are now only awaiting an appropriate storage device. For example, a reasonably short time delay (less than one second) could facilitate the solution to certain problems in television and standard audio broadcasting, electronic computer memory, frequency changing and multiplexing in communications, and in signal comparison, where either both signals are not available simultaneously or where it is desirable to make the comparison at an arbitrary phase relation. This last problem of signal comparison was uppermost in our minds during the development and testing of the barrier grid storage tube which is described, and the effect of this viewpoint will be felt in the presentation and in the nomenclature used. However, it will be pointed out that certain characteristics measured are practically directly convertible into characteristics needed in the design of other

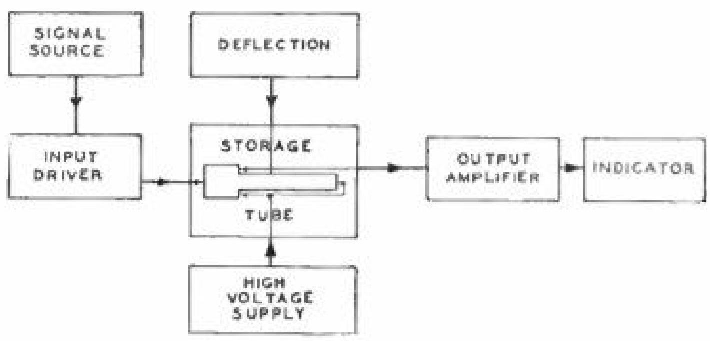

Fig. 1—Block diagram of storage tube cancellation circuits.

systems requiring storage. Likewise, since the storage times observed are of the order of days, the tube is also applicable to relatively long time storage problems.

In any of these applications a pertinent parameter of design is the fidelity with which a given signal may be reproduced and the functional relation of this fidelity to variables of the tube's operation. A critical method of measuring this fidelity is one in which a reproduced signal is compared with the original by subtracting one from the other and observing the difference. If the signals mutually cancel, reproduction is at highest fidelity, and the comparison of any residual signal to the useful output of the tube would be a measure of that fidelity. This measure, referred to as "cancellation ratio", is defined more specifically later on. It will be noticed that this method in one step compares reproduction fidelity in both amplitude and phase. The barrier grid storage tube by its design is particularly suited for this method of measurement since this subtraction or cancellation can be accomplished internally. Naturally, this fits the tube to that class of applications in which such an internal cancellation is desirable, insofar as it eliminates the need for the balanced circuits which would otherwise be required.

The procedure followed consists of impressing upon the tube on one scan a signal consisting of two square pulses whose amplitudes, polarities, and phases may be controlled, and on the succeeding scan two pulses, one of which, the "steady signal", is identical in amplitude, polarity and phase with one of the preceding, the second of which, the "variable signal", is different from the other of the preceding pulses only in polarity. On successive scans the steady signal remains as before, but the variable signal again changes in polarity only. The output from the steady signal then is a measure of the unfaithfulness of reproduction. The output of the variable signal is a measure of the output one would expect from the tube's simply storing and subsequently reproducing a desired signal. In the following, therefore, the output of the variable signal may be referred to now and then as "the desired signal."

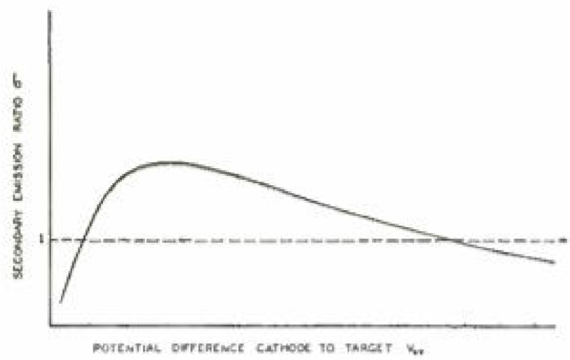

Fig. 2—Secondary emission ratio as a function of primary electron voltage.

The principle of electrostatic storage on an insulating surface has long been known and used in television pickup tubes, such as the iconoscope.[4] If an insulating surface is bombarded by an electron beam, the secondary emission ratio will vary with the energy of the bombarding electrons, according to the approximate curve shown in Figure 2. If the energy is such that the secondary emission ratio is greater than unity, then the potential of the target surface will change with respect to the electrode which collects the secondaries until the net number of secondaries leaving the target surface is exactly equal to the number of primaries arriving there. The surface potential, at which this action takes place, is known as the equilibrium potential. The remaining secondary electrons collect in the form of a space charge and rain back on the insulating surface, charging the unbom-

[4] V. K. Zworykin, G. A. Morton, and L. E. Flory, "Theory and Performance of the Iconoscope", *Proc. I.R.E.*, Vol. 25, pp. 1071-1092; August, 1937.

barded parts of the surface to a negative potential. Thus, a charge pattern is built up on the surface in the absence of any applied signal. The returning electrons, of course, partially neutralize any charges already on the surface and, thus, would make any comparison of signals from scan to scan impossible. Several ways have been attempted in the past to eliminate the redistribution effect, some of which are listed below:

1. Operation with a low energy beam where the secondary emission ratio is less than unity, as is done in the orthicon.[5]
2. Operation with a high energy beam where the secondary emission ratio also is less than unity.[6]
3. Maintaining the surface at a negative potential by a rain of electrons from a separate low energy source.[1]

Fig. 3—The barrier grid storage tubes: STE electrostatic tube in background, SDT magnetic tube in foreground.

4. Use of a grid or screen on or near the surface, operated at a potential preventing return of the electrons to the insulating surface.[6]

Each of these methods is adaptable to a particular use, the last one being chosen for the particular storage tube to be described. This tube consists essentially of an electron gun, an insulating target with a signal plate on the back and a fine mesh screen within a few mils of the front surface of the insulator, and a means of collecting the secondary electrons from the surface. The primary and secondary beams can be focused and deflected, either magnetically (SDT type) (Figure

[5] H. Iams and A. Rose, "Television Tubes Using Low Velocity Electron Beam Scanning", *Proc. I.R.E.*, Vol. 27, pp. 547-555, September, 1939.

[6] V. K. Zworykin and G. A. Morton, TELEVISION, John Wiley and Sons, New York, N. Y., 1940.

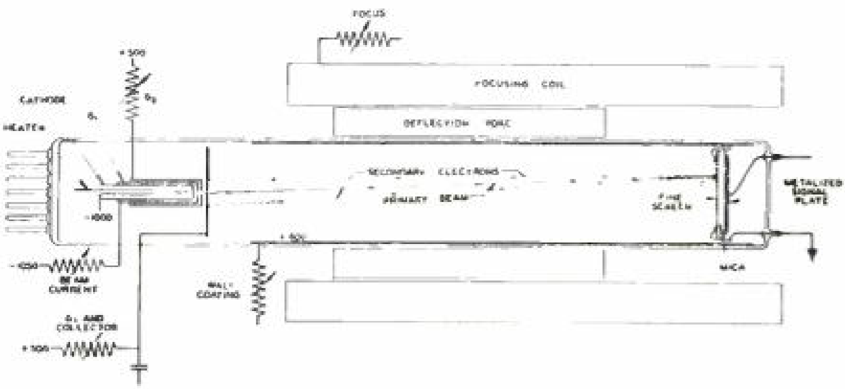

Fig. 4—Schematic diagram of SDT storage tube.

4), or electrostatically (STE type) (Figure 5). Means are provided to scan the insulating surface in a repetitive pattern, as for example, in a spiral or a "staircase" scan: In the spiral scan (Figure 6), since the angular velocity is usually constant, the linear scanning speed will vary from one end of the scan to the other. As is demonstrated later, the cancellation ratio will vary in a like manner. This is undesirable for experimental purposes, but may be used to an advantage in some applications.[7] The staircase scan (Figure 7) features constant scanning speed and constant interline spacing, both independently variable, which makes experiment simple and direct. Both scans use the target area equally efficiently. However, the spiral scan rejects the center of the target where the deflection disturbance is the least, and is, therefore, less desirable in this respect.

Since the target is an insulator, the only source of current to it is the primary beam, and the only drain of current from it is the sec-

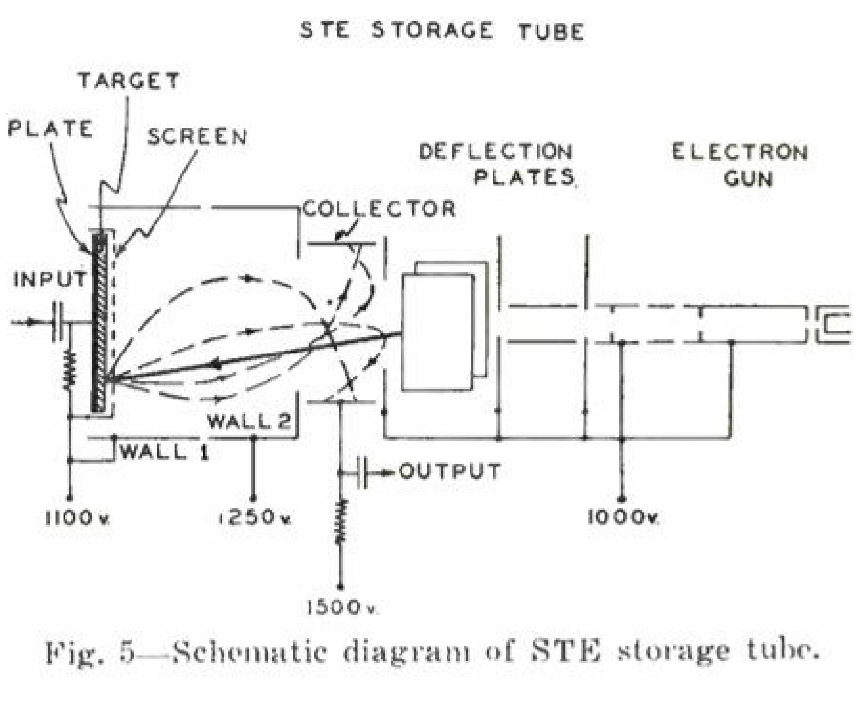

Fig. 5—Schematic diagram of STE storage tube.

[7] Calculations made by N. I. Korman, J. R. Ford, and L. Goldman, RCA Victor Division, Radio Corporation of America, Camden, N. J.

ondary beam. At equilibrium, these two must be equal, and any deposition or removal of charge on the surface will appear as a modulation of the secondary beam. However, since the energy of the primary electrons when they strike the dielectric is such that the secondary emission ratio is greater than unity (actually about two), those secondary electrons in excess of the number arriving in the primary beam must return to the target surface.

The barrier grid or screen functions as a virtual collector, so that the target equilibrium potential is established with respect to the screen and not to the actual collector electrode. At this potential a number of secondaries just equal to the number of arriving primaries are sufficiently energetic to penetrate the screen. These cannot return to the target, as appropriate fields outside the screen urge them away and toward the collector as the secondary beam. Meanwhile, the excess electrons are not sufficiently energetic to reach the screen, and

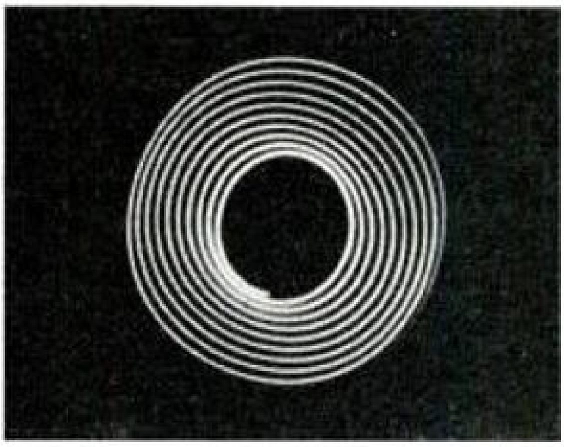

Fig. 6—Spiral scan used in SDT barrier grid storage tube.

are restricted in their motion by the close proximity of the screen to the dielectric surface. Thus, their redistribution to portions of the target not directly under the beam is considerably reduced.

When a signal is impressed upon the plate of the tube, the beam deposits on the insulating target a charge pattern, varying in intensity, that is a linear reproduction of the time variation of the impressed signal. If the surface is again scanned over the same path with no signal impressed upon the tube, the beam will remove the charge pattern, thus reading off a signal which is in polarity a mirror image of the original signal. Both during the writing and the reading, the signal will appear on the collector as a modulation of the secondary beam. In this operation, the tube has acted as a memory device, storing and subsequently reproducing a signal.

If, however, the same signal is impressed upon the tube on each successive scan, the beam will already have deposited the charge pattern necessary to match this signal variation. Therefore, that area

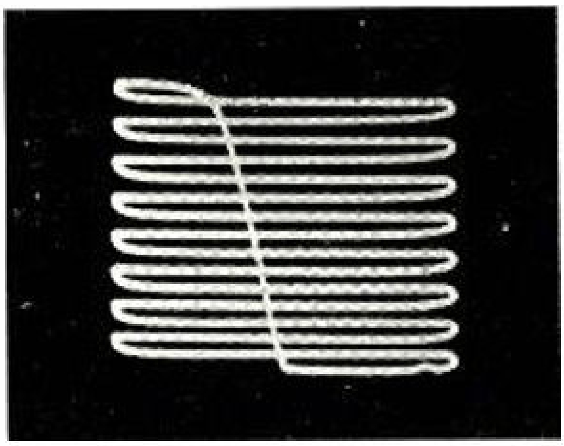

Fig. 7—Staircase scan used in STE barrier grid storage tube.

under the beam is instantaneously at equilibrium potential. No charge will be deposited on the target on succeeding scans, so that the secondary beam will be constant and unmodulated. Thus no signal will appear on the collector for steady input signals, constant in both amplitude and phase. However, any variation in the input signal will require deposition of charge by the beam. This will result in a modulation of the secondary beam and appear as a signal on the collector. In this fashion, steady signals are cancelled while varying signals are passed by the tube, the tube acting as an internal cancellation device (Figure 8).

An approximate alternate view of the internal cancellation operation considers the tube as a mixer. One signal is the presently impressed signal, the other is the charge pattern that has been deposited by the previous scan on the insulating target. Each modulates the

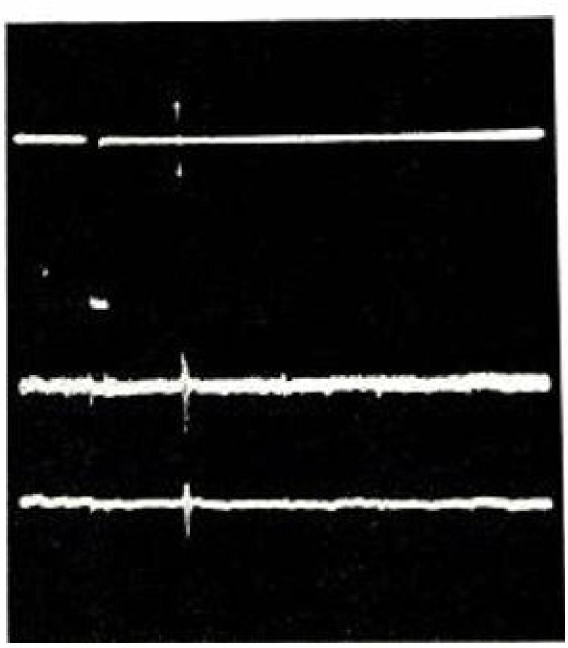

Fig. 8—Top line: Synthetic input signals used in tests. Variable signal is a pulse exactly like the steady pulse, but varying in amplitude from scan to scan. Middle line: Output without filter. Bottom line: Output filtered. Signals are in the same phase in each oscillogram.

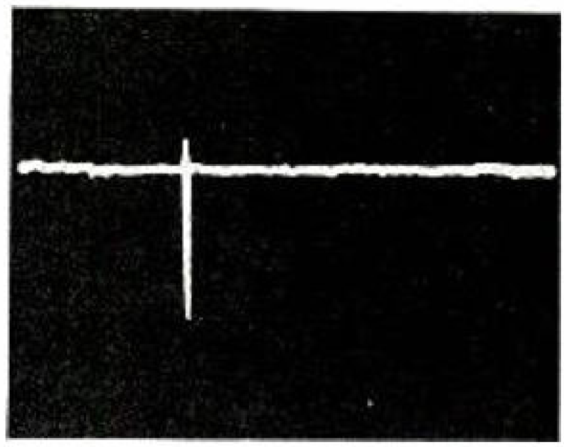

Fig. 9—Output signals, filtered, when output variable signal is a maximum, showing dynamic range. Signals are in the same phase as in Figure 8.

return beam with different polarity so that their mixture modulates the secondary beam with their difference. This indicates correctly that any part of the charge pattern that is not a faithful reproduction of the original signal will give rise to a residual signal.

Target Behavior

The behavior of the target can be better understood by reference to Figure 10, in which is plotted the general relation between the energy of secondary electrons emitted from a surface and the number of secondaries emitted per unit energy interval. If M electrons in the primary beam strike the target, the area under this curve will be σM, the total number of secondaries emitted. Equilibrium will occur for the target surface at a potential of V_e with respect to the screen, for which the number of secondaries with sufficient energy (more than eV_e) to penetrate the screen is just equal to M. This is the area under the curve from V_e to infinity. The remaining $(\sigma - 1)M$ secondaries, the area under the curve from zero to V_e, will not have sufficient energy to penetrate the screen, and will be returned to the target by the field between the screen and the dielectric surface.

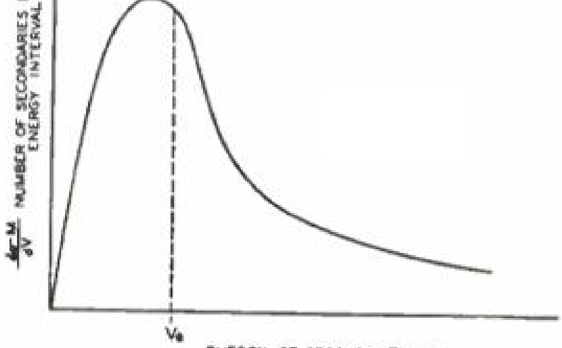

Fig. 10—Energy distribution of secondary electrons.

If, with the surface at equilibrium a few volts (V_e) positive to the screen, a signal is impressed upon the plate, the entire target will be swung capacitatively to a new potential. Now the number of secondaries that return to the target will be the area under the curve in Figure 10 from zero to this new potential. The net instantaneous current to the target will be the difference between these last areas per unit time, and the general curve is plotted in Figure 11. Note that in a restricted region around equilibrium the curve is essentially linear. This allows the tube to act as a more or less linear device to reproduce signal amplitudes. At the upper limit, for positive signals, the curve approaches the primary beam current as an asymptote. At the lower end, for negative signals, the curve is tangent to $(1-\sigma)$ times the beam current at a signal equal to $-V_e$. For this and more negative signals, all the secondaries will penetrate the screen and go to the collector.

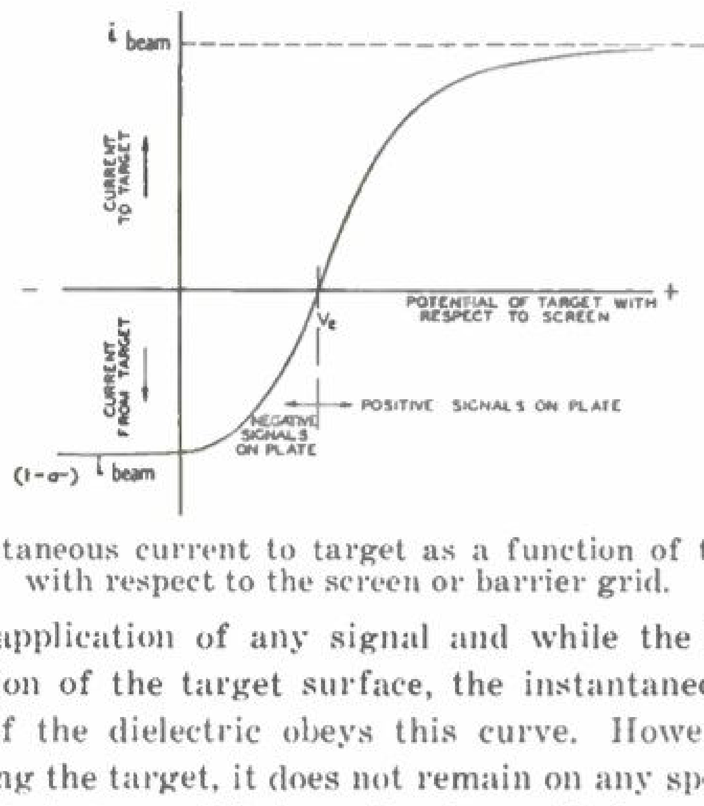

Fig. 11—Instantaneous current to target as a function of target potential with respect to the screen or barrier grid.

After the application of any signal and while the beam is on a particular region of the target surface, the instantaneous current to that portion of the dielectric obeys this curve. However, when the beam is scanning the target, it does not remain on any spot long enough to bring it entirely to equilibrium, that is, to discharge it completely to the equilibrium potential. The percent discharge effected per scan is called the "discharge factor".

The curve in Figure 11 points out that there is an essential difference between the responses to positive and negative signals, both in the manner of response and in the maximum value. As a result, the discharge factor for negative signals depends on both the signal amplitude and upon the beam current, whereas except for small signals, the discharge factor for positive signals depends on the beam current alone. This may, however, be chosen to give an acceptable discharge factor for both signs of reasonable signals. For both polarities the discharge factor is an inverse function of the capacitance per unit target area, the width of the beam and the scanning speed; and can, of course, never exceed unity. For the present mica targets, a discharge factor of 70 per cent has been measured for a beam current to the target of about 5 microamperes.

Signals

The external connections, shown in Figures 4 and 5, allow the tube to give an output signal, as described above, which is to a first approximation, the difference between the signal applied during scan I and that applied during scan II. Figure 12 shows in succession the input

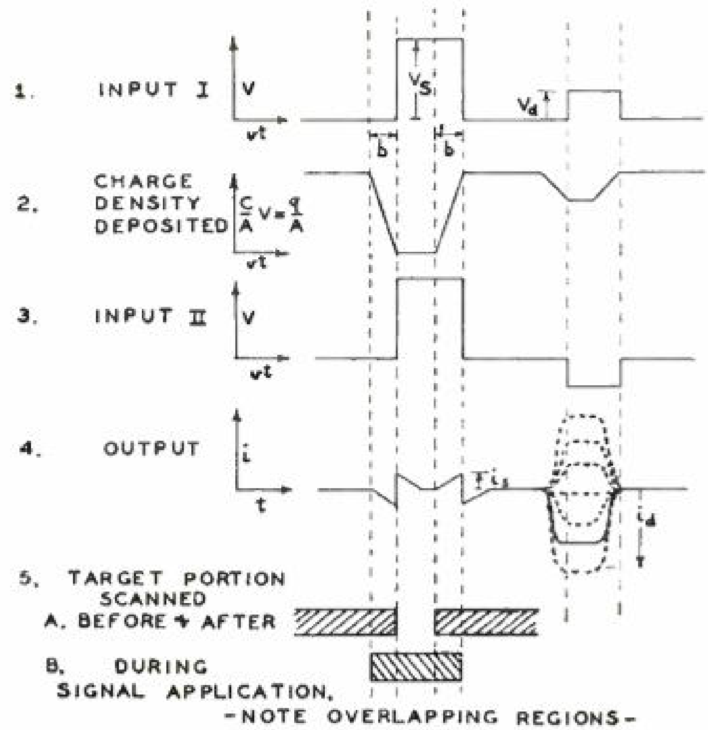

Fig. 12—Target behavior. In lines 1 to 3 the abscissa is the position (vt) of the beam spot along the scan line on the target. Line 4 is the output signal during scan II. The dotted lines indicate schematically the variable signal output for different variations in amplitude between scans. In line 5 is shown the actual target area scanned, with that area scanned during the signal removed to the side for clarity.

on scan I, the charge density deposited on scan I, the input signal on scan II, and the output signal on scan II. Note that the output is essentially the sum of the second and third lines of the figures.

Variable Signals

In general, a new signal (V_{sig}) on the plate will require the deposition of an amount of charge equal to the product of the capacitance per unit area of the target, the area of the target scanned by the beam during the signal, and the fraction of the signal discharged (fV_{sig}). The capacitance considered is that between the target surface and the signal plate. The net current to the target then will be:

$$i_{\text{sig}} \propto f\ (\kappa/s)\ wv\ V_{\text{sig}} \tag{1}$$

where wv is the area of the target scanned per unit time and κ/s is proportional to the capacitance per unit target area. It can be shown that, since the variable signal is changing in polarity from scan to scan, the effective signal, considering the effect of the discharge factor, is:

$$V_{\text{eff}} = \left(\frac{2}{2-f} + \frac{b}{vt} \right) V_d. \tag{2}$$

For simple storage of a signal for a single scan previous to which the target was at equilibrium with no charge deposited at that portion of the target, the expression is:

$$V_{\text{eff}} = (f + b/vt)\ V_d.$$

From Equations (1) and (2) the output variable signal is:

$$i_d \propto f\ (\kappa/s)\ wv \left(\frac{2}{2-f} + \frac{b}{vt} \right) V_d. \tag{3}$$

The first term in these expressions considers the simple charging of the scanning line of the target surface to the equilibrium potential as the spot moves along, while the second term is concerned only with the variation of the input signal with time. Hence, this latter remains of importance for very low scanning speeds (v approaching zero), and contributes the intercept ($R = 1$) in Figure 16.

In Figure 11 and in the text to this point, "the beam current" has referred to the current actually reaching the target and of that the portion actually returning to the collector. The screen, however, intercepts a portion of the primary beam from the gun before it reaches the target and a similar portion of the secondaries before they reach the collector. As a result, the a-c signal current will be considerably less than the d-c primary beam current from the gun. For a screen of 60 per cent transmission, the maximum modulation is only 36 per cent. The remainder goes to the collector as a direct current component, consisting of secondaries from the screen. Since this is an a-c system, however, this component may be neglected unless it is subject to a variation that would appear as a disturbance or noise, a spurious signal (q.v. below).

Residual Signals

Figure 12 shows the center of a steady signal completely cancelled. To obtain this, first, the dielectric target must have a sufficiently high product of resistivity and dielectric constant, such that an appreciable amount of charge cannot leak through the dielectric between scans. Second, there must be so little surface leakage across the dielectric, and the successive lines of the scan must be sufficiently spaced relative to the spot size that the beam cannot remove the charge that was deposited when it previously scanned a neighboring line. Either of these requires the deposition of additional charge on the next scan, and results in incomplete center cancellation. The latter results also in the appearance of a signal of opposite polarity at the time the portion of the charge is removed. This effect is usually called "interline crosstalk".

The spacing of the screen from the dielectric surface is determined by a not too critical compromise. If the spacing is too great, redistribution effects will shade the signals, introducing more interline crosstalk, and reduce the resolution. If the spacing is too small, whenever negative signals are applied to the plate, the very negative portion of the target surrounding the beam spot may, by a "coplanar grid effect", erect a potential barrier outside the screen, over which many of the secondaries cannot go. As a result they will be collected by the screen, and their absence from the secondary beam each scan will cause a positive signal to appear on the collector. It has been found that some few mils spacing of the screen is enough to prevent this coplanar grid effect. In a practical case, the use of a woven wire screen, whose thickness of weave provides a virtual spacing, is sufficient.

Considering the idealized signals in Figure 12, it can be observed (line 5) that the portion of the target scanned before the application of the signal overlaps that portion scanned during the application of the signal by just a beam width. This causes the charge pattern deposited (line 2) and hence the reproduced signal that would result from a simple storing on one scan and removal on a second scan, such as would be used for a simple memory problem as in a computer, to be shifted to an earlier phase by an amount proportional to the beam width. When the signals are compared from scan to scan, this shift in phase results in a residual signal output. Considering the internal subtractive procedure, the action is as follows: After a charge pattern has been laid down on the first scan, during each succeeding scan the beam will remove charge from the overlapping region before the application of the signal and replace it after the application of the signal. This transient removal and replacement of charge modulates the secondary beam and results in the residual uncancelled "spike" output for the steady signal input. The amount of charge involved depends upon the width of the beam and the discharge factor, and inversely upon the length of the target scanned during the signal rise time:

$$i_s \propto f\ (\kappa/s)\ wv\ V_s\ (b/vt). \qquad (4)$$

The effectiveness of the tube as a cancellation device and the fidelity with which the tube can reproduce a signal may conveniently be measured by the "cancellation ratio", the ratio of the peak values

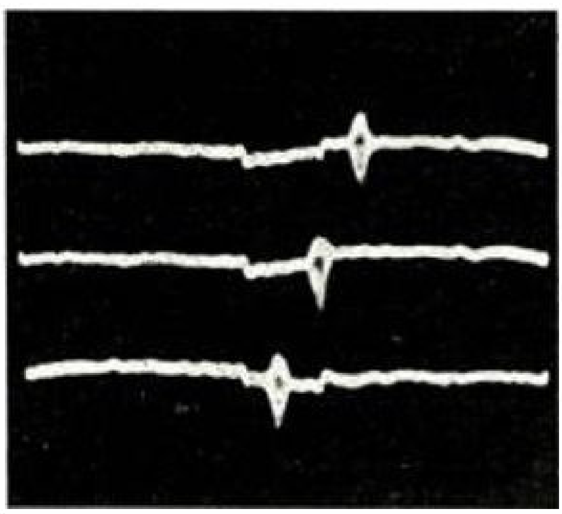

Fig. 13—Top line: Spike output from steady signal alongside of variable signal. Middle line: Variable signal coincident with one spike. Bottom line: Variable signal in center of steady signal.

(amplitudes) of the steady to the variable input signals for equal output signals:

$$R = V_s/V_d \qquad \text{when } i_s = i_d. \qquad (5)$$

Since the variable signal will appear on the output with nearly the same amplitude, whether it is phased coincident with the center of a fixed signal or the spikes or not, except for very large values of the steady signals, Figure 13, this definition of cancellation ratio is practically independent of the phase of the variable signal. Thus the cancellation ratio may be calculated from (3) and (4) above:

$$R = [2/(2-f)]\ (vt/b) + 1. \qquad (6)$$

Calculations[7] of spike output signals for more realistic wave shapes

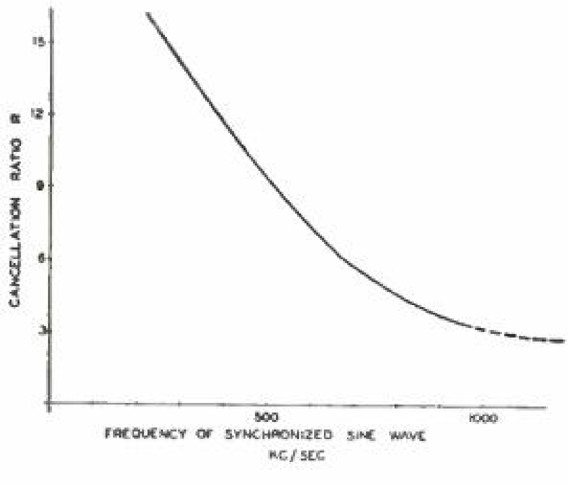

Fig. 14—Cancellation ratio as a function of frequency of a synchronized sine wave steady signal.

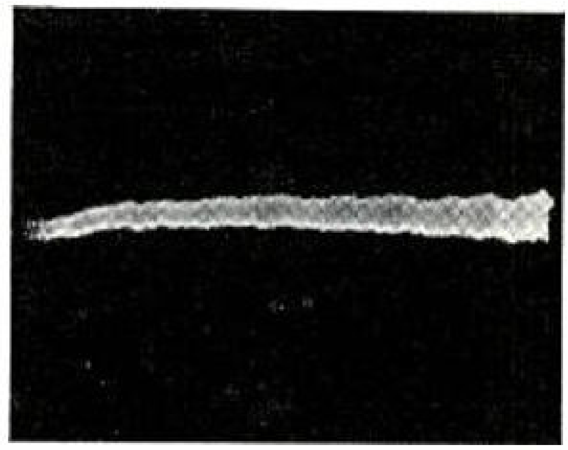

Fig. 15—Synchronized sine wave output from SDT tube using a spiral scan. The scan spirals inward so the scanning speed decreases from left to right and the cancellation ratio correspondingly decreases.

results in very complex integrals, but this same general trend prevails. It appears that the beam may be considered as a low pass filter whose frequency cut-off is roughly proportional to the ratio of the scanning velocity to the beam spot size. Thus to accurately cancel or reproduce signals of short rise times, the tube should either have a very fine spot or a rapidly moving spot. When a synchronized sine wave, whose phase is kept constant with respect to the start of the scan, is applied to the tube, a plot of the cancellation ratio as a function of the frequency of the sine wave is indicative of the operation of the writing beam as such a low pass filter (Figure 14). Likewise, the application of a synchronized sine wave signal to an SDT, using a spiral scan, shows qualitatively the relationship between cancellation ratio and scanning speed (Figure 15). Making use of the simplicity of control

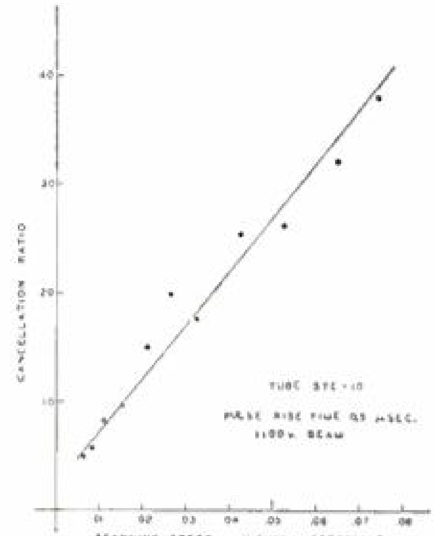

Fig. 16—Relation between cancellation ratio and scanning speed for a given pulse length.

of the scanning speed in an STE using a staircase scan one can measure quantitatively this relationship which is plotted from experimental data in Figure 16. This curve demonstrates essential agreement with Equation (6), which gives cancellation ratio as a linear function of scanning speed.

OPERATION

Another source of residual signal is input-output coupling. Unless normally careful external shielding is used and unless either the capacitance between the signal plate and collector is kept small by sufficient spacing or internal shields are used, an appreciable amount of the input signal will appear on the output by simple capacitative pickup. The screen acts as probably the most important internal shield as long as its impedance to ground is kept very low. It must have a short direct metallic lead out of the tube. If it has appreciable impedance to ground, not only does its shielding properties decrease, but as it swings with the signal it will modulate that portion of the primary beam which it intercepts, and which is normally a d-c component of the secondary beam. Since this is at least as large as the maximum a-c signal, modulation of it is serious. Measurements indicate, however, that in normal tubes this modulation can be negligible.

Disturbance

A number of factors individually contribute disturbance signals which may be viewed as a kind of noise and which represent a lower limit to the useful magnitude of the desired variable signal. A variable signal whose output is lower than the disturbance level is likely to be lost to an observer. The extent to which these contributions to the disturbance may be reduced depends largely on their character and source.

a. **Thermal noise:** Presently, tubes are operated at such beam currents that the output signals of all types are well above the noise and it is not a limiting factor. The worst disturbance is some five times the noise in amplitude. However, if smaller beam currents (with an appropriately smaller target capacitance per unit area to keep the discharge factor up) are attempted, to reduce the spot size further, the noise could be an important consideration.

b. **Deflection pickup:** In the STE type of tube, the collector must be properly internally shielded from the deflection plates to prevent pickup. The present design is successful in this respect.

c. **Deflection corners:** Target action theory[7] shows a second order signal that can arise as a result of change in curvature of the scanning pattern. This signal has not been observed and must be well below the noise.

d. **Deflection disturbance or shading:** The electric fields off the target surface must be designed such that the secondaries are collected uniformly from the surface. When this is not so, the resultant shading gives a signal that is synchronous with the frequencies in the scanning pattern. This is the most serious disturbance signal because both the secondaries from the target and those from the screen contribute. This means that there is available more than twice the current for modulation by this disturbance as there is for the desired signal. In the SDT tubes, this disturbance can be quite pronounced and control is difficult, since the same fields are used to focus both primaries and secondaries. In the STE, secondary and primary focus are separate, and this disturbance is more easily removed.

e. **Screen:** The successive interception of the beam by the screen wires generates a signal that is second in importance only to that of shading. If the beam does not extend for more than about three screen wires (this is usually the case), the signal resulting from the screen's intercepting the beam depends upon the secondary emission ratio of the screen wires and upon the ratio of the screen wire diameter to the beam spot length parallel to the direction of scanning.

The upper limit to the dynamic range of the variable signal is determined by its saturation value. Reference to Figure 11 will show the existence and limits of this saturation. A measure of this dynamic range is then the ratio of the maximum variable signal output (its saturation value) to the maximum disturbance output (the variable signal output's practical lower limit). This is called the "disturbance ratio".

$$D = i_{d\ \max}/i_{\text{disturbance}}. \tag{7}$$

If the only contribution to disturbance is that from the screen,

$$D_s = b/(\sigma_s - 1)\ u. \tag{8}$$

Reducing the secondary emission ratio of the screen wires to unity gives the greatest promise for improvement of the disturbance ratio since it has been shown (Equation (6)) that the beam spot size must be small for good cancellation ratio and there are mechanical limitations on the fineness of the screen wire. Tubes with gold sputtered screens have shown disturbance ratios greater by a factor of two than those with stainless steel screens.

Figure of merit

From Equations (6) and (8) a figure of merit, some indications of the limitations of the tube, and means of improvement may be deduced.

$$(R-1)\ DN \propto [A/\delta\ (\sigma_s - 1)\ u]\ [(2/(2-f]\qquad(9)$$

where N is the number of pulses of rise and fall times t that can occur successively during the total scan, usually referred to as the number of storage elements on the target. Note that the three desired quantities, cancellation ratio, disturbance ratio, and number of elements available per tube, are so related that no one can be improved except at the expense of the others, or by enlarging the tube, or by causing the screen wire secondary emission ratio to approach unity. A finer spot,

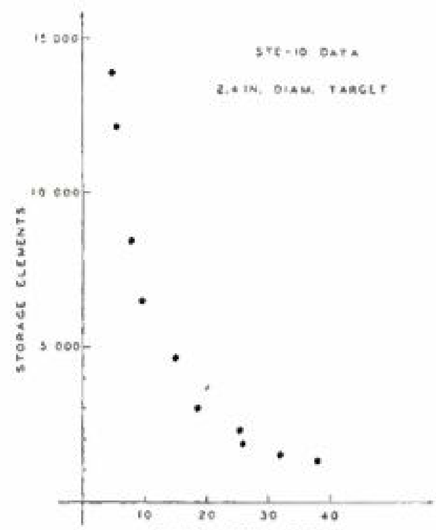

Fig. 17—Storage elements in an STE tube as a function of fidelity.

allowable if σ_s is reduced, would also allow δ, the interline spacing, to be reduced.

This product $(R-1)\ DN$ appears to be a convenient figure of merit for this tube and similar cancellation devices. The value for present two-inch target tubes is roughly $6 \cdot 10^5$ or greater.

In Figure 17 is plotted the same experimental data as in Figure 16, having calculated the number of pulses of 0.5 microsecond rise and fall times that can be placed on the 2.4 inch target of the tube with an interline spacing of 0.030 inch. This curve together with Equation (9), which it substantiates, indicates that for a given tube, wherein the spot size is essentially determined by the primary gun structure, the number of storage elements on the target is a function only of the cancellation ratio, being independent of the scanning speed or the pulse length. It follows then that these elements may be used to store information using pulses of *any* duration, the scanning speed varying inversely with the pulse length.

The storage area required per element (A/N) would be a figure of merit for the target construction; the present value for the usefully scanned portion of the target can be conservatively set approximately $6 \cdot 10^{-4}$ square inches per element for a cancellation ratio of 20.

Another figure of merit useful for some considerations has been suggested.[7] The "limiting cancellation ratio" can be defined as the ratio of the variable signal input to the steady signal input when the variable signal input is adjusted to give an output equal to the disturbance, and the steady signal is adjusted to give best overall performance from other considerations (e.g. sufficient discharge factor or linearity of response). This ignores the output dynamic range for cases where it is not important. Present STE tubes have limiting cancellation ratios of roughly 100 for which they should have sufficient area for about 600 elements (extrapolating Figure 17).

If two equal adjacent pulses are very close together, then the output signal from simple storage will not go to zero between them, but only to some finite value of amplitude (y). The ratio (Y/y) of the pulse amplitude (Y) to this finite value of the output signal (y) between the pulses can be taken as a measure of the resolution or the fidelity of reproduction. In fact, this is exactly the cancellation ratio defined above, $R = Y/y$. Another term, "percentage modulation" may be applied and defined as $P = (Y - y)/Y$ so that cancellation ratio may be related to "percentage modulation" such that $P = 1 - (1/R)$. For many applications such as television values of "percentage modulation" (P) as low as 5 per cent are useful. This would correspond to a cancellation ratio of only 1.05, which from Figure 17 extrapolated would indicate about $5 \cdot 10^5$ storage elements. The lowest percentage modulation, and therefore the greatest number of storage elements, that can be used is limited by the disturbance.

As a circuit element, the tube may be viewed in general as a high internal impedance generator, similar to ordinary electron tubes. Its output is essentially a current signal fixed in magnitude by the tube operation and characteristics. A reasonable figure would be 30 per cent modulation of a 3 microampere beam or an a-c signal of approximately 2 microamperes peak to peak. The output capacitance is about 20 micromicrofarads; the input capacitance approximately 400 micromicrofarads for a 2.4 inch target. The full 30 per cent modulation is attained for an input variable signal of 50 volts peak to peak. This may be summed up as a transconductance of 0.04 micromhos, from which the tube performance can be calculated in the usual manner.

Tube Data

Average characteristics for the latest STE type tubes are plotted in Figure 18. From these can be deduced the operating data. It is to be noticed that, similar to other vacuum tubes, there are different modes of operation possible depending upon whether or not the application permits saturation of certain signals. If the variable signal may be saturated for any large value of input the following is true. Data for SDT type tubes using mica dielectric about 0.8 mil thick, 230 mesh gold sputtered stainless steel woven wire screen spaced about 5 mils from the dielectric is $R = 20$, $D = 25$, $v = 0.020$ inch per microsecond, $t = 0.3$ microsecond, and $f = 80$ per cent. N can be calculated to be 1000. Limiting cancellation ratio is 50. For $t = 1$ microsecond,

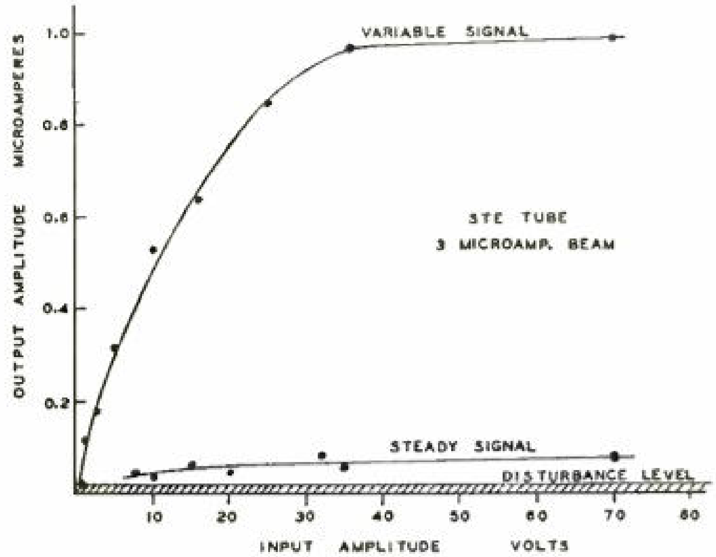

Fig. 18—Characteristic curves of operating storage tubes. Pulse length: 2 microseconds; scanning speed: 0.025 inch per microsecond; output filtered.

R becomes 45. STE electrostatic tubes use the same kind of target: 0.8 mil mica dielectric, 230 mesh gold sputtered stainless steel woven wire screen spaced about 5 mils from the dielectric; and their performance data is $R = 25$, $D = 25$, $v = 0.025$ inch per microsecond, $t = 0.3$ microsecond, and $f = 80$ per cent. Calculated N is 2000. Limiting cancellation ratio is 100. If saturation is not permissible, then reference to the characteristic curves in Figure 18 will show that for the STE tube, the cancellation ratio is about 12 while the limiting cancellation ratio is about 50. For this type of operation involving smaller input signals, the discharge factor is somewhat higher.

The SDT tube has a measured spot of 0.006 inch diameter for a beam current of 10 microamperes. The STE tube has a measured spot size of 0.008 inch diameter 8.5 inches from the main lens for a beam current of 10 microamperes and the screen 1000 volts above the cathode.

Storage Time

The present available apparatus does not allow the application of signals at repetitive rates less than 50 cycles per second. These slow repetition rates have given cancellation and disturbance ratios the same as for rates as high as 4000 cycles per second. This means that such signals are stored without appreciable change for at least 1/50th of a second. However, in a television test set in which the target is scanned in a standard television pattern and in which the output from the collector can be applied to the grid of a kinescope, so that the signals can be viewed at positions corresponding to the positions on the target from whence they came, signals that were impressed on the tube were observed to have negligible reduction or diffusion across the surface after 100 hours, during which time the beam was off. This tube had the same type of mica target as was described above.

Filtering

The data presented above are for the tube alone without the benefit of optimum aiding circuitry. The bandwidth of the amplifiers used in the measurements was 3 megacycles per second. By a judicious choice of the frequency response of the output amplifier, however, the performance of the tube as a cancellation device can be improved, since the spikes may contain frequency components roughly three times as high as the variable signal. A filter having a sharp cut-off just above the highest useful frequency can thus increase the cancellation ratio by attenuating the spikes. This is a true gain in a cancellation system; for other applications it simply indicates that the bandwidth of the system should be no greater than that required to pass the highest desired frequency. In addition, it was found that both disturbance and cancellation ratios could be improved by the introduction of a simple LC low pass filter, in this particular case having a half-value at 300 kilocycles per second, in the output circuit. This is shown in Figure 19 and also in Figure 8. The filter must have a fairly shallow low frequency cut-off to affect the screen disturbance, since the beam in scanning the screen crosses the wires at various angles. This means that there is generated not only the highest frequency due to scanning directly across individual wires, but the lower frequency components due to scanning the wires at more oblique angles. This spectrum unfortunately extends down into the region of useful signals and cannot be filtered out completely.

Concatenation

In an application requiring a cancellation device the use of two storage tubes in cascade has brought results which in many ways are gratifying, despite the added equipment and greater complexity from an operational standpoint. The concatenated set-up is made by feeding the conventional signal into the first storage tube as before, amplifying its output to a level to properly drive a second storage tube, then feeding this into the second tube.

This arrangement offers three distinct advantages. The disturbance contributed by the first tube constitutes a steady signal input to the second tube, which in turn cancels it. This means that the overall disturbance output is only that from the second tube alone. This tube may be carefully chosen so that this overall disturbance is a smaller than average amount. Secondly, since the output of each tube is essentially the first difference of its input signal, the output of the second tube is the second difference of the original input. Hence, the response to slowly varying signals is reduced, and the overall discharge factor

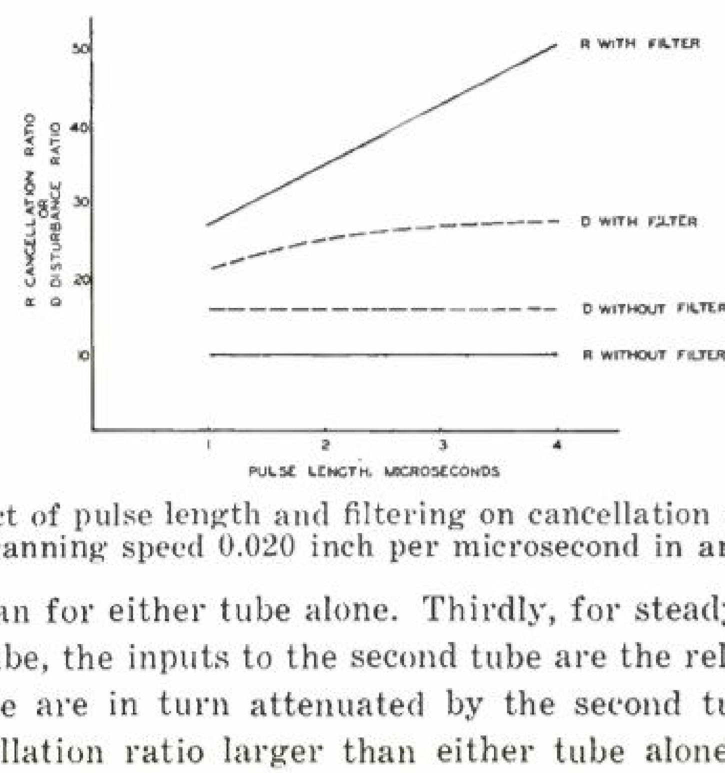

Fig. 19—Effect of pulse length and filtering on cancellation and disturbance ratios. Scanning speed 0.020 inch per microsecond in an SDT tube.

is greater than for either tube alone. Thirdly, for steady signal inputs to the first tube, the inputs to the second tube are the relatively smaller spikes. These are in turn attenuated by the second tube to give an overall cancellation ratio larger than either tube alone. This overall cancellation ratio is not as large as the product of the two tubes' cancellation ratios, however, since the spikes (see Figure 12, line 4) have rise times which are smaller than those in the original signal. The cancellation ratio of the second tube will be correspondingly smaller than that measured in the usual fashion. This is assuming the use of raw signals without filtering between tubes. Two SDT tubes, each of which showed an $R = 10$ singly, in cascade showed an $R = 60$. Variable signals that were lost in the disturbance of the first tube were readily visible in the output of the second tube.

Circuits

A quick survey of the stability of the associated circuits would show that there should be less than a pulse rise time jitter between the initial signal pulse and that which triggers the scanning pattern. Further, the deflecting circuits should allow the scanning raster to move only a small fraction of a line width. This would indicate deflection constant to one part in 1000. For both tubes, the spiral and staircase generators were fed from standard regulated supplies. The high voltage supplies were not regulated.

CONCLUSIONS

Besides being a direct measure of the characteristics of a storage tube as used in signal comparison problems, the described method of comparing input and output signals is of value in determining the general characteristics useful for the design of any system involving signal storage. In any storage system, the fidelity of reproduction of the stored signal is a primary consideration. This is measured by the cancellation ratio. Discharge factor is important in determining the writing and erasing requirements in any application. The disturbance ratio gives the output dynamic range while the limiting cancellation ratio is the input dynamic range. The limiting cancellation ratio may also be viewed as the greatest fidelity detectable since this is the fidelity for which the difference between the input and the reproduced signals is just equal to the disturbance introduced by the tube. The number of storage elements required by a signal is simply the amount of information that is contained in that signal. The number of storage elements then gives directly the number of discrete pulses which may be stored on the target with a given fidelity, as indicated by the cancellation ratio. Likewise, for more complex wave forms the number of storage elements can be taken as equal to the product of the bandwidth of the signal and a time t which is the duration of the signal which can be stored. Figure 17, which shows that the product of the cancellation ratio and the number of storage elements is a constant for any tube, than may be interpreted as indicating that the product of the bandwidth, the duration of the stored signal, and the fidelity is a constant. Thus for a given fidelity of reproduction the number of storage elements is fixed and for a signal of given bandwidth, the maximum duration is determined. Conversely for a certain desired duration of signal, the bandwidth (and hence the highest frequency) that could be stored is fixed by the same relation.

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SYMBOLS

- A Useful area of target; $A = \delta\lambda$
- b Beam width parallel to scan.
- C/A Capacitance per unit area of target (target surface to plate).
- D Disturbance ratio; $i_{d\ max}/i_{disturbance\ max}$.
- e Electronic charge.
- f Discharge factor; percent discharge per scan.
- i_d Output from variable signal; a-c component of secondary beam.
- i_s Output from steady signal; a-c component of secondary beam.
- i_{sig} Output from any new signal on the scan during which the signal first appeared.
- M Number of primary electrons bombarding target during a convenient time interval.
- n Pulse repetition rate.
- N Number of pulses of rise and fall times t that can occur successively during the total scan; $\lambda = 2v\,tN$; total number of "elements" available in tube.
- P Percentage modulation $(Y - y)/Y$.
- q/A Charge density deposited on target.
- R Cancellation ratio; V_s/V_d for $i_s = i_d$.
- s Thickness of dielectric target.
- t Rise time of input pulse.
- u Diameter of screen wires.
- v Scanning speed.
- V_d Input variable signal amplitude.
- V_{eff} Effective input variable signal, considering the effect of discharge factor.

V_e Equilibrium potential of target surface with respect to screen.

V_{kt} Potential difference between cathode and target, determining bombarding electron energy.

V_m eV_m is the energy of the most numerous secondaries from the dielectric surface.

V_s Input steady signal amplitude.

V_{sig} Amplitude of any new signal.

w Beam width perpendicular to scan.

y Amplitude of output between two adjacent pulses.

Y Output amplitude of a single pulse.

δ Separation, center to center, of scan lines. Interline spacing.

κ Dielectric constant of target insulator.

λ Total length of scan.

σ Secondary emission ratio of dielectric.

σ_s Secondary emission ratio of screen wires.