PRINCIPLES OF DIRECT-VIEWING
STORAGE TUBES

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December 15, 1961

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CONTENTS

(continued)

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CONTENTS

Page

8. Half-tone Tubes.

SECTION I. THE PURPOSE AND METHOD

The purpose of this report is to outline the basic operating principles of both bi-stable and half-tone direct-viewing storage tubes (as opposed to electrical read-out tubes) in a manner that is intended to be convenient for those whose experience is not in the field of storage tubes. The discussion is limited to the principles of the two commercially important kinds of direct-viewing storage tubes; the half-tone or 'charge-storage' type manufactured by RCA, Philco, Farnsworth, Hughes, and Westinghouse, and the bi-stable or 'Haeff-principle' type of storage tube manufactured by Hughes and Machlett.

Much of the literature on storage tubes appears to presume an unrealistic degree of prior knowledge of this specialty on the part of the reader. This report starts at a more elementary level, with the assumption that while the subject is not unusually complex, it is accumulative.

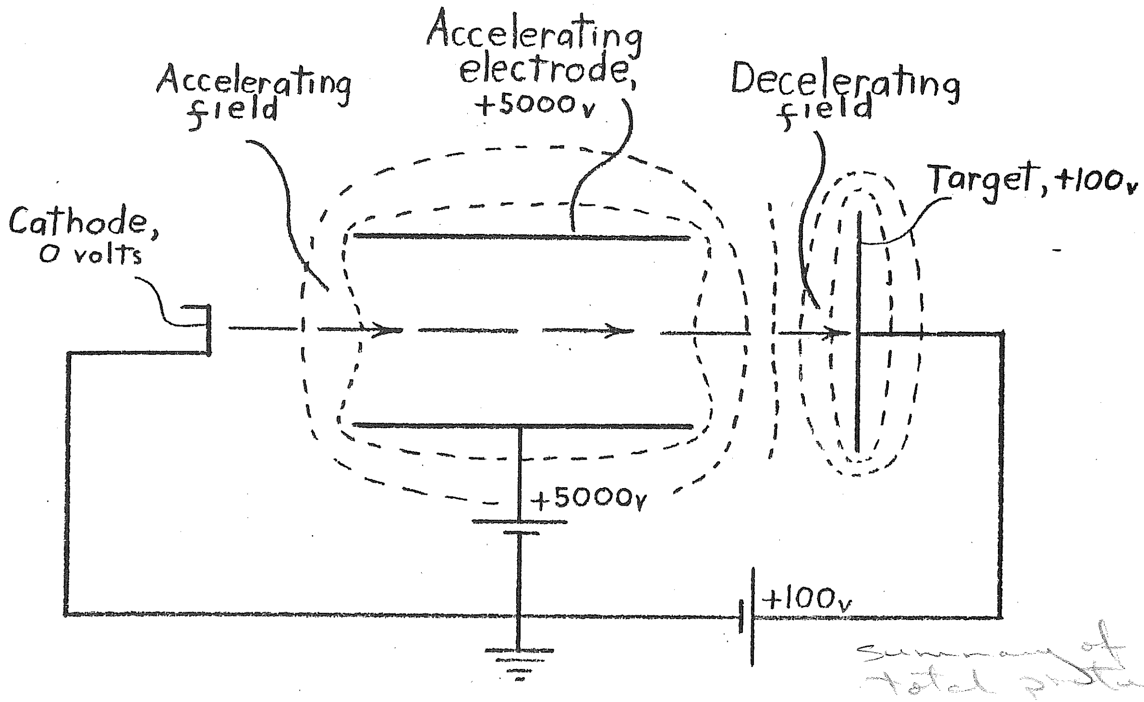
The method of description used here, at least in the middle portion of the report, is to begin with the discussion of a simple experimental vacuum tube, in Section 3, to which are added electrodes, one by one, until the structure evolves into a complete storage tube in Section 7. The subject lends itself to this treatment because the various functions of storage tubes are fairly well identified with the individual tube electrodes. The discussion thereby advances step-wise from a rather elementary level to the level consistent with the functional complexity of the tubes. The reader who is already knowledgable in tube physics may wish to begin reading part way through the report. The appropriate starting point may be found by first reading the summaries in Sections 3, 5, and 8, or the final Summary in Section 9.

SECTION 2. THE ENERGY OF ELECTRON BOMBARDMENT

Dependence on Target Voltage:

In analyzing storage target behavior, we will repeatedly need to know, at least relatively, how much energy or velocity a bombarding beam of electrons has as it arrives at some surface, such as a dielectric storage target. It may then be helpful to recall that in static fields the energy of electron bombardment depends on the voltage of the target being bombarded (relative to the voltage of the emitting cathode.) For example, in Figure 1, electron emission from a thermionic cathode at zero volts may be accelerated through a high voltage field, such as +5000 volts, and then bombard a target whose voltage is lower, such as a target voltage of +100 volts. The bombarding electron energy at the target is then +100 electron volts, not +5000, because the high speed electrons in the 5000 volt field must pass through a decelerating field immediately surrounding the target, and cannot hit the target without going through this field. (A small correction, on the order of one volt will be made to this statement in the next section.)

Figure I.



Summary of total picture!

The same principle applies to electrons which may pass through a low voltage field, such as a +10 volt field, and then bombard a +100 volt target. In this case, the bombarding energy is still +100 volts, because in order to reach the target, the electrons had to go through the +100 volt field surrounding the target, and were accelerated by this field to +100 electron volts, even if all the acceleration took place in a short distance immediately in front of the target.

This idea is emphasized at the outset, because we will deal with more complex situations where the beam velocity controls the target voltage, and the target voltage in turn controls the beam velocity. The simplest approach will start with the idea that it is not necessary to know the whole history of an electron along its entire path in order to know its velocity. If the voltage at the emitting source and at the target are known, the bombarding velocity can only be equal to this voltage difference (plus a small correction for 'stopping potential'.) It may help to characterize this fundamental idea by thinking of the target voltage as the cause of the bombarding velocity.

Dependence on Initial Velocity. Stopping Potential.

Since the bombarding energy of an electron depends on the target voltage, an electron emitted from a cathode with no initial velocity would have no energy (or velocity) on arriving at a target held at zero volts. Zero volts would be the cut-off voltage, below which no electrons could reach the target. A target at -1/2 volt would not be reached by any such electrons, since there would be a repelling field surrounding the target.

It has been found, however, that electrons are not emitted from a hot cathode at zero velocity, but have a range of velocities. These velocities may be measured by the retarding potential where required to repell the fraction of electrons having insufficient velocity to penetrate the field around the repelling target. A target having a repelling voltage of only -.01 volt will repel about 10% of the electron current directed toward it from a typical oxide-coated cathode at 850°C and at zero volts. When the target voltage is -.1 volt, about 2/3 of the current is repelled, so about 1/3 reaches the target. At a target voltage of about -1/2 volt, only 1% of the current reaches the target, and at -1 volt, only .001% reaches the target. (This distribution of energies is closely approximated by the Boltzman distribution.) check A very small fraction of the emission has even higher velocity, and the Boltzman distribution describes some emission, or probability of emission, at any finite energy. The potential required to cut-off substantially all of the current from a particular cathode in a particular tube is often referred to as the 'stopping potential' for that tube.

The idea of stopping potential is useful in exploring the narrow transition region between the target voltage ranges in which complete collection of emission occurs, and in which reflection of emission occurs. Were there no spread in initial velocities, an abrupt 'sharp cut-off' characteristic would occur, but the actual transition is gradual. This is used shortly to explain the relatively gradual transition of current collection by electrodes in a secondary emission device.

The energy of thermionic emission is present, of course, not only when the emitted electron current is retarded and repelled after emission, but also when the emitted current is accelerated to bombard a target at a higher potential. A target at +100 volts relative to the cathode is bombarded by electrons having energies primarily in the range from +100 to +101 volts. While this is not a large departure from the energy of bombardment resulting from the target voltage alone, it is a part of the detailed description of storage effects, and appears later several times. The other forms of electron emission, including photoemission, field emission, and secondary emission, also have an energy of emission associated with them. The initial energy of secondary emission will be mentioned in a later section.

SECTION 3. SECONDARY EMISSION

The Physical Effect. First and Second Crossover.

When a surface is bombarded by electrons, some of the energy of bombardment separates other electrons from the target material, and causes them to be emitted from the target. The number of these target electrons or 'secondary' electrons depends on the number and velocity of the bombarding or 'primary' electrons, the target composition and surface condition, and the angle of bombardment. The amount of secondary emission is usually expressed as the ratio of secondary emission current (number of electrons per unit time) to the primary beam current (number of electrons per unit time) and is termed the secondary emission ratio.

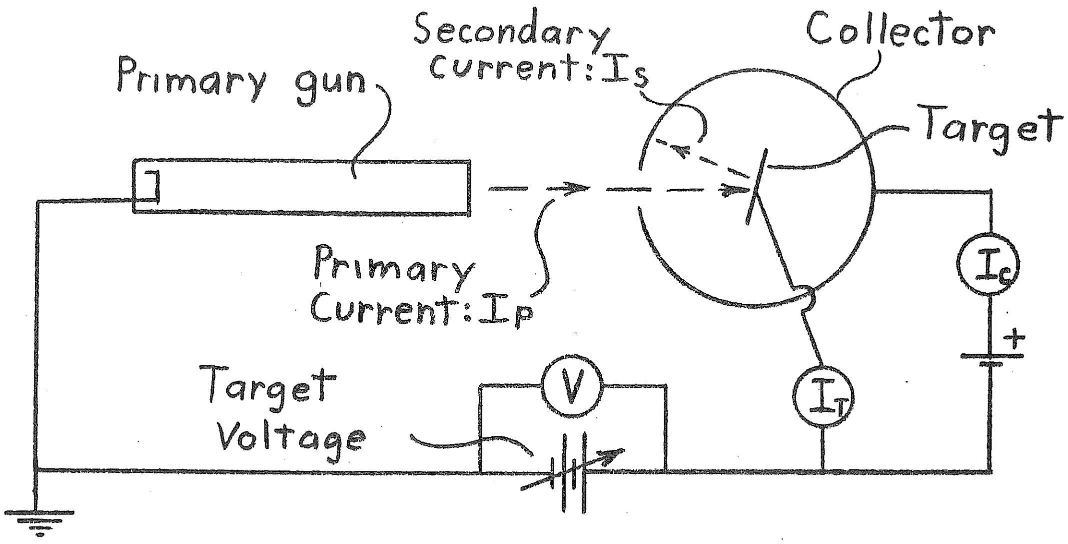
The symbol δ is usually used to represent this ratio, and we see that $\delta = I_s/I_p$, where the secondary current is I_s, and the primary current is I_p.

An elementary but fundamental experiment with this effect is the determination of how the secondary emission ratio changes when the bombarding 'primary' electron beam velocity is changed.

As we are not now interested in the actual primary electron energy in ergs, or velocity in centimeters per second, we could plot the secondary emission ratio versus the primary energy in electron-volts. As we saw in the preceding section, since the target voltage alone (relative to the cathode) is enough to closely determine the primary electron energy, we will plot secondary emission ratio (δ) vs. target voltage. This is the conventional presentation.

A typical experimental device for the measurement of the secondary emission ratios of a variety of materials is shown in Figure 2:

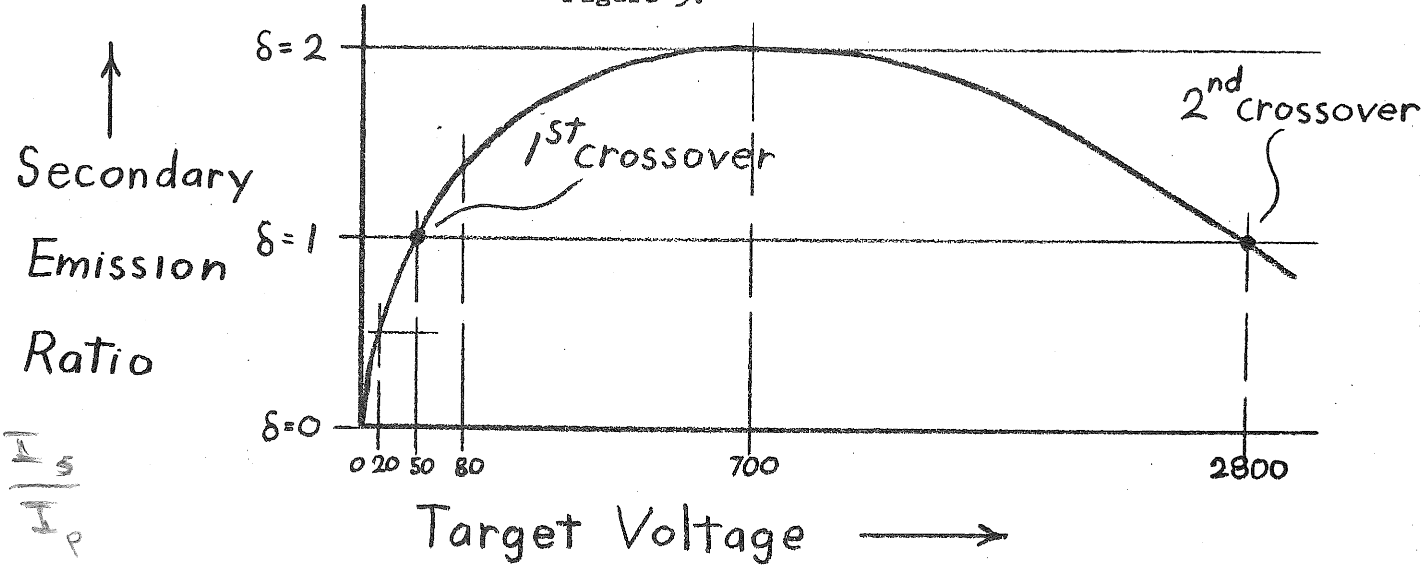
Figure 2.



In this experiment, a 'primary' electron gun forms an electron beam which bombards a metal target plate (not an insulator, in this experiment) in a vacuum. The target voltage is variable, and the meter reading of this voltage is the independent variable for the curve to be plotted. A collector electrode surrounds the target, so that all the secondary electrons will be collected. The target is tilted away from the entrance hole in the collector so that the few high energy secondary electrons will less easily leave through this hole and escape being measured as collector current. (The target may also be tilted through various angles to determine the effect of target angle on secondary emission ratio, but we will not measure this variable.) The collector electrode is held a few volts more positive than the target electrode by a voltage supply which is between the target and the collector, so that there will always be a strong enough field around the target electrode to insure collection of all the secondary electrons.

When the target voltage is very low, the amount of secondary emission may be so small that it is difficult to measure. Side effects in the apparatus obscure the secondary current, and these will be described shortly. We may safely reason, however, that no secondary emission occurs when the primary beam energy is zero, since the liberation of secondary electrons from the target requires the delivery of energy to the target. This is the zero point on the curve of Figure 3.

Figure 3.



At some low positive target voltage, such as +20 volts, for example, the primary beam energy is sufficient to cause a readily measurable secondary current. A primary beam current of 10 μa milliamps may cause a secondary current of perhaps 5 μa to flow from the target to the collector at this voltage, so the secondary emission ratio would be 5 μa/10 μa or 1/2. Notice that the target is receiving 10 μa of primary beam current, but is losing 5 μa of current by secondary emission, so the net electron current collected by the target, and leaving the envelope through the target lead-wire, is only 5 μamps.

At some higher target voltage, such as +50 volts, for example, the bombarding energy is higher and the secondary current may rise to become equal to the primary beam current. A 10 μa beam producing 10 μa of secondary emission current from the target to the collector then results in a secondary emission ratio of 1. Since the target is collecting 10 μa of primary current, and losing 10 μa of secondary emission current, the net flow of current in the target lead-wire is 0 μa. Conditions of unity secondary emission ratio will later be seen to have a special importance. Since the secondary emission curve crosses the ordinate line of $\delta = 1$ at such points, these points are often called crossover points, and the point just described, which is the lowest target voltage at which this crossover occurs, is usually referred to as the 'first crossover point.'

At some higher target voltage, such as +80 volts, the 10 μa of primary current may cause 13 μa of secondary current, resulting in a secondary emission ratio of $\delta = 1.3$. Notice that the net flow of current at the target surface is now away from the target, since more current is emitted than is collected. An electron current of 3 μa now flows in the direction into the envelope, in the target lead-wire. At a higher target voltage, such as +700 volts, the secondary emission ratio may reach a maximum, at a value such as $\delta = 2$. Above this voltage, the secondary emission ratio decreases until, at perhaps +2800 volts, the secondary emission ratio may again be $\delta = 1$. This is another crossover point of special interest, and is commonly called the 'second crossover point.' The drop in secondary emission which occurs above the maximum point is believed to be the result of deeper penetration of the more energetic primary beam into the target material before collision with the target atoms occurs. Large numbers of secondary electrons may be produced below the surface, but many are captured within the target before they reach the surface, and do not contribute to the secondary emission current.

Typical values for the important characteristics of target materials chosen for tubes utilizing their secondary emission effects are: first crossover voltage in the range of 20 to 100 volts; maximum secondary emission ratio of $\delta = 1$ to 4 at target voltages from about 500 to 1000 volts; and second crossover occuring at 1500 to 4000 volts.

Typical values for common tube construction materials not chosen for secondary emission effects may include the above ranges, but many materials do not exceed $\delta = 1$ at any voltage, and accordingly have no first or second crossover points. Ratios of $\delta = 1$ to 2 are also fairly common.

Secondary emission ratios from 4 to 12 have been obtained by some observers, but this seems more common under laboratory conditions than in a production environment.

Some materials are grouped below by their maximum secondary emission ratio (δ_{max}) which occurs at different voltages for different materials.*
Not all of these materials are suitable for use in vacuum tubes.

Materials in the range $\delta_{max} = .5$ to 1 are: Al, Ba, Be, C, Cs, K, Li, Mg, Rb, Ti and WS_2.

Materials in the range $\delta_{max} = 1$ to 1.5 are: Ag, Au, B, Bi, Cd, Co, Cu, Fe, Ge, Mo, Nb, Ni, Si, Sn, W, Zr, Ag_2O, MoS_2, MoO_2, and Cu_2O.

Materials in the range $\delta_{max} = 1.5$ to 2 are: Pt, and sometimes Al_2O_3.

Materials in the range $\delta_{max} = 2$ to 4 are: CaF_2, BeO, MgO, BaO, CaO, Mica, Quartz, and many glasses.

Materials in the range $\delta_{max} = 4$ to 8 are: LiF, NaF, NaCl, KCl, RbCl, CsCl, NaBr, KI, Cs_2O, $SbCs_3$, and BaF_2.

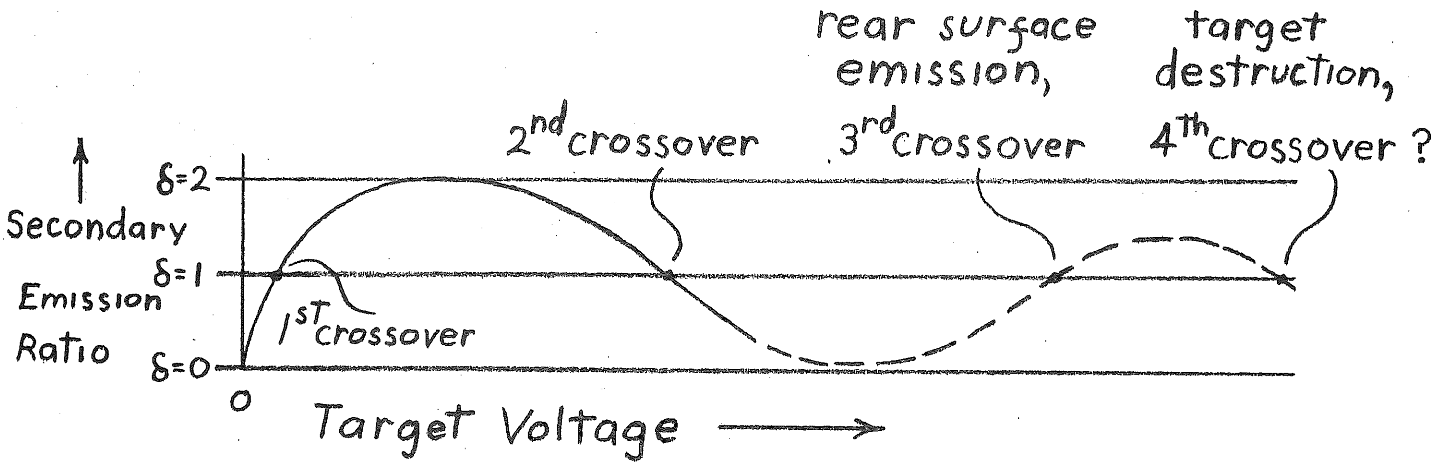
At energies above the end of the curve of Figure 3, two more effects exist, at least as possibilities. It is known that the primary beam may penetrate the target so deeply that collision with the target atoms occurs near the rear surface of the target. The secondary electrons can then escape from the rear surface and be collected, and the secondary emission ratio can rise to a higher value again, crossing the line $\delta = 1$ a third time. This is usually a thin film effect, observable from the thinnest self-supporting films obtainable, at voltages in the range of at least 50 KV to 100 KV.

The other effect in the high voltage region is the existence of some practical limit to the dissipation of thermal energy in the target. Evaporating and melting of the target material will presumably limit the secondary emission

* Reference No. 3

by destroying the target at some combination of current and voltage. These effects are not used in storage tubes, and are included only to show the possibility of a third and fourth crossover point, as in Figure 4, and to account for extremes of the range of target voltages.

Figure 4.

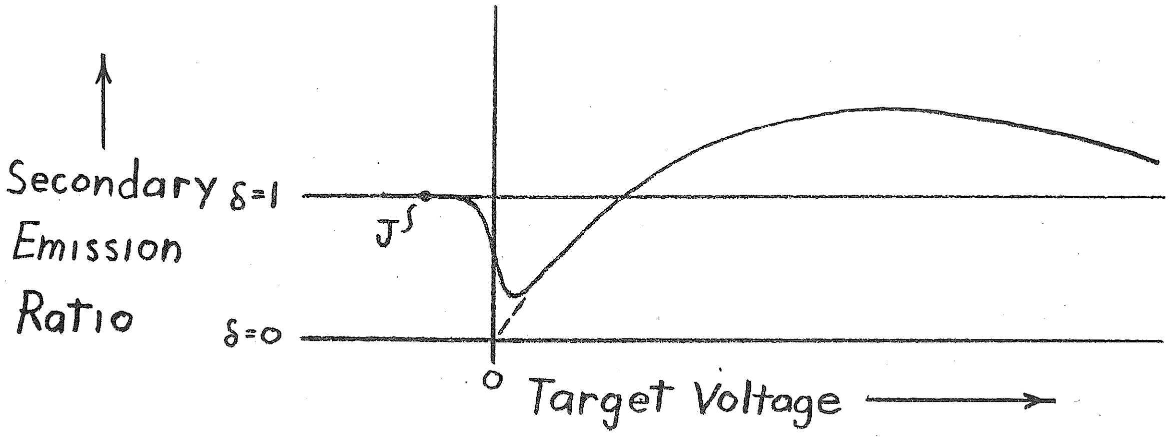


Apparatus Effects:

The preceding Section outlined what might be called the physical effect of secondary emission, which is the consequence of energy transfer from the primary electrons to the target electrons. There are other effects which occur, due to the configuration and potentials of the apparatus. These are primarily electron-optical effects, and some of these are present even in the simple apparatus of Figure 2. The region of the secondary emission curve near a target voltage of zero volts, and below zero volts, is modified greatly when these effects are taken into account. Figure 5 shows the 'effective' secondary emission curve which results in this region when these apparatus effects are added to the physical effect of secondary emission.

See Figure 5 on the following page.

Figure 5.



At some point 'J' which is substantially below zero volts, such as -5 volts, the target is well below the 'stopping potential' for the cathode of the primary beam, and the target is surrounded by a negative repelling field which reflects all primary electrons away from it, to be collected by the collector. When all primaries are reflected to the collector before reaching the target, external current measurement shows that the collector current equals the primary current, and the target current is zero. These are the same current measurements which occur when the secondary emission ratio is one, so the target has an <u>apparent</u> or <u>net</u> <u>effective</u> secondary emission ratio of one, at this voltage.

Notice that since these conditions at point J are also the conditions at the first and second crossover points, the current measurements in this device (Figure 2) cannot distinguish between the total reflection of primary electrons and the physical effect of a true secondary emission ratio of unity.

As target voltage is increased, approaching zero volts from the negative side, it begins to get out of the region of reflection of primary electrons and into the region of actual target bombardment and true secondary emission.

However, the curve does not make an abrupt discontinuous transition at zero volts, to the curve of true secondary emission; but instead, makes a gradual transition for the reasons which follow below. Several paragraphs are devoted to this transition region because storage targets are so often at the voltages in this region.

As the target voltage is raised from point J to a point only a fraction of a volt negative, it is above the 'stopping potential' but below zero volts, so some (but not all) primary electrons have sufficient energy of thermionic emission to penetrate the retarding field around the target, and reach the target. The physical effect of this fraction of the primary electrons is a very low secondary emission ratio, near zero, since they have very little energy. The remaining fraction of the primary current which is still reflected to the collector, has an apparent secondary emission ratio of one. The combined effect of all primary electrons is to cause the curve to drop down in a gradual transition to a value between zero and 1, in the region just below zero volts, and above the stopping potential. This explains why the curve is rounded just below zero volts.

In the region of the curve from zero volts to a target voltage a few volts positive, some primary electrons which approach the target at an angle can fail to reach the target, even when their total energy would otherwise be sufficient to carry them to the target, because a substantial component of their velocity is parallel to the target surface. This necessarily reduces the velocity component in a direction normal to the target (for a particular resultant total velocity). A component of the field between the target and the collector then may act as a deflection system, reducing the target bombardment.

Since these reflected electrons appear as collector current, when measured externally, the curve at zero and just above zero volts is higher in apparent secondary emission ratio than is the curve of the physical effect of true secondary emission ratio, which drops to $\delta = 0$ when the primary energy is zero. This explains why the curve is rounded in a gradual transition region just above zero volts.

The value of the curve at zero target voltage, and the exact shape of the curve in the zero volt region also depends on the geometry of the device and possible space charge effects. The curve of Figure 5 depicts only the main characteristics of this region.

This region around zero target volts is of particular interest since both half-tone and bistable storage targets operate partially in this region.

Another important 'apparatus effect' is the effect achieved by setting the collector voltage at a fixed predetermined value. The device of Figure 6 differs from that of Figure 2 in that the collector is fixed at a voltage such as +200 volts with respect to ground, instead of being always a few volts more positive than the target.

Figure 6.

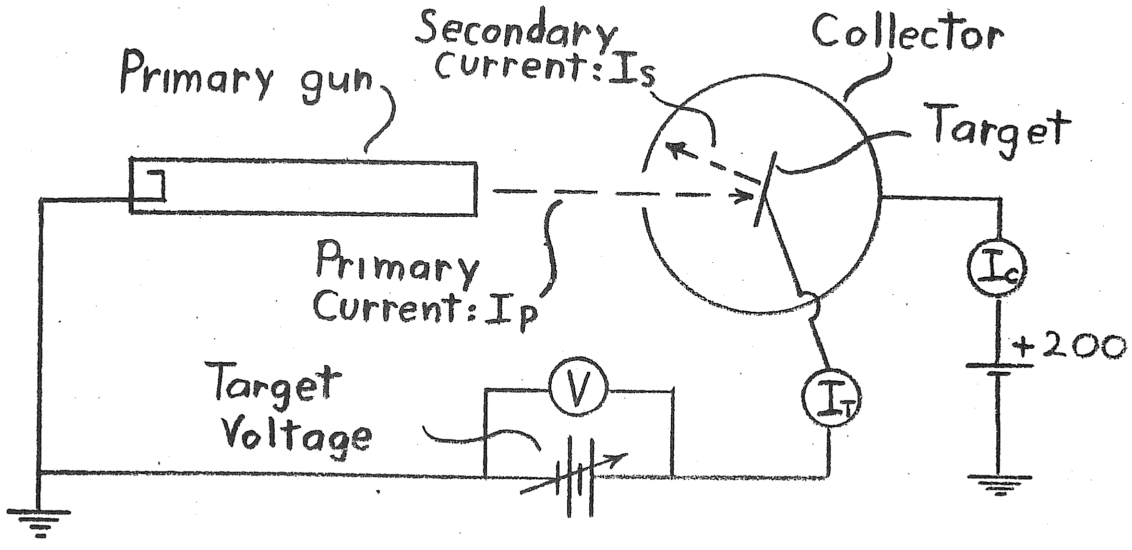


Figure 6 shows the first of a series of changes which will result in the step-by-step evolution of the device of Figure 2 into a direct-viewing storage tube. Several additional basic effects must be described, however, before discussing a tube capable of storage, and the reader who has some familiarity with storage tubes is cautioned not to assume that the primary electron gun shown here is specifically either one or the other of the two guns usually found in storage tubes.

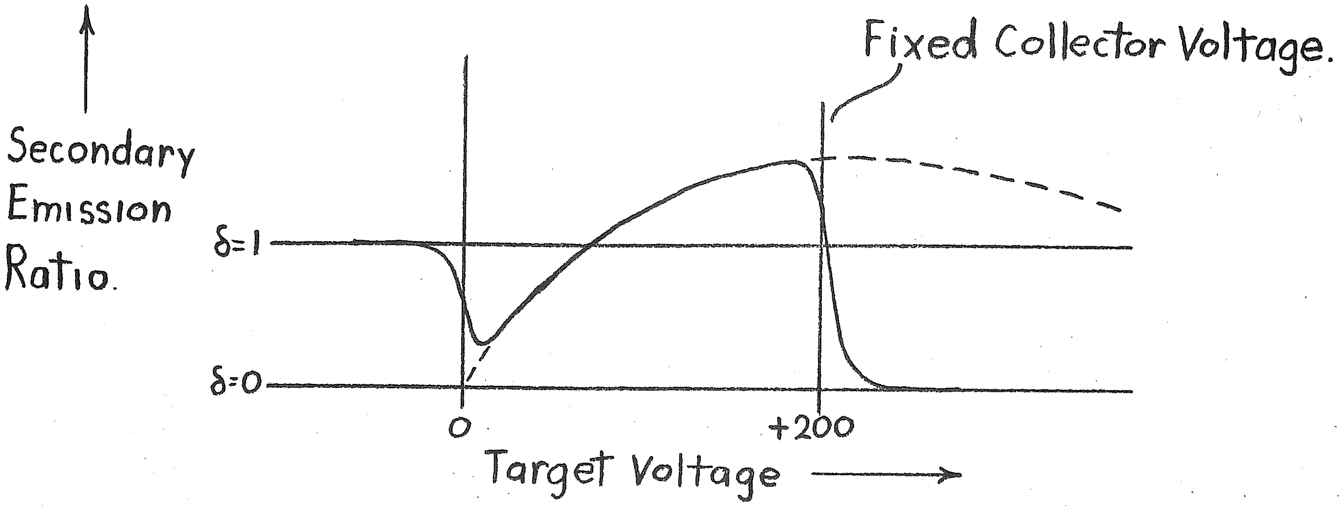
With the arrangement in Figure 6, secondary emission which occurs when the target is below +200 volts is collected as it was in the device of Figure 2, since the collector is then more positive than the target.

When the target is well above the collector voltage, at + 500 volts, for example, secondary emission leaves the target surface due to its energy of emission, but the electrons are emitted into a retarding field caused by the lower collector voltage, which reflects most of them back to the target. Under these conditions, when the target voltage is well above the collector voltage, the net secondary emission current is near zero, since essentially no secondary current reaches the collector. The target is receiving the primary beam current, however, and is acting simply as a collector of the primary current. Current measurements from outside the envelope would show that the target current almost equals the primary beam current, and there is no collector current.

Since these are also the current conditions for a target material which is such a poor emitter of secondary electrons that no substantial emission current is collected, we see that current measurements in this device (Figure 6) cannot distinguish between the total return to the target of secondary electrons by the collector, and a true secondary emission ratio of zero.

The result of this ' apparatus effect' is the 'net' secondary emission curve of Figure 7.

Figure 7.



The curve in the immediate vicinity of target voltage equal to the collector voltage, like the curve around target voltage of zero, is rounded in both directions, and for similar reasons. This rounded transition region is also of some interest because storage targets are often in this region, so several paragraphs will be devoted to it.

At target voltages just <u>above</u> the collector voltage, some secondary emission is able to pass from the target to the collector, against a retarding field, due to the energy of secondary emission. The initial velocity of secondary emission is generally much higher than that of thermionic emission. Retarding voltages of around -30 volts are usually necessary to act effectively as a 'stopping potential' to cut-off most secondary emission (unless the primary energy is below 30 volts). Accordingly, the net effective secondary emission ratio for targets up to 30 volts more positive than the collector is generally greater than zero, and the amount of this target-to-collector voltage difference varies with primary voltage and the resulting secondary emission ratio.

Depression of the net apparent secondary emission curve when the target voltage is just <u>below</u> the collector voltage, where the secondary collection should be aided by the collector field, is believed to be due to reflection of some secondary electrons by a space-charge potential near the target, when the current is high. (In structures more complex than that of Figure 6, some high energy secondaries would also fail to be collected when their trajectories cause them to miss the collector and return to the target.) These effects explain the gradually rounded transition region of the curve in the vicinity of the collector voltage.

Summary of Sections 2 and 3.

To summarize the principles covered so far: the dependence of the bombarding electron energy on the target voltage has been reviewed, and the small correction of this energy due to initial velocity of emission has been discussed. The physical phenomena of secondary emission was then described in terms of the previously developed idea that the target voltage causes a particular bombarding energy. This bombarding energy then causes a particular amount of secondary emission.

The physical effect of secondary emission was then modified by so-called 'apparatus effects'; that is, the 'apparent' or 'net' effects of unity secondary emission at negative target voltages, and the zero secondary emission when the target is much above the collector voltage. These conditions cannot be distinguished from true secondary emission changes by external measurements in the tube described. The previously developed idea of electron repulsion and 'stopping potential' was used to describe the rounding off of the net-effect curve in the two important transition regions around zero target volts and around target voltage that is about equal to collector voltage. All effects were described in terms of a simple vacuum tube having a single electron gun, and a single metal (conductive) target, where the target voltage was controlled by an external voltage supply.

In the next section, control of the target voltage by electron beams instead of by an external power supply will be described, as in a storage tube.

The description will be based on the last curve described (Figure 7) in which the net apparent secondary emission ratio was shown to be the joint result of apparatus effects and the physical effect of 'true' secondary emission.

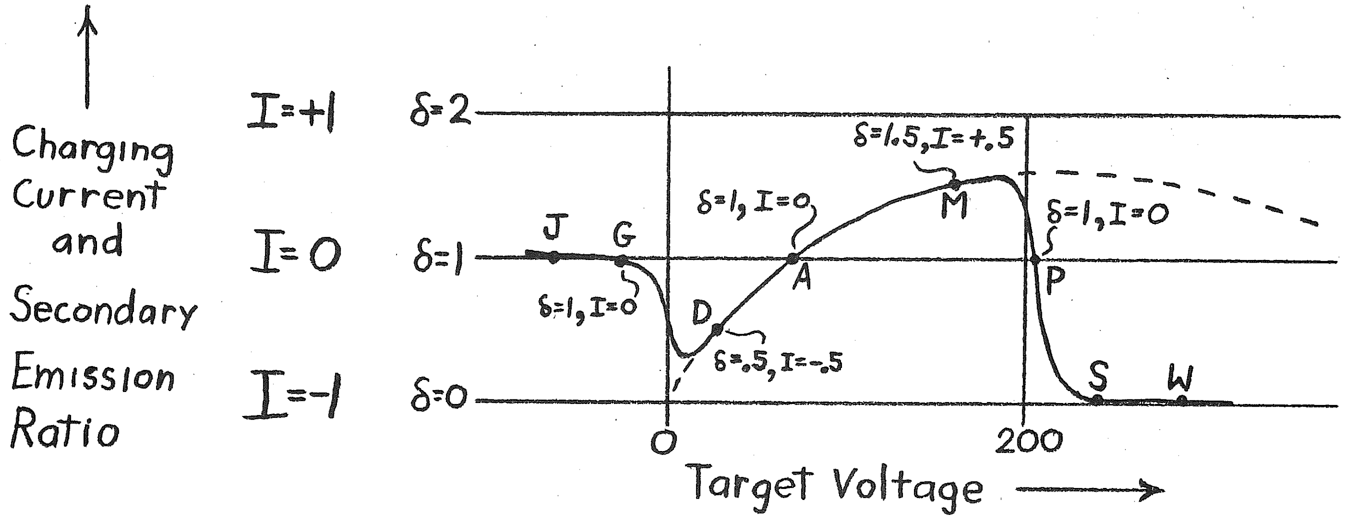
It should be understood that the next few figures describe experimental tubes which are used here to illustrate basic principles, but these tubes are not widely applicable to commercial equipment, and are not known to be in production anywhere. The commercially produced tubes will be described in later pages.

SECTION 4. TARGET CHARGING WITH A SINGLE CONDUCTIVE TARGET

Charging Current Curve.

In several previous examples, it was shown that the direction and amount of flow of current in or out of the secondary emission target surface and in the lead-wire to the target depends on the secondary emission ratio.

Figure 8.



In Figure 8, the net secondary emission curve of Figure 7 has been re-drawn, and an additional scale of ordinates has been added on the left side, to show net current through the target surface. The current scale is in units such that one unit equals the total primary beam current. At points J, G, A, and P, for instance, since the secondary emission ratio is one, the secondary current equals the primary current; that is, the current leaving the target surface equals the current arriving at the target surface. Since currents leaving and arriving at the target are equal, there is no net flow of current to or from the target, and the current in the target lead-wire is zero at these points. Notice that A and P are the first and second crossover points. At point M, each unit of primary current arriving at the target produces 1.5 units of secondary current leaving the target, resulting in a net loss of .5 units of current into the vacuum, from the target surface. The current in the lead-in wire is then .5 units in a direction into the envelope to the target, as shown on the current ordinate scale. The current ordinate in Figure 8 is given a positive direction for the current flow direction into the envelope, since the target surface is losing negative charge, which is equivalent to gaining positive charge. (This polarity is the most convenient in later examples.)

At the low target voltage of point D in Figure 8, the secondary emission ratio is only .5. Primary current of one unit produces secondary current of .5 units, so the target is a net collector of .5 units of current, which flows in the target lead wire in a direction out of the envelope, as shown by the current ordinate of I = -.5 on the curve. It may be noted that the charging current scale, in the figure, is being derived by converting the ratio between two currents into the difference between two currents.

At points S and W, where practically no secondary current can escape to the collector, the effective secondary emission ratio is almost zero, and the target simply collects the primary beam current, which flows out of the envelope in the lead wire, as shown on the graph by I = -1.

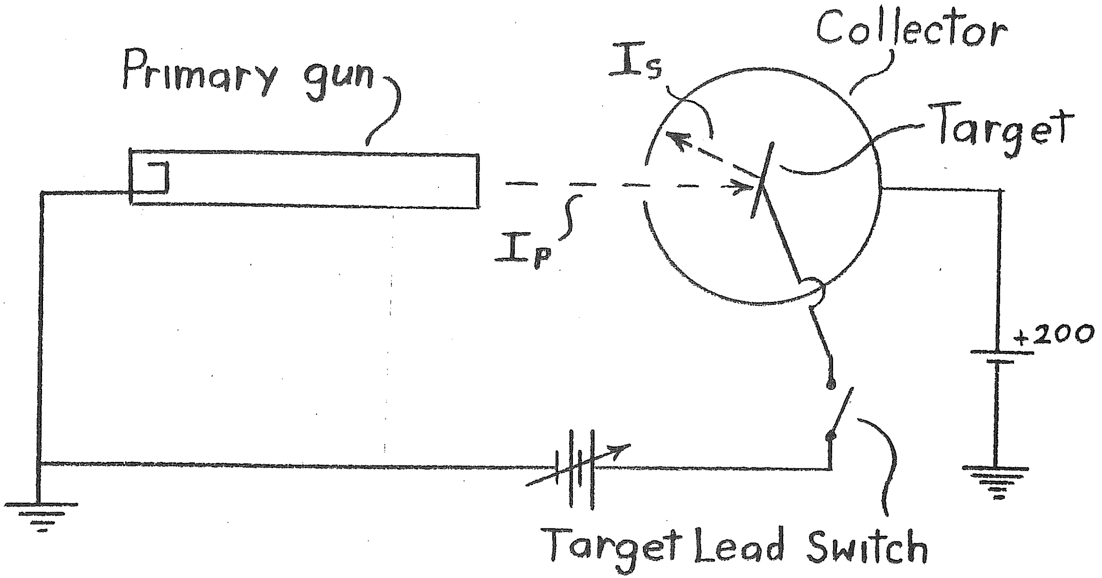
Notice that the whole length of the segments of the curve between points G and A, and also between P and W, show net collection of current by the target surface, since the secondary emission ratio is less than one over each entire segment. Similarly, the curve segment from A to P shows net emission of current by the target surface, since the secondary emission ratio is greater than one.

Open Circuit Charging Direction.

At this point, we are prepared to make another important change in the experimental tube, which will result in the introduction of the first device described here which is capable of simple storage effects. This will be accomplished by the use of a floating target instead of a target whose voltage is externally controlled.

In Figure 9, the device of Figure 6 has been changed again by adding a switch in the target lead.

Figure 9.



This tube can now be used to determine experimentally which way the potential on the floating target changes due to target charging, for any particular initial target voltage. With the switch closed, we may adjust the target voltage supply to any starting condition, and then open the switch and measure the changing target voltage (with meters which are not shown in the figure). The charging direction at 'every point' on the curve may be measured and plotted this way.

When the target voltage is adjusted to some low voltage such as +20 volts, for example, a secondary emission ratio of about .5 may typically result, as shown at point D in the curve of Figure 8. At this point we saw that for every unit of primary current collected by the target, .5 units of secondary current leaves into the vacuum, so the net collection effect is .5 units of electron current, which flows out of the envelope on the target lead-in wire. The target voltage is not changing while the current flows, because the target power supply has been set at a fixed +20 volts. (More specifically, the target voltage is not changing because the net flow of all current both into and out of the target balances at zero, satisfying Kirchoff's law, when the current in the lead-in wire is counted, in addition to the net effect of the primary and secondary currents at the target surface.)

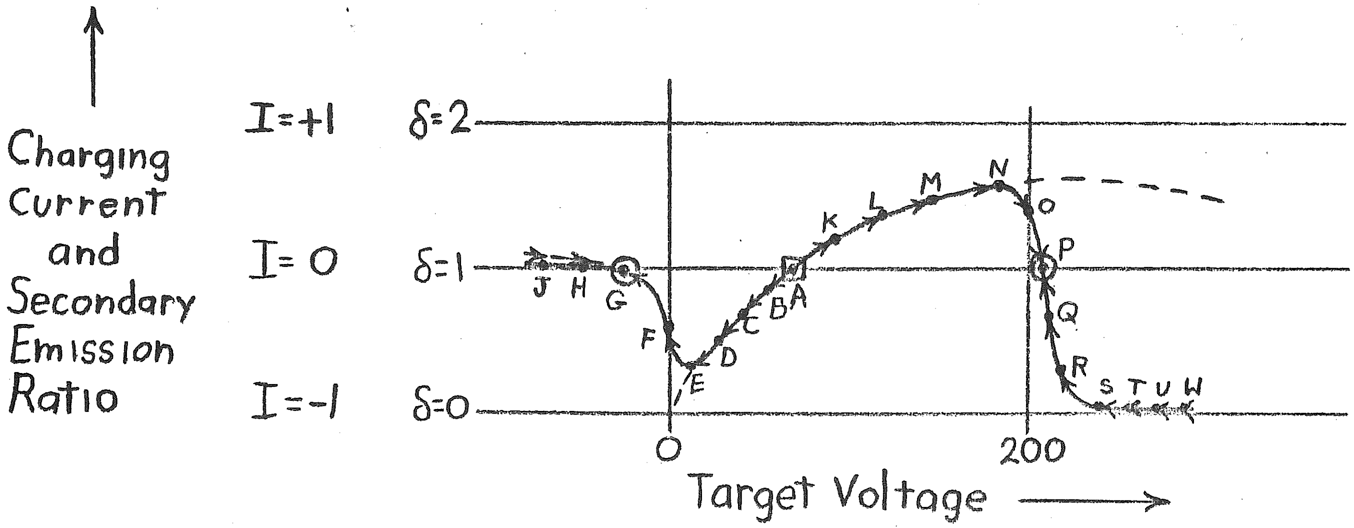
If the switch in the target lead is now opened, the current in the target lead-in wire is interrupted. The target voltage just after the switch is opened is identical to the voltage just before the switch is opened, because the capacitance from the target to all other electrodes cannot be instantaneously charged to a different potential. Since the target voltage is unchanged in this instant, so are the resulting bombarding energy of the primary beam, the secondary emission ratio, and the net negative target surface current flow of I = .5 units associated with point D on the curve, all unchanged in this instant.

The current balance satisfying Kirchoff's law has been instantaneously changed, of course, when the switch was opened, so the target capacitance starts to charge in a negative direction, due to the net collection of current at the target. The target voltage then shifts in a negative direction with the target voltage of point D as its starting voltage after the switch is opened. This is shown in Figure 10.

The curve of Figure 10 is similar to Figure 8, except that the direction of target voltage change for a floating target has been indicated by arrow heads at point D, and at other points on the curve.

The curve of Figure 10 is the result of opening the switch in the target circuit at many different target voltages, to determine its charge direction as a function of target voltage.

Figure 10.



As the target charges more negative from point D, its voltage drops to the voltages of points E, then F, and G on the curve. The secondary emission ratio changes as the target voltage changes, so the net collected target current varies over a range of values. However, since the secondary emission ratio remains below one, between points A and G, the direction of target charging remains negative, although the charging rate varies.

If the switch in the target lead is opened when the target voltage is at point B for instance, we see that since the secondary emission ratio is less than 1, the target charges in a negative direction until the target voltage of point D is reached. The target behaviour at point D has already been described, and we may note that a target, when at point D, charges in a negative direction whether the switch was just opened at the voltage of point D, or the target is now at point D after charging down from point B. Accordingly, the curve of Figure 10 is not only a presentation of the initial charging direction of a target following the opening of the switch in the target circuit, but also shows the target charging direction as a function of target voltage, independent of the history of the target prior to its instantaneous voltage condition. This is perhaps a small distinction, but one which may be helpful in preparing for discussion of floating targets having no lead-in wire and switch, and not accessible to an external power supply or to external meters.

As a target charges negative toward point G, along the segment of the curve A-G, the rate of negative target charging decreases as the target voltage closely approaches voltage G, since the secondary emission ratio approaches 1. When the target reaches point G, the net charging rate becomes zero, so there is no further drop in target voltage.

If the target circuit is opened when the target is below point G in voltage, at point J, the curve of Figure 10 shows us that there is still no net target charging, and the target remains at this voltage indefinitely. In real devices, however, the effects of positive ion bombardment and conductivity across the insulating target support structure usually cause the target to charge slowly in a positive direction, until point G is reached. The dotted portion of the curve above point J shows that this effect results in a positive direction of target charge, just as if the secondary emission ratio were greater than one.

The portion of the curve from G to J is the important range of target voltage in half-tone 'charge-storage' tubes. The portion from G to P is the important range of target voltage in the bi-stable or 'Haeff' principle tubes. (Developed by A. V. Haeff.)

Stable Points. Storage.

A target becomes stable in its target voltage, when it arrives at point G, because the charging effects balance to zero at this point, whether the target has been dropping in voltage from a higher voltage point, or charging positive from a lower voltage point.

Notice that if a target at point G is temporarily disturbed from its rest position at point G by a small voltage shift, in either direction, the net charging effect is no longer zero, and a charge effect arises having a direction which restores the target to the voltage of point G. Since there is a restoring force on a target in the vicinity of point G, this point is a stable point in target voltage, as long as the primary electron beam is present to preserve this stability. (Strictly speaking, the point G is often referred to as a quasi-stable point, since there is no restoring force due to secondary emission alone, below point G.)

The curve segment P-W is similar in charging direction to segment A-G, as it also lies entirely below a secondary emission ratio of 1, and has a net charging direction which is negative over the whole segment. When the target circuit is opened at the target voltage of point W, for example, the target charges in a negative direction toward point P. As point P is approached, the charging ratio decreases because the secondary emission ratio is approaching one, and the net target current is approaching I = 0. At point P, the target voltage stops dropping and becomes stable, because the net charging rate is zero.

The segment A-P of the curve lies entirely above a secondary emission ratio of unity, so at every point on the segment, the net flow of target current is away from the target, and this loss of target electrons (loss of negative charge) drives the target voltage more positive. A target floating from point K increases in voltage until it reaches the voltage of point P, the rate of charge dropping to zero as it approaches and reaches point P.

When a target has charged to the voltage of point P, either from a higher or lower target voltage, it has reached a voltage which is stable in the sense that a small disturbance of the target voltage will be corrected by restoring forces that return the target voltage to point P, as long as the primary beam is present to preserve stability.

Notice that at the two stable points G and P, the curve of Figure 10 crosses the line $I=0$ with a negative slope. A stable point in a floating target's voltage occurs wherever the curve of net target charging current crosses $I=0$ with a negative slope.

At point A, the net charging current is also zero, but a small perturbation in target charge from any 'noise' source will send the target charging up or down to point P or G, depending on which way the target voltage is first shifted by noise. Point A is a uniquely unstable point, and we may note that an unstable point in the voltage of a floating target occurs wherever the curve of net target charging current crosses $I=0$ with a positive slope.

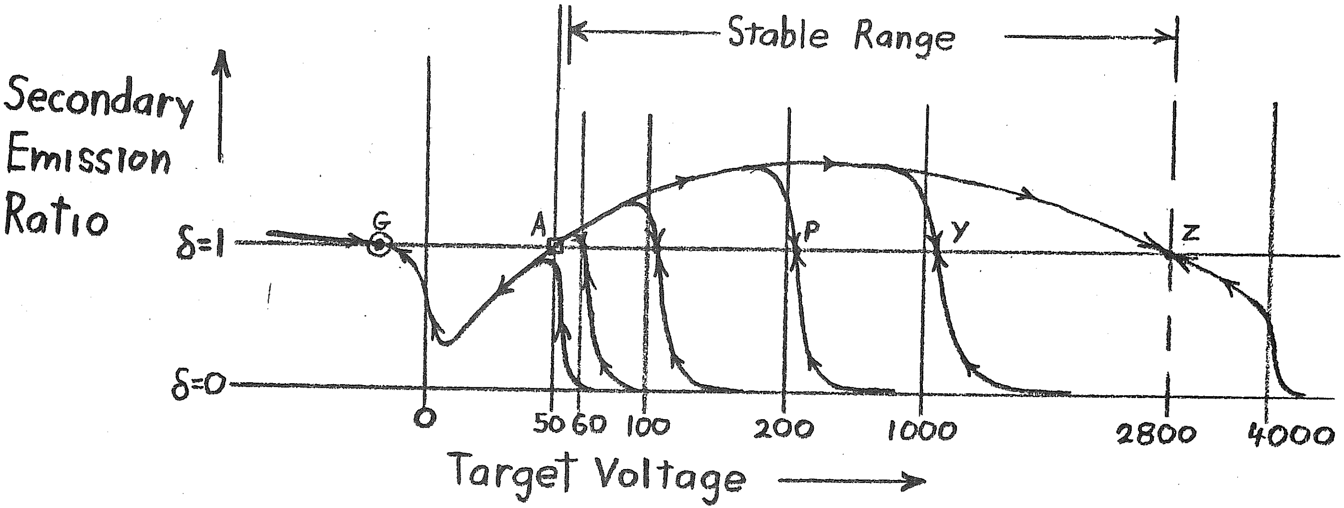
Since the target now has two stable points, G and P, at which its voltage will be held by restoring forces, (which point depending on its history before the switch in the target circuit was opened) we see that this device is an elementary bi-stable storage tube, and it is the first tube of this report which is capable of storage. This tube (Figure 9) may be interrogated by measuring the target voltage, and the measurement will tell us whether the target voltage supply was above or below the voltage of point A at the time that the switch was opened. The information is present as the voltage at the target lead wire, and there is no image displayed, so the tube is an electrical read-out tube (of one-bit capacity) as opposed to a direct-viewing storage tube. Bi-stable storage is frequently referred to as having 'infinite' persistance, since the tube will retain its stored information indefinitely.

The term 'to store' will be used repeatedly to mean: to hold the target voltage at <u>either</u> of its two stable points by the use of the restoring forces due to electron bombardment described above.

The Stable Range of Collector Voltage.

If some other voltage is chosen for the voltage of the collector in the tube of Figure 9, and this voltage is between the first and second crossover points of the secondary emission curve (Figure 3), the general features of the net target charging curve are not much changed. In Figure 11, a family of charging curves is plotted for various collector voltages:

Figure 11.



The curve in the region of a collector voltage of +200 volts is the curve discussed in the preceding section, and the stable points G and P appear on the curve, as well as the unstable point A. If the collector voltage is increased to +1000 volts, the upper stable point, formerly at P, now moves to a higher target voltage, Y, since the collector is now able to collect substantial secondary emission up to this target voltage.

If the collector voltage is raised above the second crossover point, to +4000 volts, for example, the upper stable point now occurs below the collector voltage at point Z because the charging curve crosses the I = 0 ($\delta = 1$) line, with negative slope, at the second crossover point. A floating target will not charge more positive than this, because it becomes a net collector of primary electrons as its secondary emission drops below unity at higher voltages. This voltage is known as the 'sticking potential' in cathode ray tubes having a floating viewing screen, where the effect limits the image brightness. While the tube will still exhibit bi-stability for higher collector voltages than this, there is no known advantage to increasing the collector voltage, and the upper stable target voltage does not increase, so we may regard the second crossover point as a practical upper limit to the useful range of collector voltages resulting in bi-stable storage.

When the collector voltage is decreased below +200 volts to +100 volts, for example, we find that the upper stable point drops in voltage, and the peak of secondary emission is lower, but the tube still exhibits bi-stable storage. As the collector approaches and then goes below the effective secondary emission unstable point A, however, the peak of the effective secondary emission curve is pulled down below δ=1, and there is no positive target voltage for which the net charging effect is in a positive direction. The target acts as a collector of primary electrons and is driven negative for all voltages above point G. There is now only one stable point, at G, so bi-stability is lost.

Since the tube will not exhibit bi-stable storage with collector voltage below approximately the voltage of the first crossover point, we see that the practical range of collector voltages which results in bi-stability lies between the first and second crossover points. The range resulting in bi-stability is commonly called the 'stable range' in the storage tube art. We will see later that in complete direct viewing tubes, the stable range of collector voltages is much more restricted, by other effects, than is shown here, where the secondary emission effect predominates.

Mechanical Stability Model.

The dependence of stability on the presence of restoring forces is a fundamental idea which can be made more familiar by comparison to a mechanical model. Figure 12 shows a shaped surface with a small ball resting on it, under the influence of gravity.

Figures 12 and 13.

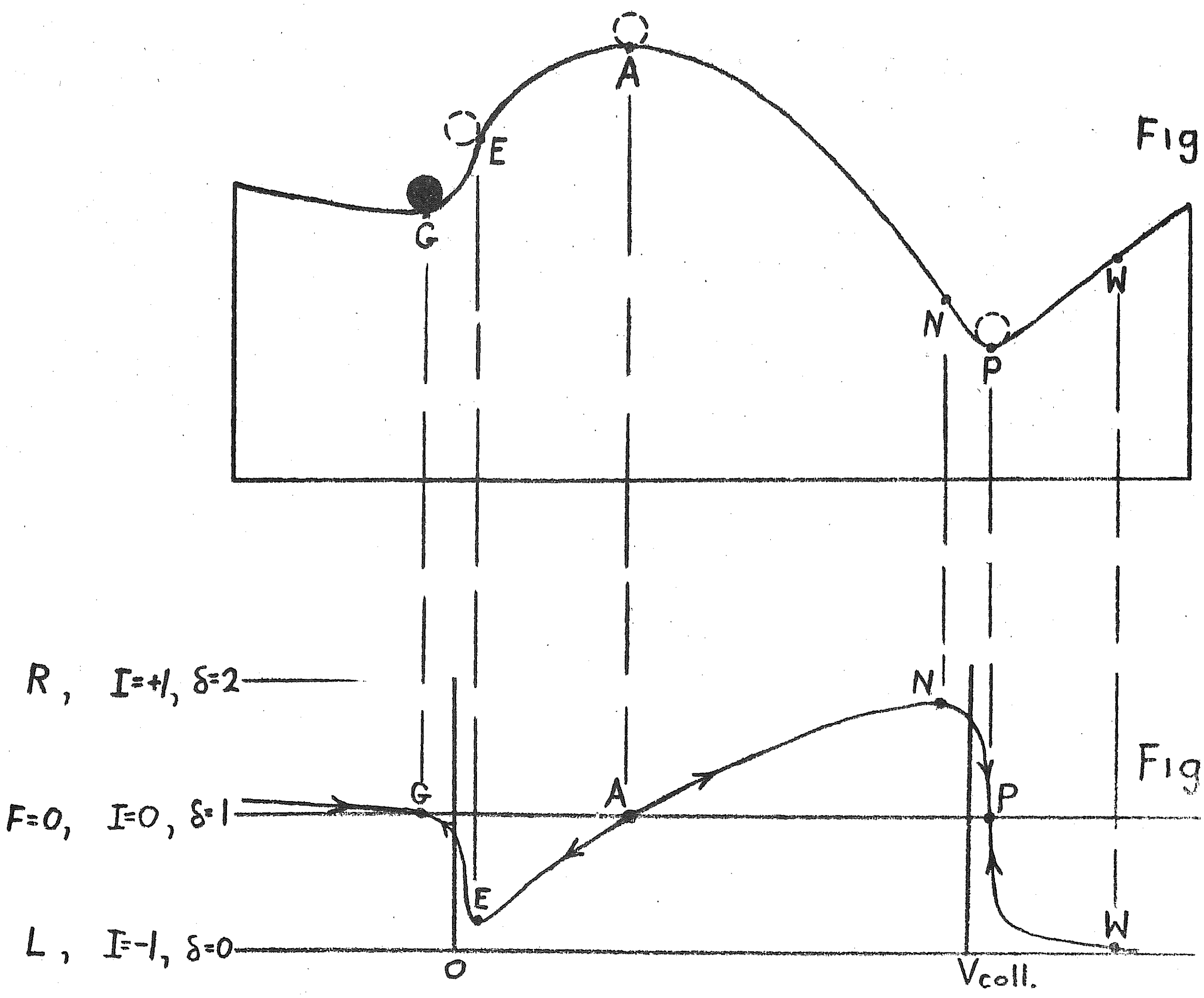


Figure 12.

Figure 13.

The ball will remain indefinitely in either of the stable positions G or P, if once placed in either of these positions. This is comparable to the stability of the storage target just described, which will remain at either of its two stable voltages indefinitely.

If the ball at point G is displaced to the right, to point E, it experiences a strong restoring force which returns it to point G; in fact, the surface at point E is the steepest slope on this portion of the surface. This is comparable to a target voltage at point E (Figure 13) which is restored to stable point G, and has the highest negative charging rate on this part of the curve at point E, where the effective secondary emission ratio is low.

If the ball is placed at point A on the mechanical model, it is unstable, and will drop to point G or P at the slightest disturbance, just as the target voltage at point A on its curve is unstable and will shift to G or P at the slightest disturbance.

Notice that points E, N, and W on the target charging curve are points of highest charging rate, and correspond to points of maximum slope on the mechanical model. Points G, A, and P have zero charging rate on the charging curve and zero slope on the model.

The slope of the surface of the mechanical model is such that a graph of the forces on the ball at any point on the model's surface has the shape of Figure 13. The graph and the arrows on it show the amount of force on the ball, and the direction of force, which is to the left where the curve is above the zero line. We may add an ordinate scale on the left of the graph, showing this force, so this one graph now shows effective secondary emission ratio of a target, the amount and direction of target charging, the amount and direction of force on the ball, and the stable points for both the ball and target.

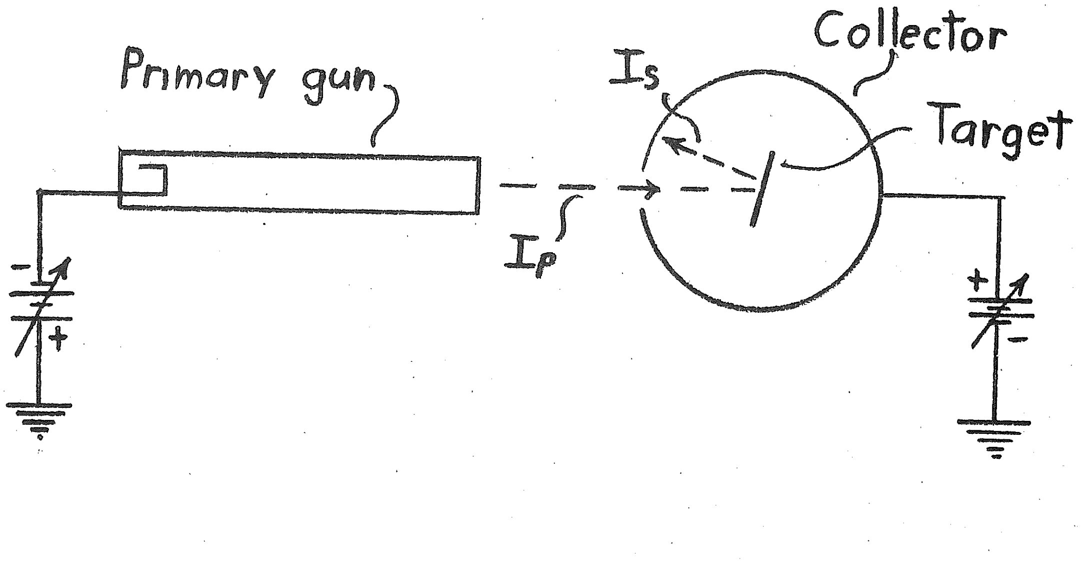
Floating Target Control with One Gun or the Collector.

The discussion in the next few pages illustrates how the target voltage can be controlled by shifting the collector voltage or the primary beam's cathode voltage. The collector voltage is used for target control in bi-stable tubes, but the cathode of a primary beam is generally not shifted in voltage, partly because the bias, focus, anode, and deflection voltages would all have to be shifted with it, to maintain the beam size, location, and current. Brief description of cathode control of the target is included, nevertheless, because facility in using the simpler concept will later help the reader who may be bothered by the idea of keeping a floating target under control, which is the central concept of storage tubes. This brief description will also give emphasis to the role of the target voltage relative to the cathode voltage in determining primary energy, which is essential in later sections where several cathodes bombard a target at a single target voltage, but with primary beams of different energies.

The reader should not yet assume that the primary beam discussed here, or in any preceding tube, refers specifically to only the 'writing gun' or the 'flood gun' in storage tubes. Several effects have yet to be illustrated in this section before describing two-gun tubes in the next section.

The device of Figure 9 may now be modified again, as shown in Figure 14.

Figure 14.



The target is supported in the tube only by insulators, and there is now no lead-in wire providing connection to the target from outside of the tube. Compared to the tube of Figure 9, we could say that the target circuit switch is now permanently open. Variable voltages are provided for the primary gun cathode and the collector, and these electrodes will be used to control the target voltage. This will demonstrate some of the possibilities of target voltage control, even in the absence of control of the starting condition of the target voltage by an external power supply.

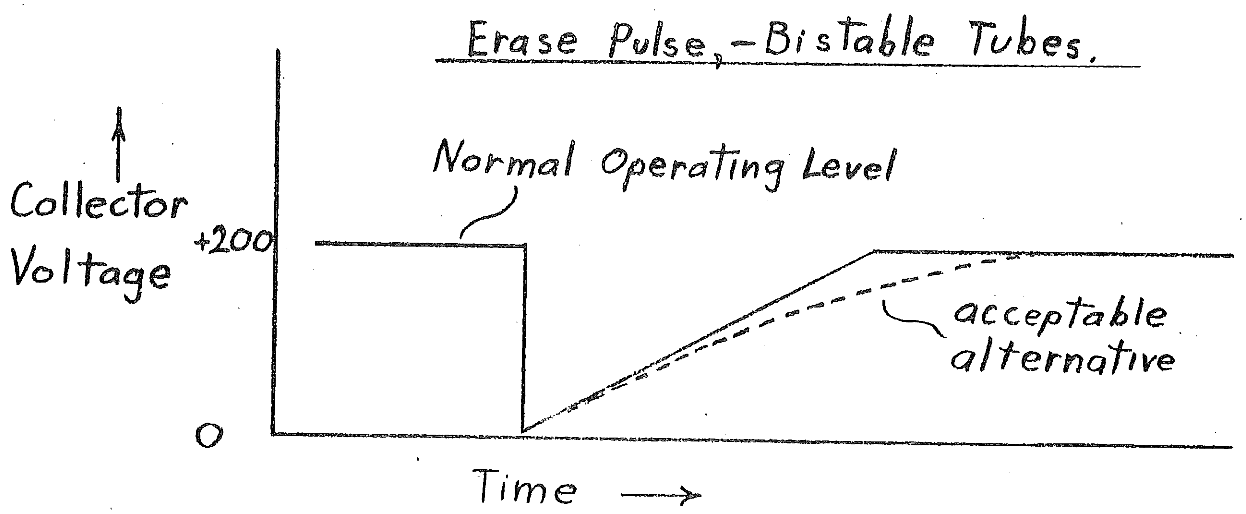
If the tube is turned on with initial voltages of collector at +200, primary gun cathode at 0 volts, and target at 0 volts, the target charges down to the lower stable point of just below zero volts (point G on Figure 10,) by collection of primary electrons. If we wish to put the target at its upper stable condition, we may suddenly lower the cathode voltage to -100 volts, for example, so that the primary energy, or the target voltage <u>relative</u> to the primary gun cathode, is +100 volts. This raises the secondary emission and net charging effect to about that of point M on Figure 10, which is above the first crossover. The target charges positive to the upper stable point (at P, Figure 10), where it has a voltage just above the collector voltage of +200 volts relative to ground or +300 volts relative to the cathode. The cathode may now be returned to its former voltage of 0 volts, without much effect on the target charge, since there is not much change in the upper stable voltage when the primary energy goes from +300 to +200 volts.

If we now wish to put the target at a zero volt stable position, we may raise the cathode voltage to +180 volts, so that the primary energy is low on arriving at the +200 volt target. The target charges negative by primary collection, until it reaches the vicinity of the new cathode voltage, around +180 volts. The cathode may then be lowered another 20 volts, and the target then charges down to the vicinity of the new cathode voltage, now around +160 volts. By repeating this process, the target may be brought down to zero volts, or any lower voltage. The same effect can be had by lowering the cathode voltage continuously at a low enough rate of drop so that the target charging can follow the cathode down, without the voltage difference between target and cathode becoming large enough to place the target above the first crossover, which would reverse the charging direction.

Having seen how the target voltage can be shifted between either of its two stable points by the adjustment of primary cathode voltage alone, we now discuss how the same changes can be accomplished by changing only the collector voltage. We start with the same conditions as above, with cathode at zero volts, collector at +200, and target at the lower stable point, just below zero. If the collector is suddenly shifted more positive, by perhaps an additional +200 volts, a part of this potential is capacitively coupled to the target, through the collector-to-target capacitance. If we assume that the capacitance from collector to target is at least equal to the capacitance from target to all other electrodes, (which is a very conservative assumption, in this tube) then half the target voltage change, or +100 volts, appears on the target. This places the target voltage above the first crossover, and the target charges positive, reaching the upper stable point just above the collector voltage, which is now +400 volts. If the collector is suddenly returned to +200 volts, the target now drops 100 volts by capacitive coupling, to +300 volts. The target then charges negative from +300 volts, by primary collection, to reach the upper stable point just above the collector voltage of +200 volts.

The target voltage may also be dropped to the lower stable point by shifting the collector voltage. This is an important effect which is used to erase the stored charge-image in bi-stable direct-viewing storage tubes. If the collector voltage is suddenly dropped by 150 volts, from +200 volts to about the first crossover point at about +50 volts, two effects occur which tend to charge the target negative. One of these is the capacitive coupling of the collector signal to the target, which immediately drops the target voltage by 75 volts (in this example) to a new target voltage of +125 volts. The other effect is the negative charging of the target by primary collection, which continues until the target reaches the lower stable point just below 0 volts. This was shown by the lowest curve in the family of curves of Figure 11, for which there is no upper stable point because the curve never passes into the region where the effective secondary emission ratio is one or more. Since the effective secondary emission is below 1, the target charges negative by net collection of primaries. The collector cannot now be suddenly returned to +200 volts without changing the target voltage, because, as we just saw in the last paragraph, the target would be pulled above the first crossover by capacitive coupling, and then carried to the upper stable point by positive charging due to secondary emission. Instead, the collector may be returned to its voltage of +200, if desired, by a series of steps of voltage, each step small enough so that the target is not driven above first crossover, and each step followed by a delay long enough for the target to charge back down to the lower stable point from which it was displaced by capacitive coupling. A more practical alternative is to raise the collector voltage continuously, but at a rate slow enough so that the negatively charging restoring forces on the target, near the lower stable point, are able to overcome the capacitively coupled positive charging effect well enough to keep the target below first crossover, so that it doesn't charge positive to the upper stable point. This is the procedure actually used to erase bi-stable tubes. A typical erase waveform applied to the collector is shown in Figure 15.

Figure 15.



The recovery time of the collector voltage depends on the particular tube design, and the primary beam current. One commercial bi-stable tube type uses about a 1/3 second pulse.

It may be convenient to introduce here the terminology of 'write' and 'erase' in bi-stable tubes, in anticipation of these effects in the tubes described later. When the target is driven to its upper stable point, we will say it has been 'written.' This will be more meaningful later, when a bright image is produced by this action, but it will be a useful economy of words to use the term now, in devices which do not yet produce an image. It is easier to say that the target has been 'written' positive, than to say that it has been 'shifted in target voltage to the upper of its two stable points.' It follows that we have 'erased' the target by shifting the target from the upper to the lower stable point, and we will see later that the bright image is indeed erased by this action. (This applies only to bi-stable tubes. Half-tone tubes do not use the stable points in the same way, for these effects.)

It should be clear at this point that the target may also be made to write and erase by using both the collector and the primary cathode voltage. Simultaneously pulsing the cathode negative and the collector positive would shift the target positive at a faster rate than either effect alone. Also, simultaneously pulsing the collector negative and the primary cathode positive would erase faster than either effect alone. (In both cases, pulse amplitude would be carefully selected for fastest charging rates.)

The voltages of the two stable points, relative to ground, can both be shifted higher or lower an equal amount by raising or lowering the primary gun cathode voltage and the collector voltage equal amounts.

The voltage difference between the two stable points may be increased or decreased by moving the primary gun cathode voltage and the collector voltage closer together or further apart, within the limitation of keeping the collector voltage within the stable range, as we saw in Figure 11.

We saw in an earlier section that the target could be put in either stable position by controlling its initial voltage with a power supply and then opening the target circuit switch. We see, in this section, that a floating target with no access to external supply voltages can be put in either stable position by control of only the primary beam energy, or by control of only the collector voltage. The voltages of the two stable positions may also be controlled by adjusting both the primary cathode voltage and the collector voltage. This is the first tube described here which writes, stores, and erases with a floating target. In all these situations, the existence of the stable point depends on keeping the beam current on. Target voltages other than the stable voltages can be reached by turning off the primary beam as the target voltage is passing though some voltage on its way to a stable point. The restoring forces of the stable points will not be present, but the drift of the target away from an unstable voltage due to leakage, ions, etc., may be very slow.

Floating Target Control with Two Guns. Writing and Erase.

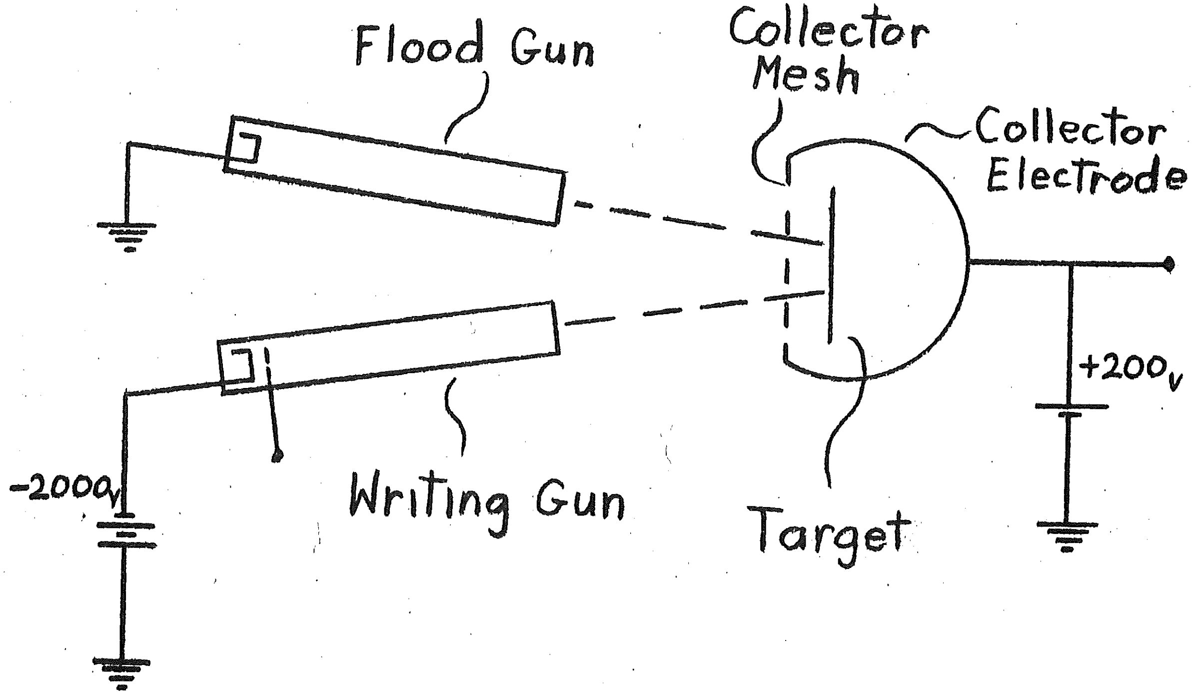
We saw in the last section that a single electron gun was sufficient to 'write' the target to its upper stable voltage, but that most of the gun electrodes would have to be accurately shifted to different voltages to accomplish this. It has been found much more practical to use two guns having their cathodes fixed at different voltages, and to keep most of the gun electrodes at fixed voltages. It will also become apparent in later pages that the two functions of writing and storing a two dimensional charge-image are so different that different gun designs are required for optimum performance of these two functions.

Accordingly, we are again ready to make a step in the series of modifications of the simple previous devices, evolving toward the complete storage tube. The next change will be to add a second electron gun, providing a second beam of primary electrons, as sketched in Figure 16. This tube will have many more of the important functions of storage tubes; however, we may note that this tube, like the preceding tubes, has as yet no provision for writing a two-dimensional charge-image, and no means for displaying a visible light-image of a stored charge-image.

In the tube of Figure 16, the entrance aperture in the collector has been enlarged to admit two electron beams. The resulting reduction of the strong collecting field in front of the target has been corrected by placing a mesh across the entrance aperture, which maintains substantially the same field that would be there if a solid part of the collector occupied that position. The mesh does intercept some of the primary electrons, however, and it may cast its shadow on the target, so a fairly transparent, high transmission mesh is used for this purpose, to minimize these effects and pass most of the primary electrons. The mesh is a good collector of secondary emission, so the tube exhibits bi-stability, as previously described. The target was tilted in the earlier device used to measure the secondary emission ratio of various materials, so that loss of the most energetic secondaries through the collector aperture would be minimized. We are not now interested in the precision of the collector current measurement, so the target may be placed parallel to the collector mesh, and close to it, to insure good collecting fields. If some energetic secondaries pass through the mesh, and are collected by the gun electrodes instead of the collector mesh, this will not alter target behaviour, because the same amount of secondary current is still leaving the target, even if it goes somewhere other than the collector.

In Figure 16, we will call the upper gun the 'flood gun' and the lower gun the 'writing gun', in anticipation of later usage. For the present the distinguishing feature of the 'flood gun' is that it will flood the target at all times, and not just intermittantly, as the writing gun does. Assume for the moment that the lower gun, the writing gun, has been biased to cut-off, and is not bombarding the target. We may then ignore it, in initial discussion of the remaining tube components, since it is not now causing any charging effect on the target. Notice that, except for the floating target, the remaining tube components are comparable to the tube of Figure 9, because the flood gun cathode is grounded to zero volts, and the normal operation voltage of the collector is fixed at +200 volts (except when the erase pulse occurs). These fixed voltages were used

Figure 16


Flood Gun
Collector Mesh
Collector Electrode
+200v
-2000v
Writing Gun
Target

in the tube of Figure 9 to show the target charging direction, the restoring forces that form two stable points, and bi-stable storage of the target at either stable point, but 'writing' and 'erase' were accomplished by connecting the target to an external power supply, through a switch, to shift target voltage. The present tube of Figure 16 cannot write and erase by this method because there is no connection to the floating target. This tube, with the writing gun cut off, also cannot write and erase with the single gun effects of shifting cathode voltage, as was illustrated in Figure 14, because we have fixed this cathode voltage instead of providing a variable voltage supply.

We see then that with these fixed voltages and a cut-off writing gun, this tube cannot write, even though the flood gun is on and continuously flooding the target with electrons, the restoring forces of bi-stability are present, and the target is being held at one of its two stable points.

As might be suspected at this point, 'writing' will be done with the 'writing gun'. Before proceeding with the description of writing, we may note that since the flood gun cathode is at zero volts, the target voltage in the charging current curves may be read directly as the voltage difference from cathode to target. This is not the case for the writing gun, as the writing gun cathode is fixed at -2000 volts.

Writing is accomplished by gating on the writing beam with the writing gun grid.

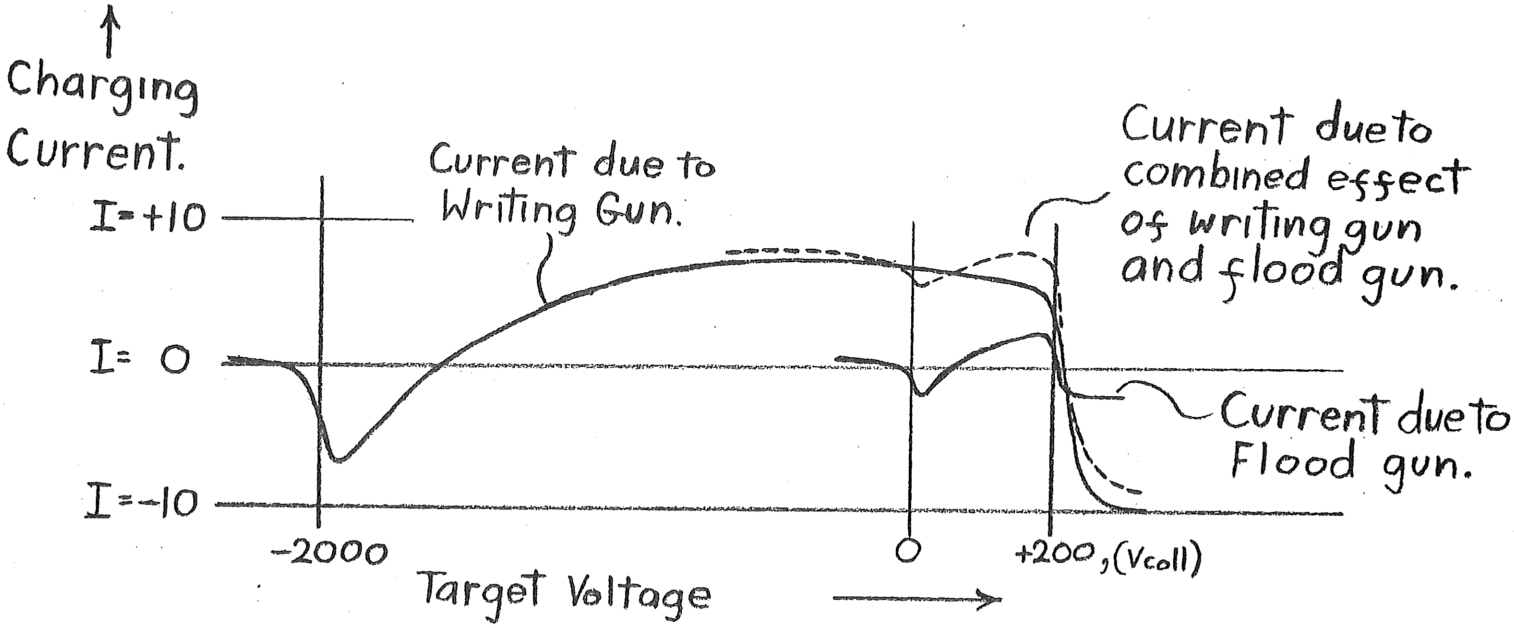
So far as is now known, the combined effect of two beams hitting the same target surface is simply the sum of the individual effects that each beam would have alone. The secondary emission ratio due to one beam is not known to be affected by the presence of a second beam having different velocity. Thismight be expected, since the addition of a second beam of the same velocity would be equivalent to increasing the beam current of a single beam, and this is known to leave the secondary emission ratio unchanged, (within limits of saturation effects.)

It is not necessary, then, to make any distinction as to whether the two beams in Figure 16, hit the target at the same spot, partially overlapping, or not overlapping at all, since the result is the same in all these cases.

When the target is initially being held by the flood gun at the lower stable point, at roughly -1 volt, and the writing gun is then gated on, the writing gun electrons arrive at the target with an energy of about 2000 volts. This is because these electrons have passed through an accelerating field of 1999 volts in going from a cathode at -2000 volts to a target of -1 volt, and in addition, the writing gun electrons are emitted with an initial velocity of thermal emission which we will take to be about 1 volt. The high secondary emission ratio of the target for 2000 volt electrons causes a high positive charging rate, so the target voltage immediately starts to increase. As soon as the target voltage leaves the lower stable point, however, the restoring forces of negative charging occur, due to the target's increased collection of low energy flood electrons, and we see that the stability effect of the flood gun <u>opposes</u> the writing effect of the writing gun.

If the writing gun primary beam current is small compared to the flood gun primary beam current, the positive charging current will be small compared to the negative restoring current, and the effect of the writing gun will only be to shift the voltage of the lower stable point a small amount in the positive direction. However, if the writing gun current is much greater than the flood gun current, the positive charging current leaving the target by secondary emission due to writing gun bombardment will greatly exceed the negative charging current received by collection of low energy flood gun bombardment. The target will then charge up to the first crossover point, and higher. During writing, after the target voltage exceeds the first crossover point for flood gun emission, the flood gun is no longer opposing the writing effect, but is aiding it, since the flood gun primaries cause positive target charging above first crossover. It is only necessary for the writing gun to be gated on long enough to carry the target just past the first crossover, since flood emission alone will carry the target the rest of the way to the upper stable point. On the other hand, even when the writing gun beam current is large compared to the flood gun beam current, if the writing beam is gated on for too short a period to carry the target past first crossover, the flood beam will return the target to the lower stable point after the writing beam is biased off. We see then that the required conditions for writing in this tube are that the effect of the writing gun current has to be substantially greater than the flood beam current, and the writing beam must be gated on long enough to carry the target past first crossover. Figure 17 shows the charging current curve during writing.

Figure 17.



In Figure 17, the charging current curves for the writing gun and flood gun are drawn to the same scale of coordinates, and illustrate the case where the writing gun current is five times the flood gun current. We see that the writing curve differs in three respects from the flood gun curve: the writing gun curve is displaced to the left by 2000 volts because of the difference in cathode voltage; the writing gun curve is five times the amplitude of the flood gun curve due to the current difference; and the collector voltage is much further from the first crossover of the writing gun curve than from the first crossover for the flood gun curve.

The dotted curve is the sum of the writing gun and flood gun charging current curves, and we see that when both guns bombard the target, the charging direction is positive over the entire normal range of target voltages from the lower to upper flood-current stable points, and the charging rate during writing is quite high almost everywhere between the lower and upper stable points.

We have seen how writing and storing are accomplished without shifting cathode voltages, by using two guns. Erasing is carried out by pulsing the collector negative. As previously described, the collector cannot collect secondaries from the target when the collector is far more negative than the target, so the secondaries are reflected back to the target, and the target collects flood gun primaries and charges negative. The slow trailing edge of the erase pulse on the collector, to avoid pulling the target positively by capacitive coupling, has been described. (The sources of collector erase pulse and the writing pulse to the writing gun grid have not been shown in Figure 16.)

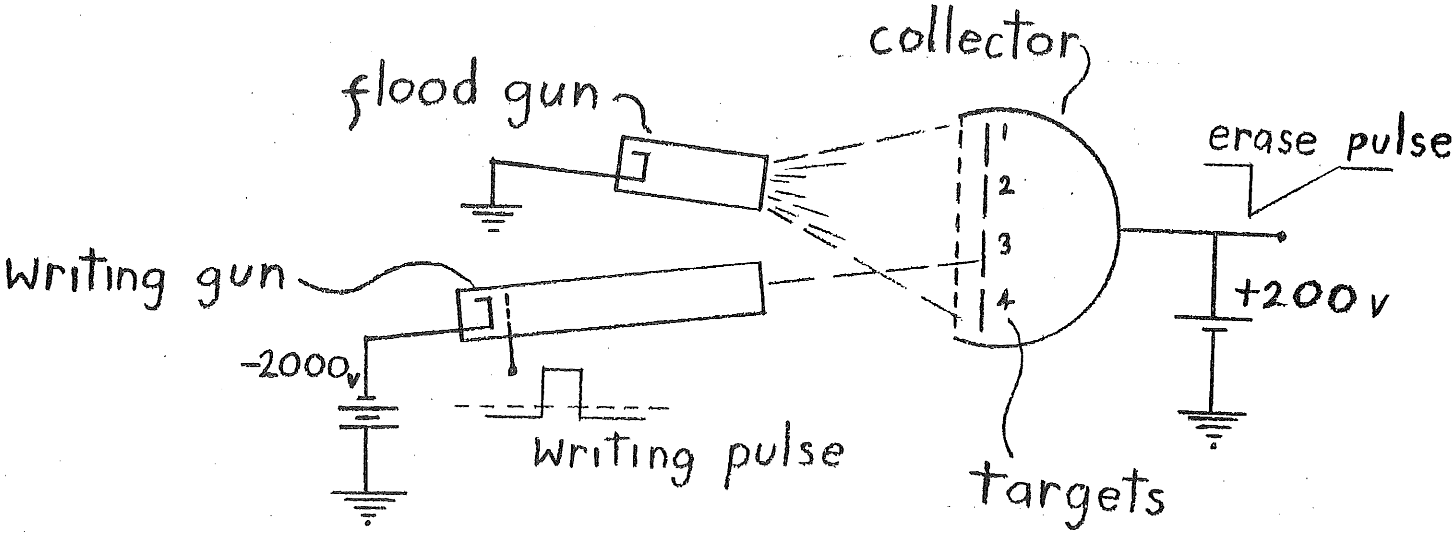
This two-gun tube does no more than the simple one-gun tube which preceded it; that is, both tubes are able to write, store, and erase. The two-gun tube is much more practical, however, and we see that it is the first tube described here which can control a floating target with guns at fixed voltages. The great advantage of the use of two guns will be immediately apparent in the next section, where more than one target is used, and the flood gun can simultaneously hold one target negative and another target positive. This will then be extended to stored images in which some areas are negative and some positive.

Section 5. BISTABILITY IN MULTIPLE TARGETS AND DIELECTRIC TARGETS.

Control of Multiple Targets with Two Guns.

The next step in the structural evolution of a bi-stable storage tube is shown in Figure 18. The target of the preceding tube has been divided into several parts here, or what amounts to the same thing, three additional targets have been added. (The specific number of targets doesn't matter here, for the purpose of this illustration.)

Figure 18.



In the previous tubes all the current from each gun was directed toward the sole target. In this tube the flood gun spot size has been very greatly enlarged, to extend over all of the targets. This can be done with a relatively simple short gun having no need for deflection plates. This has been schematically indicated by the change in appearance in the flood gun in the figure. The writing gun still emitts a focused, directed beam, and all of the writing beam current is directed toward some one target at a time, such as Target 3 in the figure.

Starting with consideration of the effects when the writing gun is biased off, we see that with the flood gun cathode grounded to zero volts and the collector fixed at +200 volts (except during the erase pulse), this portion of the tube has the bi-stable characteristic of the earlier simple tube of Figure 9. When the flood beam is turned on, all of the targets charge negative, by flood electrons collection, from their (assumed) initial voltage of zero volts down to the lower stable point of about -1 volt. The restoring forces of bi-stability are present for all of the targets, and the flood gun is able to hold each target at either of its two stable points, once they are written or erased to those points.

When the writing beam is gated on and bombards target No. 3, for instance, this target charges positive, and is written to its upper stable point if the writing beam current is high enough and the beam is on long enough to write. Target No. 3 is then held at its upper stable point by the flood gun restoring forces, just as the single target in the preceding tube was held at its upper stable point after writing.

The other targets, No's 1, 2, and 4, have not been bombarded by the writing gun beam, and they remain held at their lower stable point by the flood gun. After the writing beam is biased off, the flood gun holds Target No. 3 at its upper stable point, and at the same time holds the other targets at their lower stable points. When the erase pulse is applied to the collector, the written target is made to act as a net collector of current, and is driven to its lower stable point, as previously described. The unwritten Targets, 1, 2, and 4, are driven negative and then positive again by capacitive coupling to the collector as the erase pulse goes negative and positive.

During the short time that these targets are below the 'quasi-stable' lower stable point, they are in the region of weak restoring forces, and may become slightly charged in a positive direction by ion bombardment and leakage across their insulating supports. They would then be returned to slightly above the lower stable voltage when the trailing edge of the erase pulse has passed. Flood gun restoring forces would then return them to their lower stable point, where they started from before the erase pulse occurred.

Writing may also occur with the writing beam in motion. Assume that the writing beam is gated on while directed at target 3, and remains on after this target has become written positive. The writing beam may then be deflected upward across target 2 and brought to a stop on No. 1. After the writing beam crosses the lower edge of target 2, the full writing beam current is delivered to target 2, until the beam passes off the top edge of this target. Target 2 experiences the sudden rise of bombarding writing current, which reaches a maximum value, remains at that value for a period of time, and then suddenly decreases to zero. This is the same sequence of events which occur if the beam were to be directed to target 2, and gated on andoff without being deflected during the time that this target is charging positive. The results are the same; that is, target 2 becomes 'written positive' if the current is high enough and the period of bombardment long enough to charge the target to a voltage higher than the first crossover point.

For a particular value of writing beam current, it will be seen that a very slowly moving beam will deliver more than enough current to the target to charge it over the first crossover point, because the beam dwells on the target for a long time when it is moving slowly. There will also be some speed of deflection that is so high that the beam does not dwell on the target long enough to charge it to the first crossover point, and the target is drawn back down to the lower stable point by flood electrons collection, remaining unwritten after the writing beam has left the target. There is some intermediate speed of the writing beam which is the highest beam velocity which will deliver enough charge to the target to leave it in a written condition. This is a threshold velocity, above which writing does not occur, and this is usually termed the 'writing speed' of the target. Since the writing speed of a particular target depends on the beam current, the current must be stated, or agreed upon as a standard operating condition, by the group using this term. A 'writing time' can also be defined in terms of a writing beam which is not moving, and would then refer to the minimum time the beam has to be gated on to cause writing at a specified beam current. For any one target, the writing time should be related to the reciprocal of the writing speed by a constant. (A more precise definition is necessary, and will be given, for target elements smaller than the beam diameter.)

The single column of targets in Figure 18 could be extended to become a row of columns, such as in an array of 16 targets placed in a square having four targets along each side. The flood beam would again be enlarged to cover all targets, and the writing beam would be deflected both vertically and horizontally to reach any target. Any combination of targets could be written positive to correspond with any bi-stable pattern that can be formed with 16 elements in a square array.

The charge-image would be very coarse, having a resolution of only four lines in both the vertical and horizontal direction. While there would be no visible image, this tube would be the first in this description to have the capability of writing, storing, and erasing a bi-stable two-dimensional charge-image.

Control of a Dielectric Sheet with Two Guns.

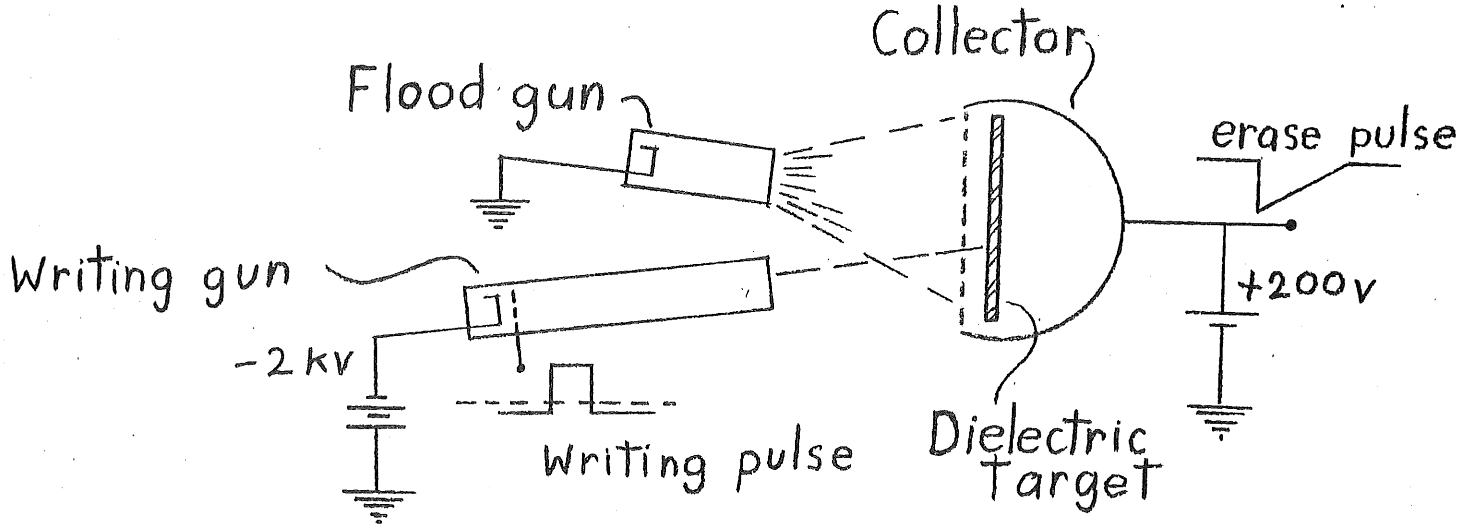
In the preceding multiple-target tubes, the writing beam may be much smaller than each target it bombards, but the whole target is charged to the same potential during writing, since the metal target is a good conductor. Any change in the target charge immediately under the writing beam spot is conducted to the parts of the target which are a little distance away from the writing beam spot.

If we reduce the target size and change its shape, so that it is just covered by the writing beam, and we assume an idealized condition where the writing beam current density is exactly uniform throughout the beam, and the effective secondary emission ratio is uniform over the whole target, then during writing, all parts of the target surface are written to exactly the same potential. There is no potential difference transversely across the target face, and no current flows in any direction parallel to the target surface. Since no transverse current is flowing across the face of this small target, the target does not need to be a conductor in order to charge up perfectly uniformly to the written stable point, and we may substitute an insulator for the conductive target material.

To extend this analogy from a single target to an array of targets, we may increase the number of rows and columns of targets indefinitely, at the same time decreasing the size of the targets and the space between them. When the targets become much smaller than the beam, we substitute a dielectric material for each target, as well as for the vacuum which insulates each target from its neighbors. The result is that the target array is replaced by a single dielectric sheet which is capable of having any area element of its surface written and held positive, or erased and held negative.

This structure is shown in Figure 19.

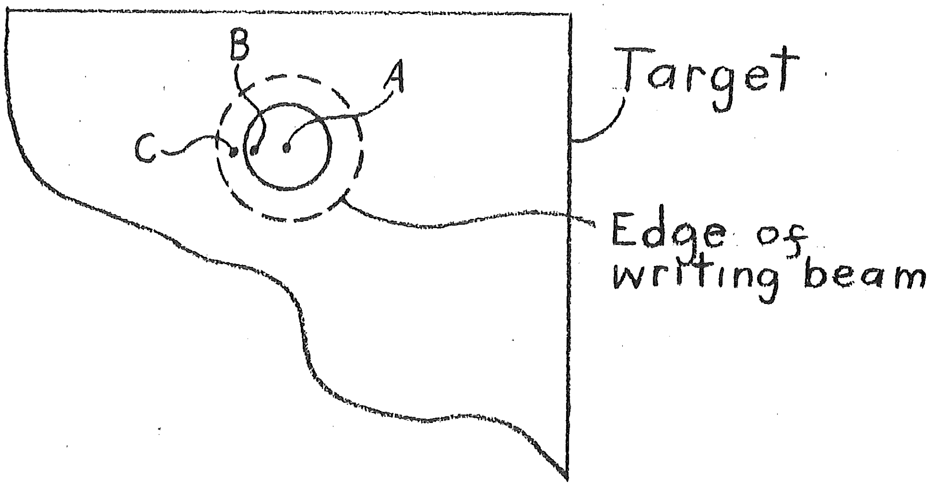
Figure 19.



The dielectric material may be a sheet of glass or mica, or other dielectric materials known to have a high secondary emission ratio, such as simple compounds of the alkali metals including the alkali oxides and halides. These materials often have secondary emission ratios which reach a maximum in the range of 2 to 5 and sometimes higher.

Writing on this target is illustrated in Figure 20, which represents a view of part of the target surface.

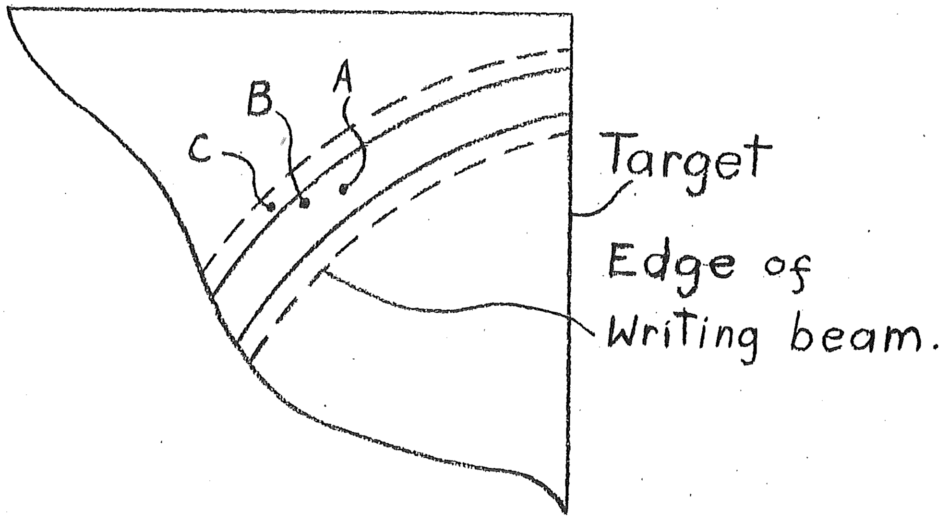
Figure 20.



The dotted circle represents the outline of the spot where the writing beam bombards the target. The writing beam is not deflected, in this figure, but remains fixed in this spot while it is gated on and off. The current density is not uniform, in an actual writing beam, but tapers off toward the edge of the spot. During writing, the high current density at the center of the beam, at point A, easily carries the potential there over the first crossover voltage, and the target at point A becomes written quite early in the duration of the writing pulse, (for some combinations of beam current and writing pulse widths.) For the same writing pulse width, the point B receives less beam current density, since it is further away from the spot center, and it charges positive more slowly, crossing the first crossover point later in the duration of the writing pulse. Point B may not be written all the way to the upper stable point by the time the writing beam is gated off, and may be carried over the later part of the charging by the flood beam. At point C, the charging rate is much lower due to the lower current density at the edge of the spot. When the writing beam is gated off, the voltage at point C is below the flood gun first crossover, so it is carried down to its lower stable point, and is not written positive. The solid circle represents the outer boundary of the region in which all points have been charged at least to the first crossover, so the area within this circle is the charge-image spot which is actually written by the larger diameter writing beam spot. The 'writing time' for this target may be defined in terms of the maximum current density at the center of the spot. If any area of the target is written by the spot, however small the area, it may be convenient to define this as a written spot. The writing time then can be defined as the minimum time in which some target area is written positive by a writing beam having a specific maximum current density.

A similar situation occurs when the writing beam is in motion. In Figure 21 the path of a moving writing spot across the target surface is shown.

Figure 21.



As above, point A has been more than adequately written, point B has been written somewhat above the first crossover, and point C has been carried only part way toward first crossover, and will fall back to the lower stable point. Each of these points begins to receive writing current as the leading edge of the writing spot passes over the point, and continues to receive writing current until the trailing edge of the spot passes over this point. At the moment that the trailing edge of the writing spot passes over any point, the point has been written or not according to whether or not it has reached the first crossover voltage. In this situation, an elliptical spot will usually write at a faster speed when moving in the direction of its major axis than when moving in the direction of its minor axis, because the total current bombarding any point in the path of the spot is higher. As a practical matter, however, a writing speed may be defined for a target as the highest spot speed which will leave an unbroken stored trace of specified length, for specified spot diameter and current.

After writing, the written and unwritten areas of the target, which are held at different voltages, are immediately adjacent to each other on the target. Conductivity tends to blurr the dividing line between such areas, destroying the image, so highly insulating target materials are chosen to minimize the effect. Good targets will sometimes retain a charge image for a considerable time, even when the tube is stored on the shelf in the absence of flood beam current. We will see later that there are other important effects which degrade the quality of stored images.

The storage and erase mechanisms here do not differ from the last tube. This description has now covered the first tube of this report which will write, store, and erase a high resolution bi-stable two-dimensional charge-image.

Following the summary, the next tube will produce a visible light image.

Summaries of Sections 4 and 5.

The curve for the direction of net target charging current flow was developed from the effective secondary emission curve by converting the ratio of secondary to primary current into the difference between secondary and primary current. Then the tube was modified to permit opening the target circuit at various target voltages, and determining the target charging direction over a range of voltages. It was shown that the two stable points occur because the charging forces are in the direction of restoring the target voltage to these stable points. By shifting the target voltage with an external power supply, the stable points were shown to be capable of storing the simple information as to what range the target voltage must have been in when the switch was opened.

This was the first tube described here which has storage; the 'stable' range of collector voltage was defined and shown to be limited. A mechanical 'rolling ball' analogy of stability was developed in which the direction and amount of restoring force on a ball corresponded to the direction and amount of restoring force on a floating target. The tube was again modified by changing to a floating target having no external connections. This was the first tube described here which writes, stores, and erases by controlling a floating target.

Control of a floating target with a single electron gun was described, where the effect depends on shifting the relative cathode-to-target voltage, by shifting the cathode voltage. Writing and erasing with the collector were described. These two descriptions were for background in the writing and erase effects to be used in an actual storage tube structure.

The tube was modified by the addition of a second electron gun. Practical control of a target with two guns was described by showing the addition of two charging curves of different amplitude, displaced from each other on the voltage axis. Opposition of writing by the flood gun and completion of writing by the flood gun was discussed. This was the first tube here which controls a floating target with guns at fixed voltages.

The tube was again modified by introducing multiple targets and then a two-dimensional array of targets. The ability of the flood gun to hold some targets 'erased' while others are held 'written' was shown to require different areas of coverage of the targets by current from the two guns. The storage of a coarse four-line, two-dimensional charge-image was achieved in this tube, which was the first, in this report, to have a two-dimensional image.

The tube was modified again by the introduction of a continuous dielectric sheet target, in place of multiple conductive targets. The array of individual targets was allowed to approach a limit in target size and number, as an evolution into the area-elements of a continuous dielectric sheet. The charging and written pattern resulting from fixed and swept spots were described in terms of time integrated charge at an area element of target surface. This tube has now evolved into a structure capable of writing, storage, and erasure of a high-resolution, two-dimensional bi-stable charge image, and is the first one described here to have a high resolution image. The next step is a visible light image.

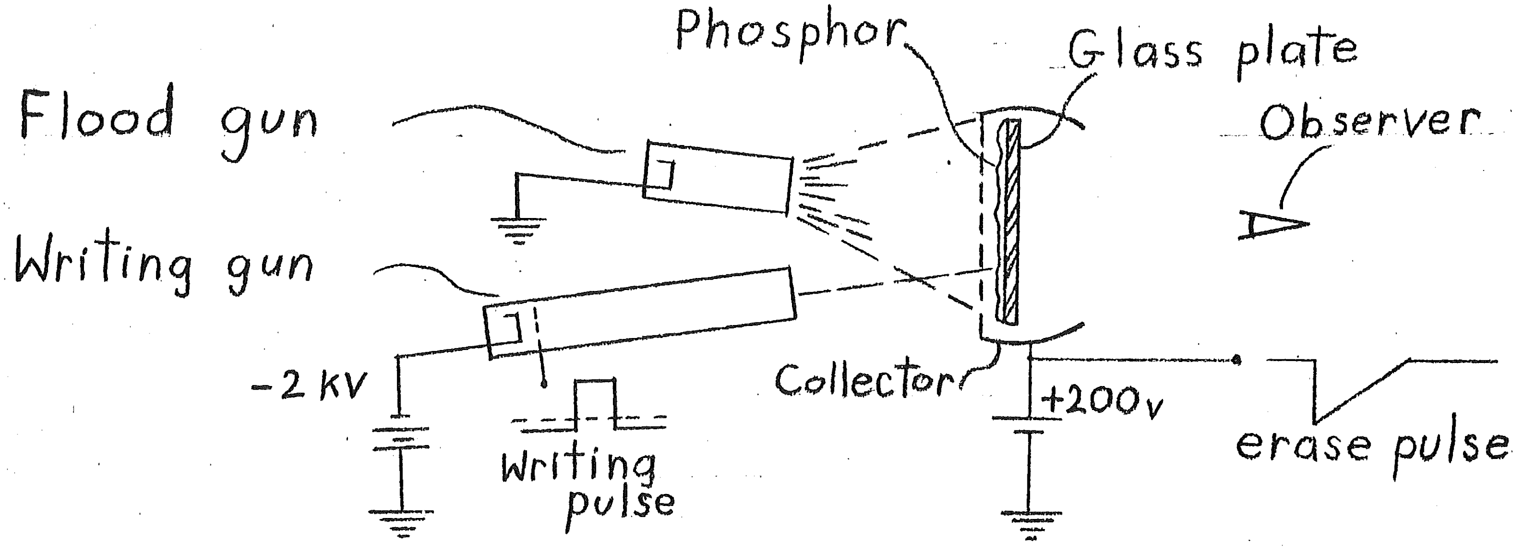
SECTION 6. AN ELEMENTARY DIRECT-VIEWING BI-STABLE STORAGE TUBE.

When the preceding tube has a charge-image stored on its dielectric target, the written parts are being bombarded by flood electrons having much more energy than the few low velocity electrons reaching the unwritten parts. We may use this energy to produce a visible light image by using a fluorescent phosphor as a target dielectric.

The target will consist of a phosphor layer coating a glass supporting plate, and the phosphor will be viewed through the glass plate from the side opposite the electron gun.

Figure 22 shows this tube:

Figure 22.



A large aperture has been placed in the rear of the collector so that the image may be viewed from that side. Since no secondary emission occurs at the rear of the backing plate, the aperture in the collector will have no effect on the storage properties.

The phosphor coating serves as a target dielectric, and has the same bi-stable storage properties exhibited in the previously described tube. Both the written and unwritten target areas are held at stable points which insure no net current flow to or from the target surface, so the target is not charging up or down when held at these stable points. Even though the arriving and leaving currents are equal, cancelling the transfer of <u>charge</u> to zero, at written areas, there is a considerable net transfer of <u>energy</u> to the target, because the primary electrons bombard the target at the potential of the upper stable point, but the secondary electrons leave the target with much lower energy. This primary energy, which was largely dissipated as heat in preceding tubes, and partly transferred to secondary electrons, is now also partially converted to visible light by the fluorescent phosphor target. In unwritten areas, most of the flood electrons are reflected without hitting the target, and the few which reach the target (to maintain equilibrium with ion collection and leakage) arrive with too little energy to cause much target fluorescence, or secondary emission.

Since all the target areas are charged to either one of only two possible stable potentials, and these areas are then bombarded with either of two energies, the resulting light output in any element of target area is either of two intensities: full brightness or minimum brightness. There is no grey scale of half-tones of brightness. This is characteristic of bi-stable storage tubes, and limits their usefulness to applications for which half-tones are not essential, but 'infinite' persistence is desirable, such as in oscilloscopes.

A tube of the type described here was built by A. Haeff, and reported in 'Electronics,' September, 1947. (It also had provision for electrical readout.) The tube is extremely interesting in comparison to the developments of succeeding years. In comparison to present day tubes, this early tube had the advantage of much simpler target construction, but suffered from low brightness, due to the relatively low energy of phosphor bombardment. It also had a very limited stable range of collector voltage, as evidenced by the tendency of the written image to spread over unwritten areas or erase into written areas. Several spurious effects were noted in this early tube which became more fully understood in later years, and are described here in later pages.

The brightness of the image formed by this tube may be increased, to some extent, by raising the operating voltage of the collector. This increases the voltage of the target surface at the upper stable point, so that the more energetic primaries cause higher brightness of the written areas.

It has been found, however, that the collector voltage cannot be increased much before the image becomes badly degraded. The written areas expand into the unwritten areas as a result of motion of the boundary which separates the written and unwritten areas.

Several effects occur at this boundary. Flood gun current approaching the vicinity of the boundary is to some degree deflected away from the unwritten area, by its repelling negative charge, and attracted to the positively charged written area. This increases the restoring charging current on the written areas at the expense of less charge reaching the unwritten areas. At the same time, conductivity across the boundary tends to pull the written areas negative and the unwritten areas positive. If the written areas are more strongly stabilized than the unwritten areas, then the unwritten areas go positive adjacent to the boundary, and the boundary moves into the unwritten region. (There are several other effects at the boundary which are not discussed here.) The opposite effect occurs when the collector voltage is low, since the written areas are then at lower voltage. The secondary emission ratio drops, the restoring forces for written areas are still present, but weaker, so conductivity can lower the voltage in written areas near the boundary, and the boundary moves into the written areas.

When operating conditions permit the boundary to move, in either direction, the image is ultimately erased, either by the entire viewing screen fading to a dark condition or by fading positive to a fully 'written' bright viewing screen.

As the collector voltage is lowered from a voltage at which the image is stable, a collector voltage is reached below which the image is no longer retained, due to boundary migration. This is the lower limit of the stable range of collector voltages, and this voltage is often called the 'retention threshold' by manufacturers of bi-stable tubes. As the collector voltage is raised from a voltage at which the image is stable, a collector voltage is reached above which the image is no longer retained, due to boundary migration. This is the upper limit of the stable range of collector voltages, and this voltage is often called the 'fade-positive' voltage. In earlier tubes in this report, in which an entire conductive (metal) target was held at either stable point, there was no boundary to migrate in either direction. The stable range of collector voltage was quite wide, since it was limited only by the first and second crossover points. In this tube, the stable range is much narrower, because the 'retention threshold' and 'fade-positive' voltages, which define the stable range, are well within the range between the first and second crossover points.

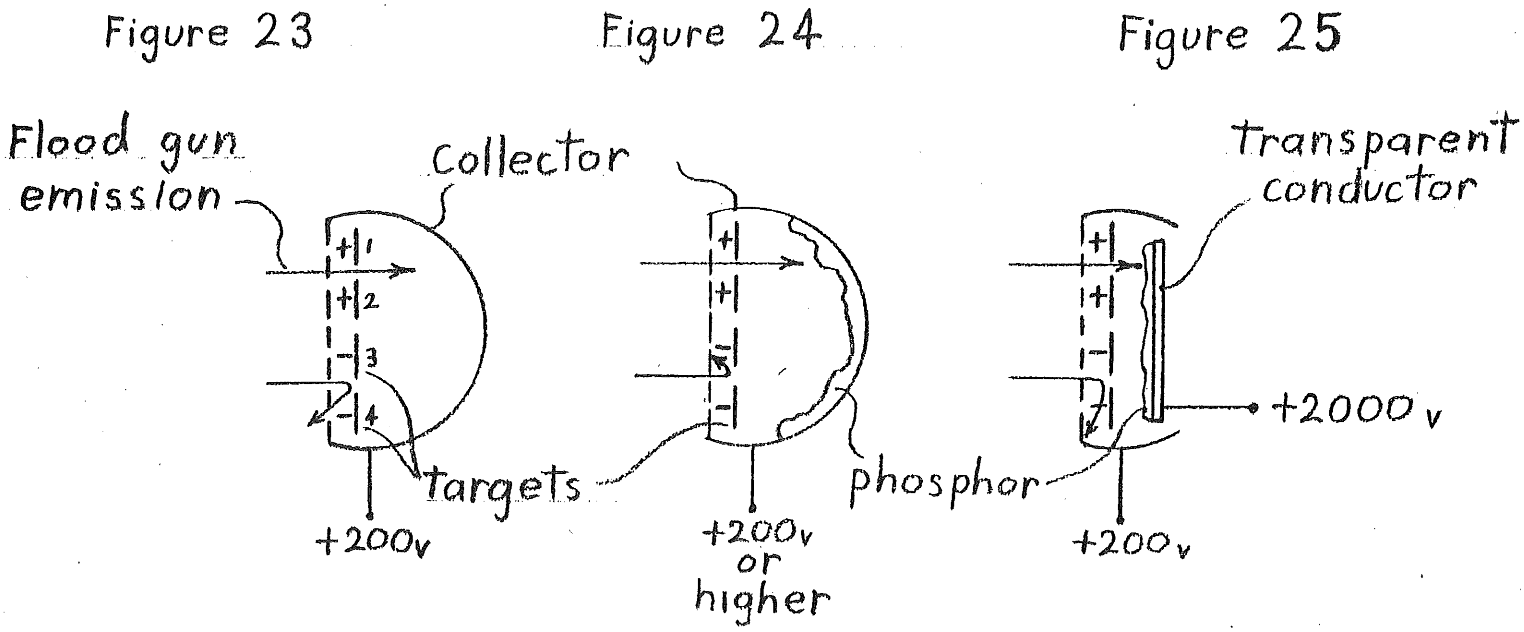
Since the collector voltage could not be raised enough to achieve high brightness in bi-stable tubes, other means were used, as described in the next section.

SECTION 7. THE DISPLAY FUNCTION IN HIGH BRIGHTNESS BI-STABLE TUBES.

'Grid Control' of Current Through a Simple Array of Targets.

When a tube has multiple conductive targets in an array such as in Figure 23, (same as the targets of Figure 18) the targets can be 'written' so that targets 1 and 2 are held positive by the flood gun (not shown) and targets 3 and 4 are held negative.

Figures 23, 24, and 25.



Flood gun emission approaching the gap between targets 1 and 2 would pass through a field having a potential not too different from the potential of the two surrounding targets. Since this voltage may be around two hundred volts positive, electrons pass through this gap at high velocity, unimpeded by the field in the gap. Flood emission approaching the gap between targets 3 and 4, however, meets with a potential near the unwritten target potential, which is slightly negative. Most of this emission is reflected in front of the gap, since most of these electrons do not have sufficient energy to penetrate the retarding field.

The flood gun current which passes between the targets may be used to form a visible image by placing a phosphor layer in its path. In Figure 24, a phosphor viewing screen has been deposited on the collector electrode, behind the targets. Electrons hit this layer with the velocity resulting from the collector potential, which at +200 volts is enough to produce a visible image. The image still suffers from low brightness, but in this simple tube we may now increase the collector voltage substantially. Since there are no image boundaries to be concerned with, for simple one-potential conductive targets, the stable range is not so limited, and the higher permissable collector voltage results in much higher brightness. (Assume a transparent conductive collector, for viewing this phosphor.)

Another way of achieving high brightness is shown in Figure 25. Here, the phosphor has been deposited on a separate transparent conductive supporting plate. This phosphor screen can be varied in voltage independently of the collector voltage. The collector could be operated at +200 volts while the phosphor viewing screen is run at +2000 volts, for example. After electrons pass the written targets, around +200 volts, they are accelerated to the much higher velocity of +2000 volts by the field between the targets and the viewing screen. The resulting image would have relatively high brightness. The tubes of these figures have only a few storage elements, so the resulting images have only a few elements of resolution. These tubes were discussed only to illustrate the basic use of <u>grid control of low energy emission</u> followed by acceleration to high energy, for high brightness. They are the first tubes discussed here to have high brightness.

Higher Resolution with a Perforated Dielectric Target.

This principle may be extended to high resolution tubes by the sequence of illustrative structures in Figures 26, 27, and 28, shown on the following page:

Figures 26, 27, and 28.

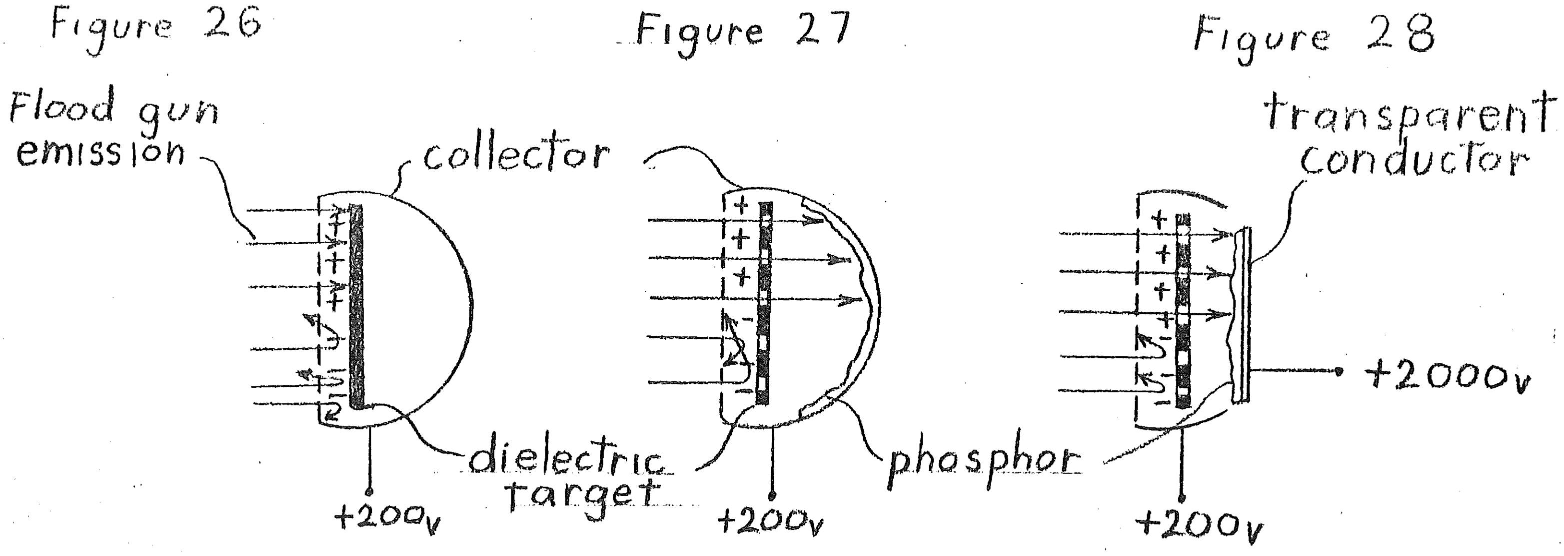


Figure 26 shows the target of Figure 19, which is a dielectric sheet on which we may write and store a charge image, but no visible image results. In this figure the upper half of the target has been written positive and the lower half held negative.

This has been modified in Figure 27, by using a single dielectric sheet which has now been penetrated with a great many small apertures. As in the example of Figure 24, flood gun emission passes through those apertures which are surrounded by a written target surface, but is reflected where the target surface is unwritten. A phosphor viewing screen is deposited on the collector, as before, and a low-brightness image is formed on the viewing screen. In this case, however, a high resolution visible image is formed on the viewing screen (if the aperture pattern is fine enough) since the continuous dielectric sheet may be written with a high resolution charge image, not just a few discrete target potentials.

This illustrative tube structure (Figure 27) differs in another way, besides resolution, from the analogous multiple target tube of Figure 24. That is, that brightness cannot be improved much by raising the collector voltage, because the image fades positive due to image boundary migration when the collector voltage rises out of its stable range. The brightness improvement which results from a separate high voltage viewing screen is available, however, and this is shown in Figure 28, which is analogous to the multiple target tube of Figure 25. Here the collector may be maintained at +200 volts, and the written target is held a little above that voltage. Emission passing through the target apertures is accelerated to a high voltage by the viewing screen potential, and produces a bright image on the screen.

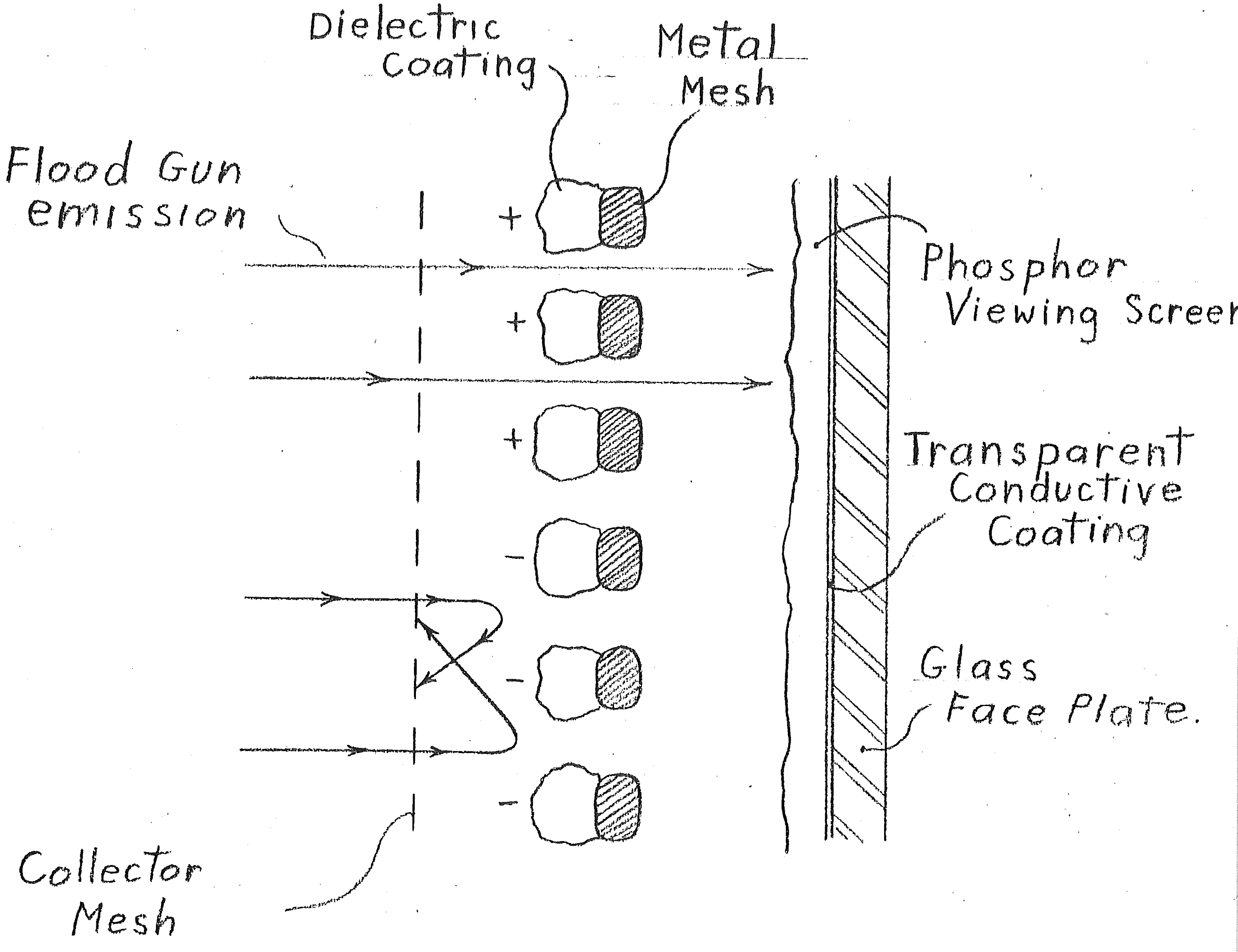
This last bi-stable tube is the first illustrative tube described here having both high resolution and high brightness. This tube, however, has the disadvantage that it would require the fabrication of a self-supporting dielectric target sheet, pierced with a great many apertures. In addition, the rear target surface and part of the walls of the aperture would be susceptible to the accumulation of surface charges on surfaces that could not be reached by the flood gun, so could not be stabilized.

A Practical Target with a Coated Mesh. Field Shapes and Transmission Curve.

These difficulties are overcome by supporting a dielectric coating on a metal mesh, as shown in Figure 29. The dielectric surface charge mechanism is the same as described before, with writing, erasing, and stability effects unchanged, since the surface may charge independent of the mesh potential, because the surface of the dielectric is insulated from the mesh by the body of the dielectric.

Please see Figure 29 on the following page.

Figure 29.



In this structure the field in the apertures is influenced by both the dielectric surface potential and the potential of the supporting mesh, which act together as a composite grid to control the passage of current through the target. The mesh is usually operated at zero volts, so that the field in the apertures of unwritten regions will remain cut off. The approximate shape of the field in the unwritten region is shown in Figure 30 and in the written region in Figure 31, on the following page.

Figures 30 and 31.

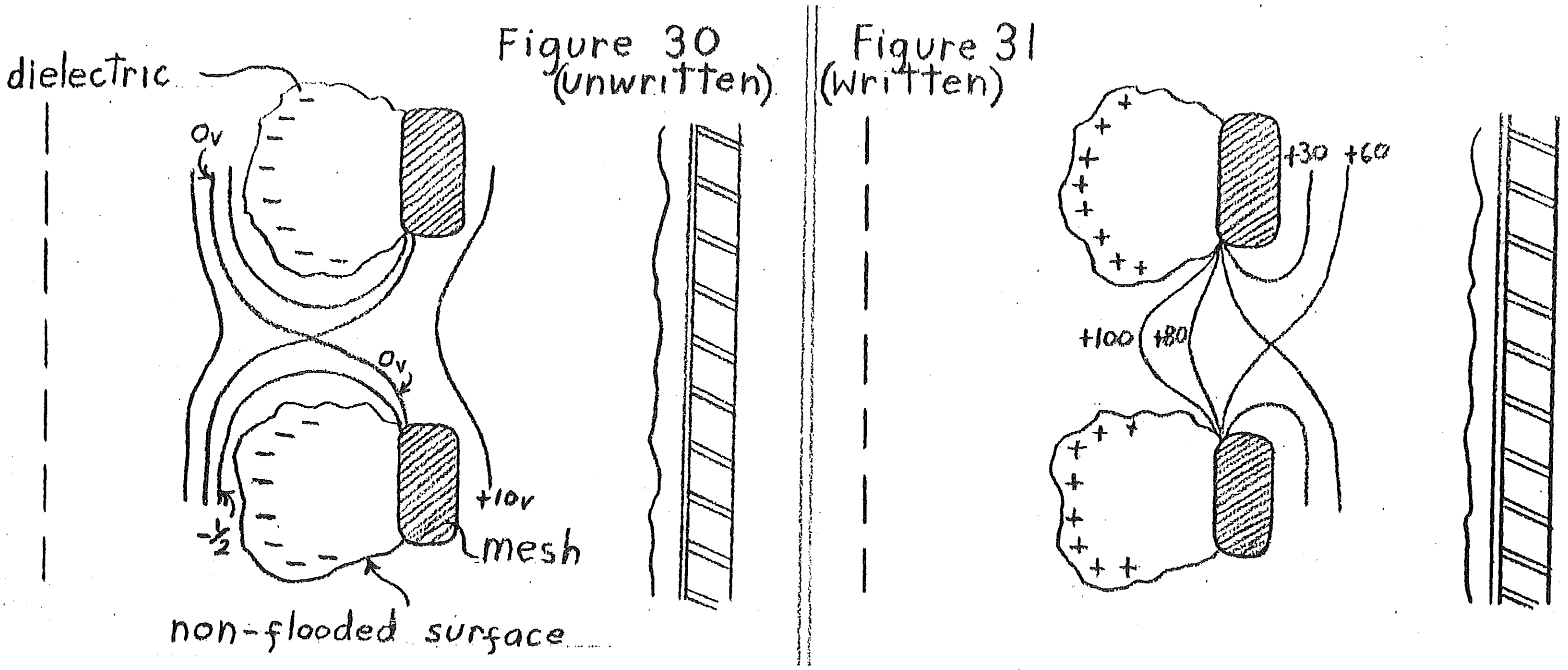


Figure 30 (unwritten)

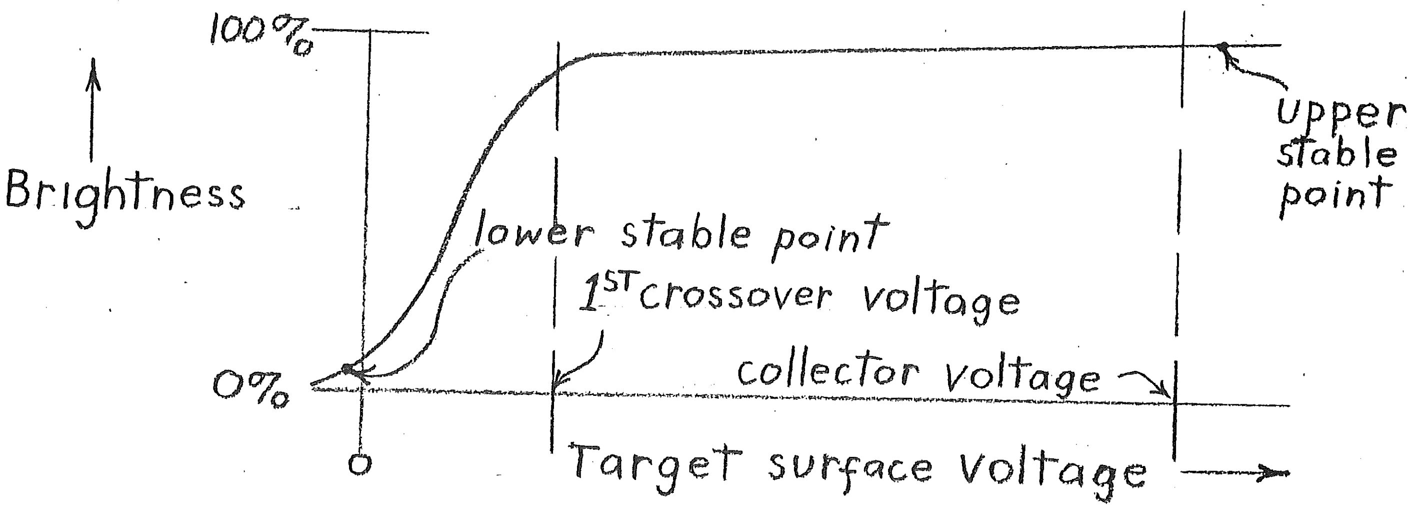
Figure 31 (written)

The lowest potential of the field in the aperture for unwritten areas varies from zero volts to below -1/2 volt across the width of the gap, so most flood gun emission is unable to penetrate this field. The lowest potential of the field in the aperture for written areas varies from +60 to below +30 volts across the width of the gap, so flood gun emission easily passes through these fields, and is then accelerated to form the bright image on the viewing screen.

This tube is the first tube described here which will write, store, display, and erase a bi-stable image having high resolution and high brightness, and which uses a practically realizable storage target structure.

The current transmission of the composite target structure varies continuously as the dielectric surface potential is varied, although only the two stable dielectric voltages are used in the bi-stable tube. Since the image brightness depends on the current transmission through the target, a plot of the image brightness vs. target dielectric surface potential will show how target transmission depends on surface potential. Figure 32 shows this curve for a typical bi-stable tube design. The exact shape of the curve depends on the dimensions of the mesh and dielectric, since these dimensions greatly influence the shape of the field in the apertures and around the target.

Figure 32.



The brightness of the written condition is taken as 100% brightness on the ordinate scale of relative brightness. On this curve, the lower stable point of target surface voltage does not fully cut off target transmission, so the image background is not completely black. This tube design is not noted for exceedingly high contrast, and contrast ratios around 8 to 1 or 10 to 1 are typical. Later it will be shown that the brightness curves are one of the few basic things that are different in half-tone and bi-stable storage tubes. The poor contast, due to the failure of the target to cut off transmission completely, is believed to be the result of positive ion charging of dielectric surfaces which cannot be reached and stabilized by flood gun emission, because they do not face the flood gun. One such surface was shown in Figure 30. This effect can be minimized by flooding the target with a wider angle of flood gun electron trajectories, by compromising the shape of the dielectric, by improving the vacuum so as to reduce ion formation, and by placing an ion repeller mesh near the target.

Ion Repeller Mesh and Contacting Collector Mesh.

An ion repeller mesh is used in the bi-stable tubes, and consists of an open-weave high transmission mesh operated at about +250 volts. A substantial part of the positive ions formed by the passage of high flood gun current through the residual gas in the tube is repelled by this mesh.

During the development of this tube type, it was accidentally discovered that improved operation resulted when the collector mesh contacts the surface of the dielectric. In areas where the collector is touching the dielectric, conductivity to the collector, and the shadowing of flood gun bombardment by the collector, appear to act to some extent as barriers to migration of the boundary between written and unwritten areas. This extends the stable range of collector voltages over which the image does not become seriously degraded by the boundary migration. The increase in stable range was quite an important development, since it had been marginal. The pitch and orientation of the collector mesh and the mesh which supports the dielectric are made dissimilar, to avoid Moire effects in the image. Observation of a magnified portion of the image shows that all of the dielectric which is exposed to the flood gun through one square opening in the collector mesh acts together in charging to either stable point. Figure 33 shows the storage target with a contacting collector of 112 pitch (per inch) on a dielectric-coated mesh of 250 pitch, as seen from the side, and Figure 34 shows the view from the flood gun. Figure 35 shows an entire tube, schematically. This is the bi-stable tube manufactured by Hughes and Machlett.

(Please see the following page for Figures 33, 34, 35.)

The discussion has advanced from the simple measuring device of Figure 2 to the complete bi-stable tube of Figure 35, by adding and modifying electrodes to provide the functions necessary to the final tube. This ends the 'evolutionary' approach to the subject. The remaining sections are more specialized, less accumulative.

Figures 33, 34 and 35.

Figure 33

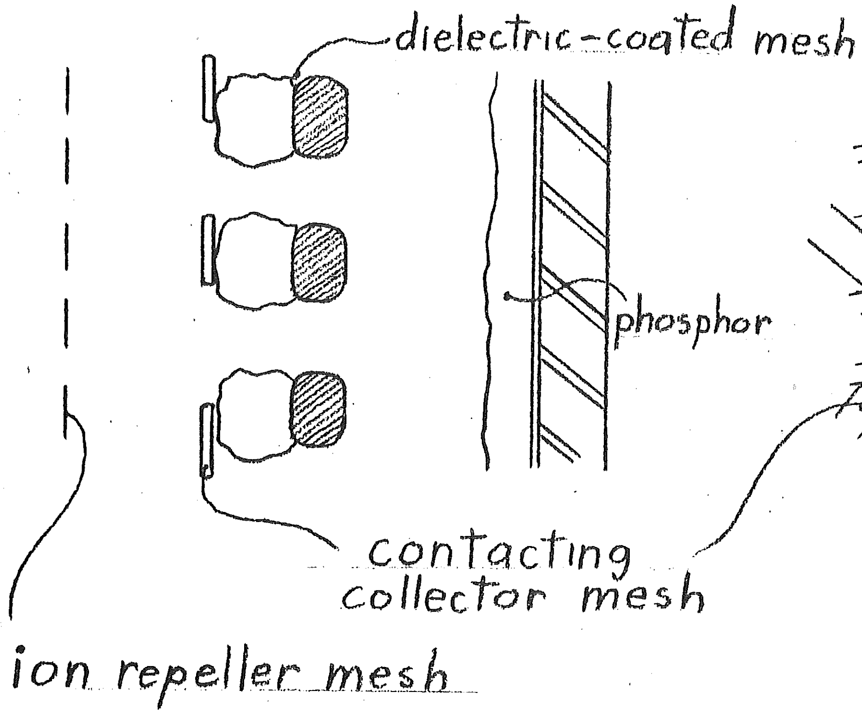


Figure 34

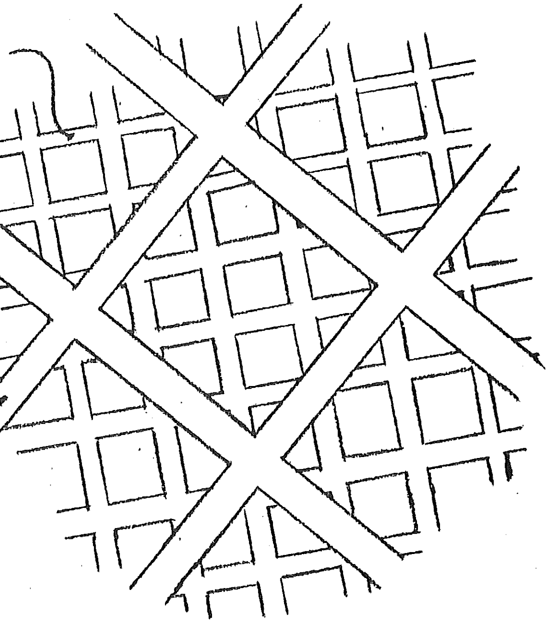
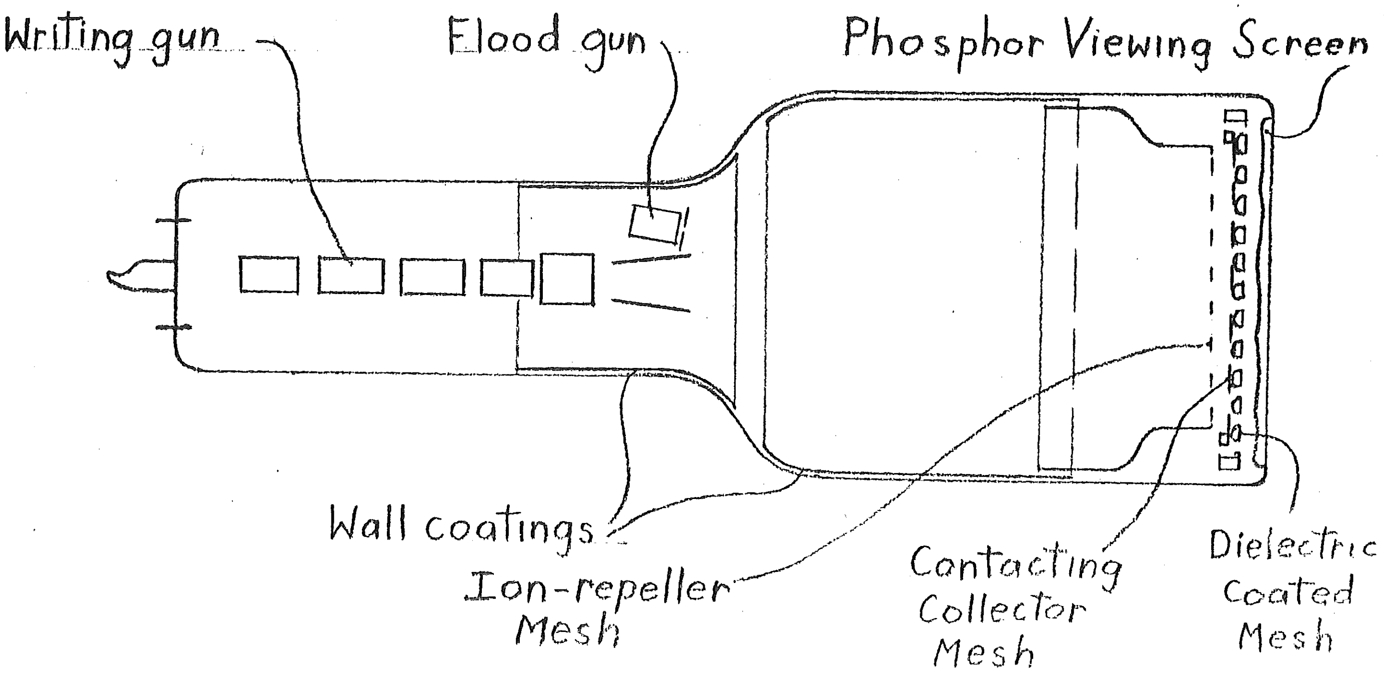


Figure 35



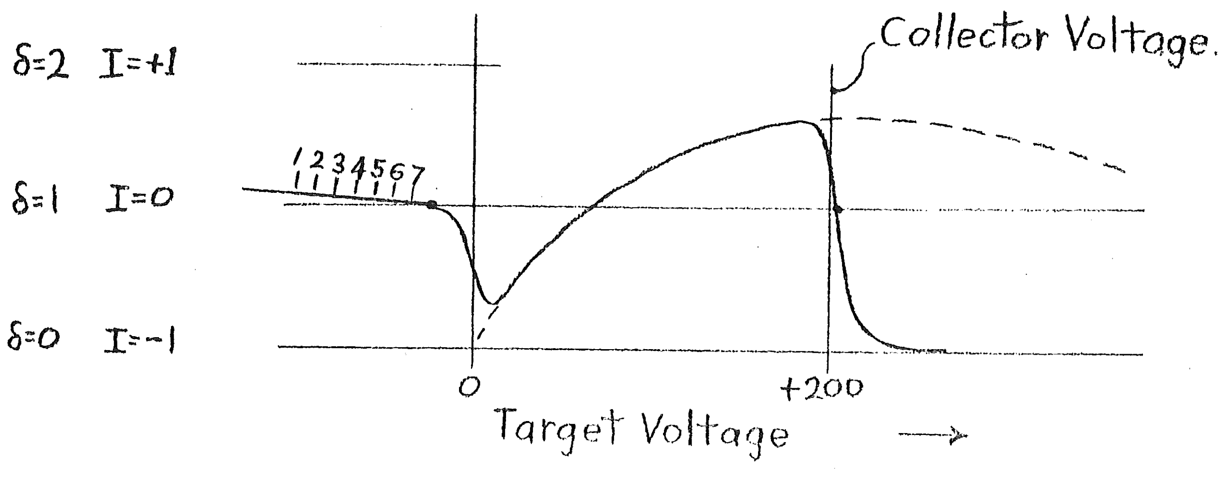
SECTION 8. HALF TONE TUBES

Half-tone Charge Storage in Bi-stable Tubes. Writing, Fading, and Erase.

It is possible to store a half-tone charge-image in the previously described bi-stable tube. No usable visible image will result, but the storage mechanism of half tone tubes is easily introduced this way.

In a bi-stable tube having a good vacuum and an ion repeller mesh, positive ion bombardment of the target may be reduced to a fraction of the bombardment which would otherwise occur. Since positive ion bombardment is the principle source of restoring charge below the lower, unwritten, stable point (or quasi-stable point) the rate of positive charging may become quite small in this region. If the target is charged to some potential in this region, the potential will not be restored to the lower stable point for a period of typically about 1 to 3 minutes. This range of target potentials is shown in Figure 36, which shows the net effective secondary emission ratio, and charging current, as target voltage varies.

Figure 36.



For half-tone storage, we are interested in the range of target voltages between points 1 and 7 on the curve. In order to store a half-tone charge image, we must write different portions of the target surface to a number of distinguishably different potentials over a range, not just to the two potentials used for a bi-stable image. The points 1 through 7 on the curve schematically represent a grey scale of seven tones of charge in the charge-image. The actual surface potential may be anywhere between these points.

The writing mechanism is the same as for bi-stable writing; that is, an energetic writing beam causes the target to charge positive, by the loss of secondary electrons. Since the writing beam writes the target positive, the target must first be charged more negative than the range in which the half-tones will be written. This is accomplished by applying a positve pulse to the dielectric supporting mesh, which causes the target surface to go positive, by capacitive coupling. The restoring forces of stability associated with collection of flood gun electrons in the region above the lower stable point then return all parts of the dielectric target surface to the lower stable point during the pulse. When the pulse is over, the trailing edge of the pulse returns the supporting mesh down to its normal operating voltage, and the dielectric surface is lowered, by capacitive coupling, to point 1 on the curve. At this voltage, the dielectric surface is ready to be written to any of the half tones of the charge-image represented by points 1 through 7 on the curve of Figure 36. Writing different half-tones is accomplished either by varying the writing spot sweep speed or current density. This varies the charge delivered to the target, and the voltage of different elements of target surface.

When the charge image has been written by the writing beam, the different target areas which have been written to different potentials, all begin to charge slowly positive by collection of the residual positive ions.

The most positive half tone target areas of points 7, 6, and 5, are the first to reach the lower stable point, where they become stabilized at the same voltage, so the half-tone distinction between these areas is the first to be lost. As these higher half tones are lost, and the more negative areas shift positive from their original value, the stored charge image increasingly fails to represent the image that was first written. The image may then be erased, in preparation for writing a new image.

The previously described pulse on the supporting mesh, which prepared the target for writing by charging it negative, is also the erase pulse. At the moment when the target is driven positive by the erase pulse, the presence of an image on the target causes different target areas to be driven to different voltages in the region a few volts more positive than the lower stable point. All of these areas are then stabilized to the same lower stable point voltage by flood electron collection.

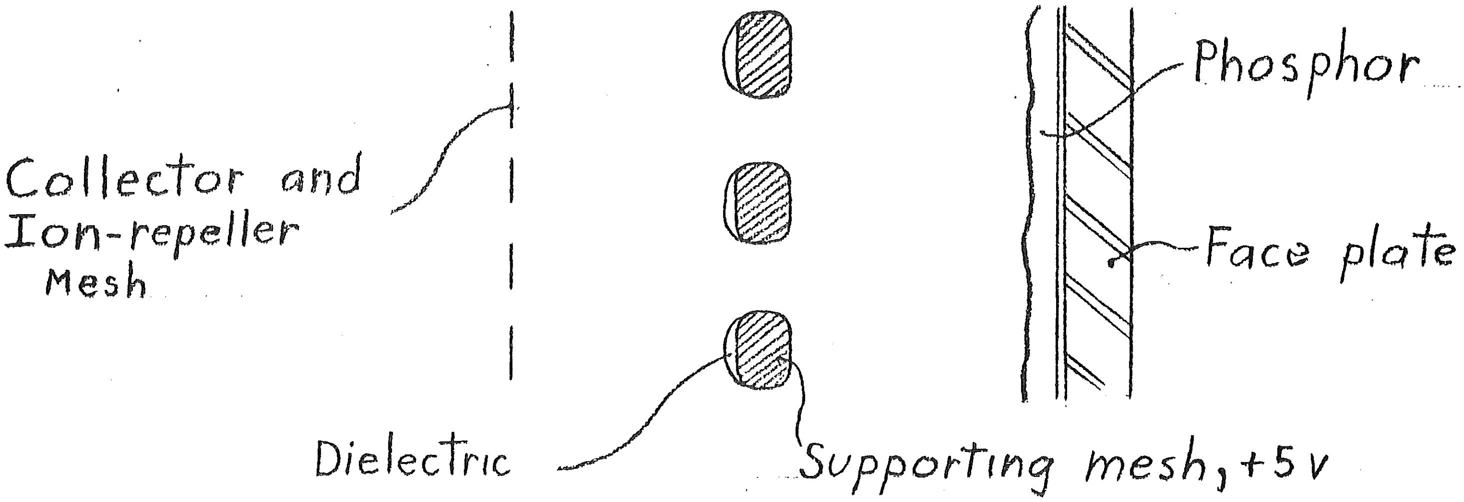
The charge image may be considered as erased, in one sense, even before the trailing edge of the erase pulse returns the surface voltage to point 1, in preparation for writing, since no information then remains on the target, because no half-tones can be distinguished.

The preceding description shows how a bi-stable storage tube can store a half-tone charge-image, although no visible display was produced. This was the first description here, of a tube which will write, store, and erase a high resolution half-tone charge image.

Visible Image in Half-tone Tubes. Some Structural and Operating Differences.

The failure of the bi-stable tube to produce a visible charge image occurs because the various image potentials are all below the cut-off of the targets transmission characteristic for flood electrons. On Figure 32, this is the region to the left of the lower stable point, where the image brightness is near zero. In a half tone tube, a visible image is formed, using target potentials in this same region, by using a target which has a different brightness (transmission) curve. In comparison with a target for a bi-stable tube, the half tone target should transmit flood electrons at the lower target potentials, which would be cut-off in the bi-stable tube, and the range of target voltages used for storage of half-tones of charge should match the range of target transmission from cut-off to saturation. This has been achieved in the half-tone target shown in Figure 37. This is the target in the half-tone tubes made commercially, by several major electronics companies.

Figure 37.



This target differs in several important respects from the bi-stable target. The dielectric coating is much thinner, and is typically a 2 micron layer of a dielectric such as magnesium flouride, which is evaporated onto the supporting mesh and forms a thin, hard, dense layer. The apertures in the mesh are not shielded from the positive potentials of the collector and viewing screen as much by this thin dielectric layer as they were by the thicker dielectric layer of the bi-stable tube, so the fields in the mesh apertures are more positive here.

This lowers the target transmission cut-off point. A further increase in the potential of the fields in the apertures is obtained by raising the operating voltage of the dielectric supporting mesh to +5 volts, compared to zero volts in the bi-stable tube.

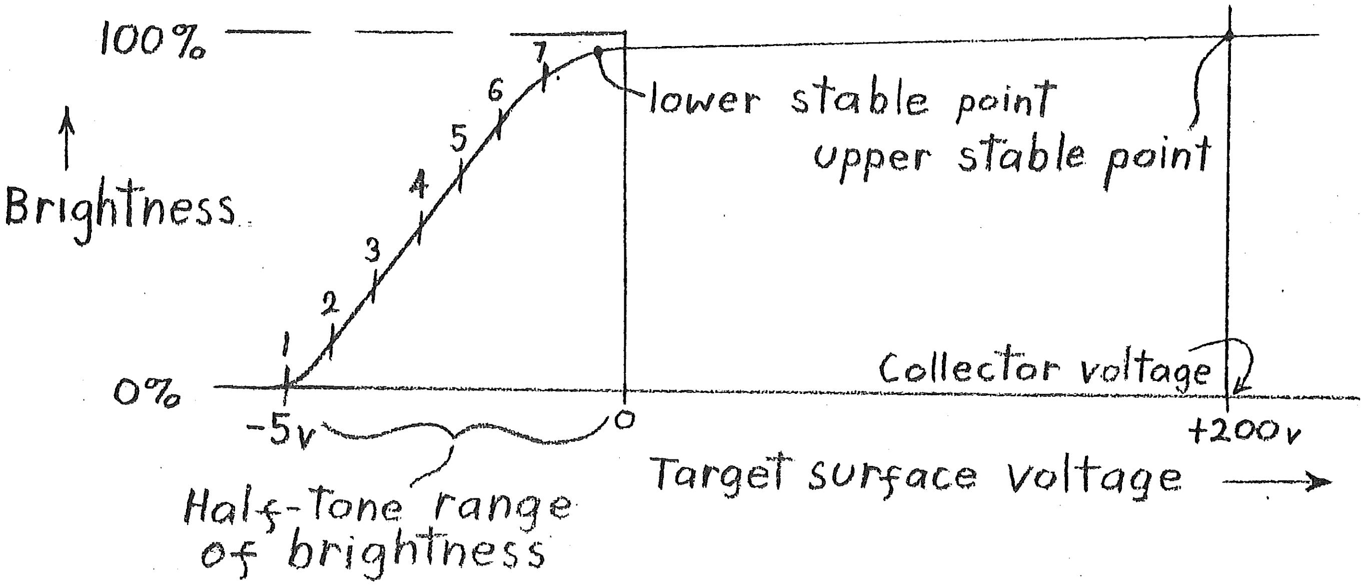
In this tube, the normal range of target surface voltages is below the lower stable point, (except during erase), so the flood emission does not reach the target surface. There is no situation where adjacent target areas are 200 volts different in voltage, and the flood gun emission causes boundary migration. A contacting collector is not necessary, (to break up boundary migration), so the half-tone tube can use the simpler structure, where the collector is spaced somewhat away from the dielectric. The collector is positive enough to serve as an ion repeller mesh, so a separate ion-repeller mesh is not necessary.

This is shown in Figure 37.

Half-tone Target Transmission Curve.

The brightness-transmission curve for this tube is shown in Figure 38.

Figure 38.



The whole range of useful target transmission occurs over only about 3 volts of change in surface potential. A short region between point 7 and the lower stable point is sometimes not used, because it is non-linear.

The viewing screen may have any brightness over the continous range shown on the curve. The seven specific target surface potentials and resulting brightness are only used to show that the screen uniformity and contrast usually cannot provide more than about seven distinguishable half-tones. The unwritten surface of the target need only be charged about 3 volts more positive, during writing, to be fully written. This tends to make the writing speed of half tone tubes somewhat higher than in bi-stable tubes, where the target may have to be charged through 20 to 80 volts for writing to occur. The writing speed is not improved as much as this would indicate, however, because more charge must be delivered to the half-tone target for each volt of change, due to the higher charging capacitance resulting from the much thinner dielectric layer.

Bi-stable Mode in Half-tone Tubes.

It is possible to 'over-write' a half-tone tube with a high current or slowly moving writing beam, by charging an area of the target above the first crossover point, so that it is carried to the upper stable point. Some further difference in brightness occurs at the much higher target voltage, but the target may be damaged by the higher voltage across the thin dielectric. This sometimes occurs during production tube testing, and the tube is then said to have been put into the 'Haeff' mode of operation. A bi-stable technique for erasure must be used to get the tube out of this mode.

This shows how a half-tone tube may store a bi-stable charge image, and we saw, at the beginning of this section, that a bi-stable tube may store a half-tone charge image. In both of these cases, no useful visible image results, but the ability of both tubes to store both kinds of charge image is worth special attention because it emphasizes the similarity in operation between the two tubes.

Comparison of Bi-stable and Half-tone Tubes.

Some other similarities between the two types are outlined here:

(1) Both bi-stable and half tone tubes use a high energy writing beam, to write the target positive by secondary emission.

(2) The visible display is produced by flood gun current, in both kinds of tube.

(3) The image is erased by collection of flood electrons in both tubes.

(4) Both types are similar in basic structure, each using two guns, a dielectric storage target, ion repeller, and viewing screen.

Some of the differences between the two types are:

(1) The bi-stable tube has long persistence, but no half-tones. The half-tone tube has its grey-scale of half-tones, but more limited persistence.

(2) The half-tone tube usually has somewhat higher writing speed than a comparable bi-stable tube. (But there is an operating technique that enhances writing speed in bi-stable tubes.)

(3) The bi-stable tube has a mechanically more complex target, which is somewhat more difficult to fabricate, but the half-tone tube is more likely to have low yield in manufacture, due to its greater sensitivity to contamination.

(4) The bi-stable tube has lower brightness, due to the target assemblies lower transparency to flood electrons. The relatively coarse collector mesh also may make the resolution somewhat lower. The contrast is lower due to the mis-match between stable voltages and brightness curve. (Both tubes are too bright for some applications. The resolution and contrast is adequate in both tubes for most applications. There is an operating technique for contast enhancement in bi-stable tubes.)

(5) The sensitivity of the half-tone tube to imperfect flood beam collimation usually requires that the writing gun be placed off-axis, to make room for the flood gun, which is placed on the axis. The bi-stable tube can use an on-axis writing gun and off-axis flood gun.

Summary of Sections 6, 7, and 8.

The transition from a stored charge-image to a visible image was made by using a fluorescent phosphor for a bi-stable target dielectric. This was a significant early type reported by A. Haeff in 'Electronics.' Limited brightness in this tube was discussed, and this led to discussion of increased collector voltage, to gain brightness by increasing the bombarding energy in written areas. The collector voltage increase is limited by loss of the image due to image boundary migration. The cause of image boundary migration was described in terms of conductivity and restoring currents at adjacent areas on the target. The upper and lower collector voltages at which the onset of boundary migration occurs, either toward or away from written areas, narrows the stable range of collector voltages, by defining a 'retention threshold' and 'fade-positive' point.

A sequence of illustrative tubes was described, introducing the idea of <u>grid-control</u> of flood electrons by the targets in a simple low-resolution multiple-target tube. Then, <u>high brightness</u> was obtained by acceleration of the electrons transmitted through the target and bombardment of a separate high voltage phosphor screen.

This system was then extended to a <u>high resolution</u> tube using an apertured dielectric sheet having its collector voltage limited by image boundary migration. High brightness was again achieved by using acceleration of transmitted flood electrons to a separate high voltage phosphor screen.

The tube was then modified again to arrive at a <u>practically realizable</u> target structure, by supporting the dielectric layer on a metal supporting mesh. The field in the apertures of the composite target was described in some detail, to show how controllable target transmission occurs in the composite structure combining a dielectric and a conductor. The resulting brightness-transmission curve was shown and the stable points noted on the curve. With the description of the ion-repeller mesh and the contacting collector, the evolution of a bi-stable tube was complete, and this is the structure of the bi-stable tubes which are commercially available from Hughes and Machlett.

<u>Half-tone</u> tubes were introduced by describing the storage of a half tone charge-image on a bi-stable target, without a visible image. The half-tone range

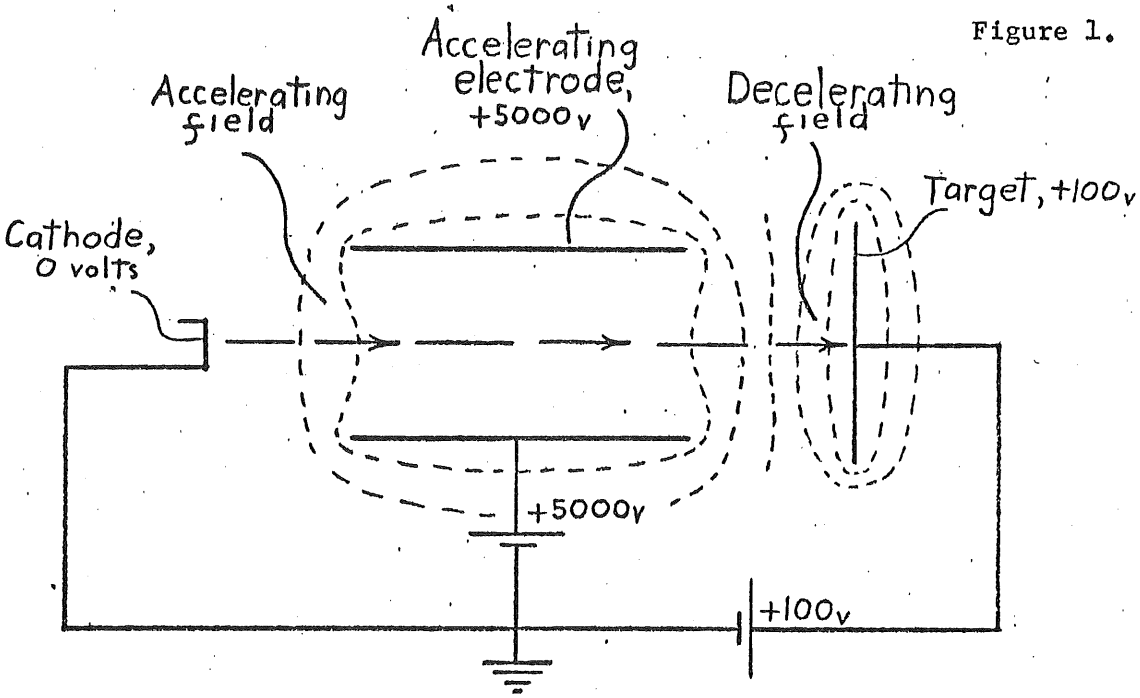
of target voltage on the secondary emission curve is below the lower 'quasi-stable' target voltage, where positive ion bombardment is a weak restoring force. Loss of the image by fading in the positive, 'bright' direction was discussed and the mechanism of erase was described.

In the actual half-tone tube both the charge-image and visible image are produced. The structure of this target was described, especially the thin evaporated dielectric and the non-contacting collector. The display mechanism differs from that of the bi-stable tube in that flood electrons do not reach the dielectric surface during display. The brightness-transmission curve goes from cut-off to saturation in only about a 3 volt range of target surface voltage. The ability of both the bi-stable and half-tone tubes to store charge-images of both bi-stable and half-tone modes is illustrative of fundamental similarity between the tubes. Similarities and differences between the tubes were outlined.

SECTION 9. SUMMARY

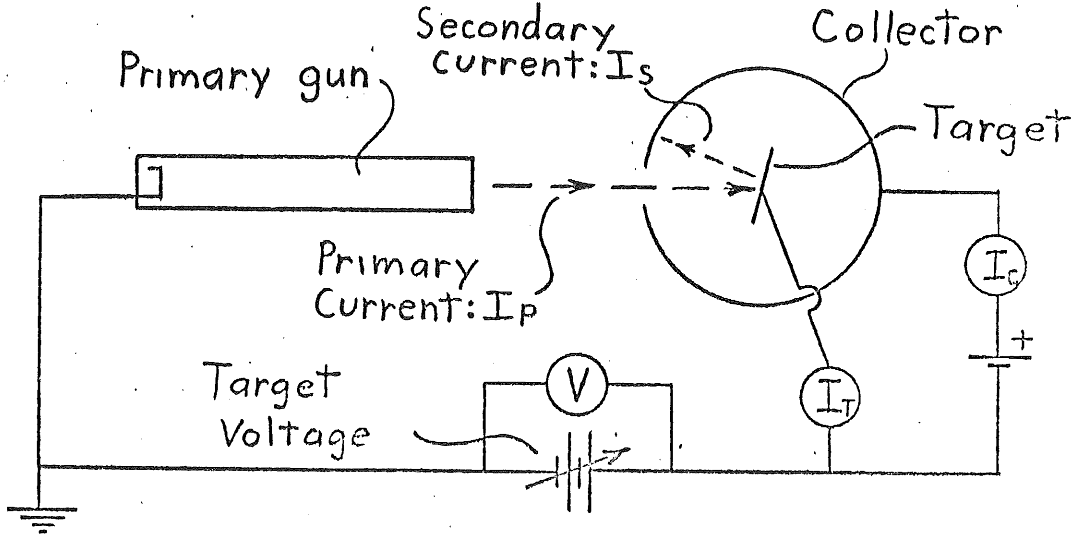
When electron-bombardment occurs, the dependence of bombarding electron energy on the target voltage is illustrated in Fig. 1. The target voltage of +100 volts determines the electron energy at the target, regardless of the voltage of the accelerating electrode. (A small correction is made for the energy of thermionic emission.)

Figure 1.



The target voltage in Fig. 2 also determines the bombarding energy. The metered collector current and target current are used to measure the secondary emission of a target as the bombarding energy changes with changing target voltage. A single metal target is used here, not an insulator.

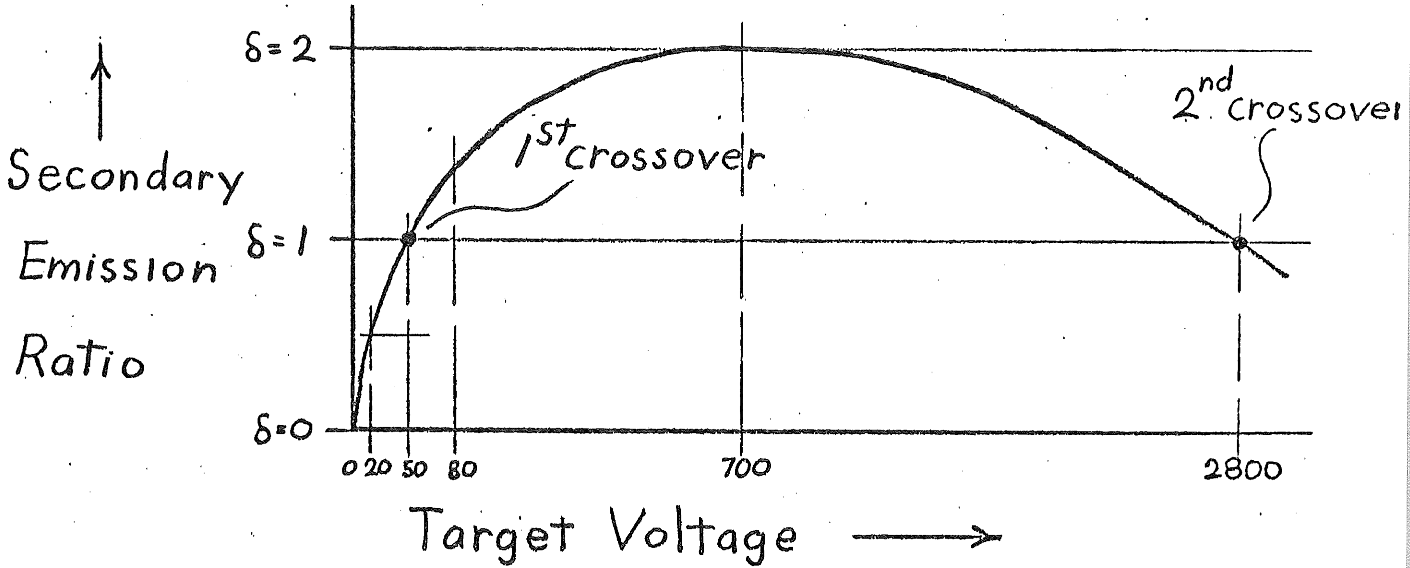
Figure 2.



The physical effect of secondary emission is then described in terms of the previously developed idea that the target voltage causes a particular bombarding electron energy. This bombarding energy then causes a certain ratio of secondary emission.

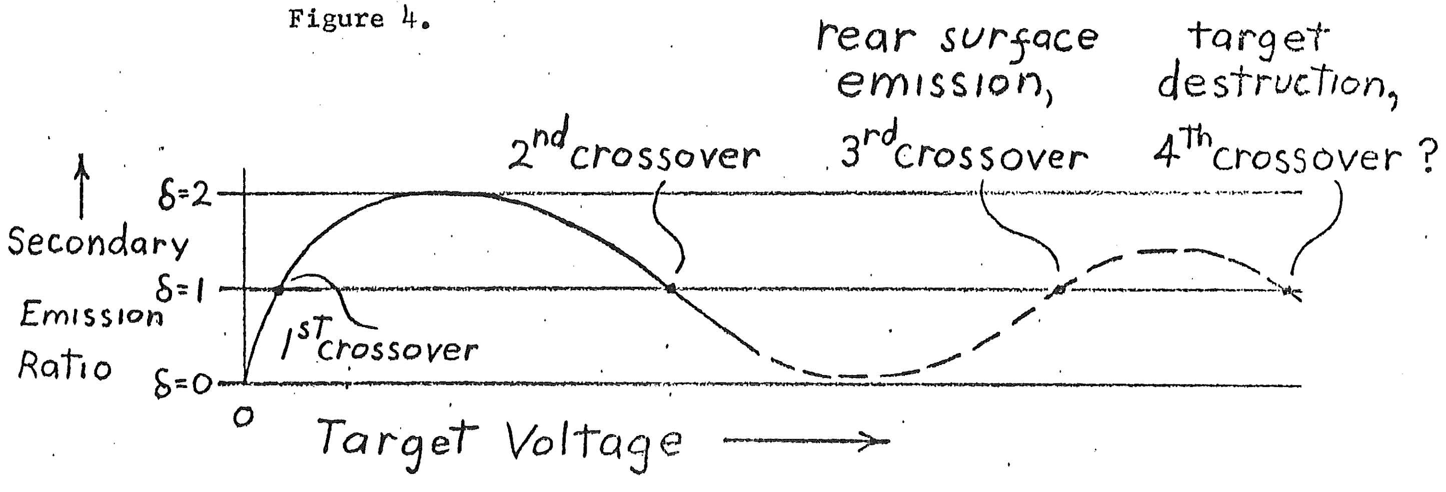
A typical secondary emission curve is shown in Fig. 3, where the first and second crossover are emphasized.

Figure 3.



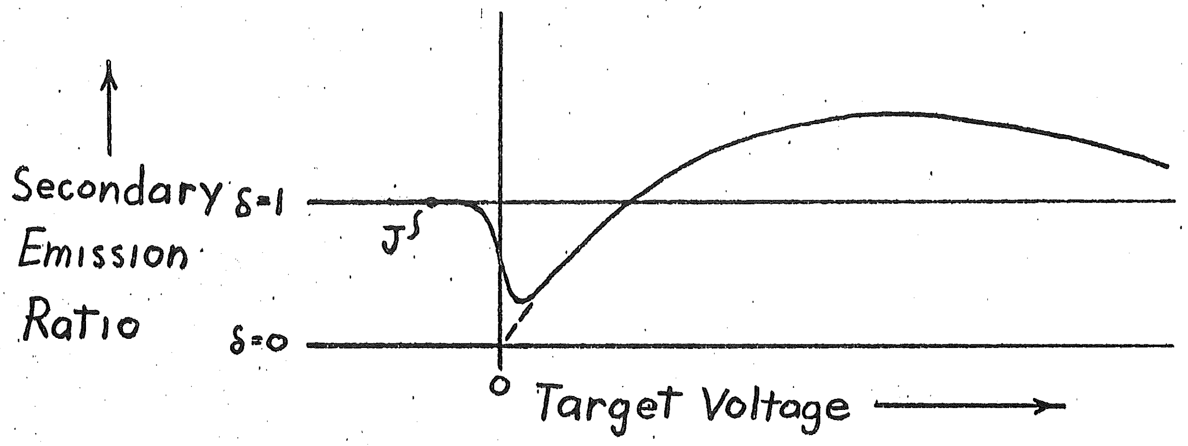
The possibility of physical effects resulting in a third and fourth crossover is illustrated in Figure 4.

Figure 4.



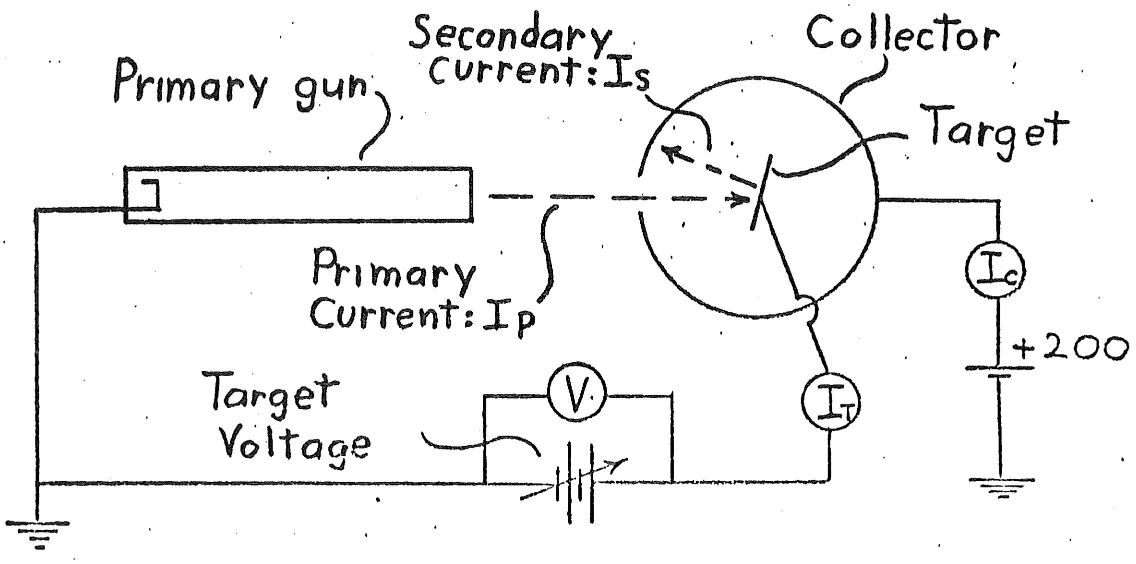
The physical effect of secondary emission is modified by an 'apparatus effect' at negative target voltages. Reflected primaries result in an apparent secondary emission ratio of one, just below zero target volts, in Figure 5. This effect cannot be distinguished from true secondary emission by external measurements. The rounded transitions of the curve are due to the energy of thermionic emission.

Figure 5.



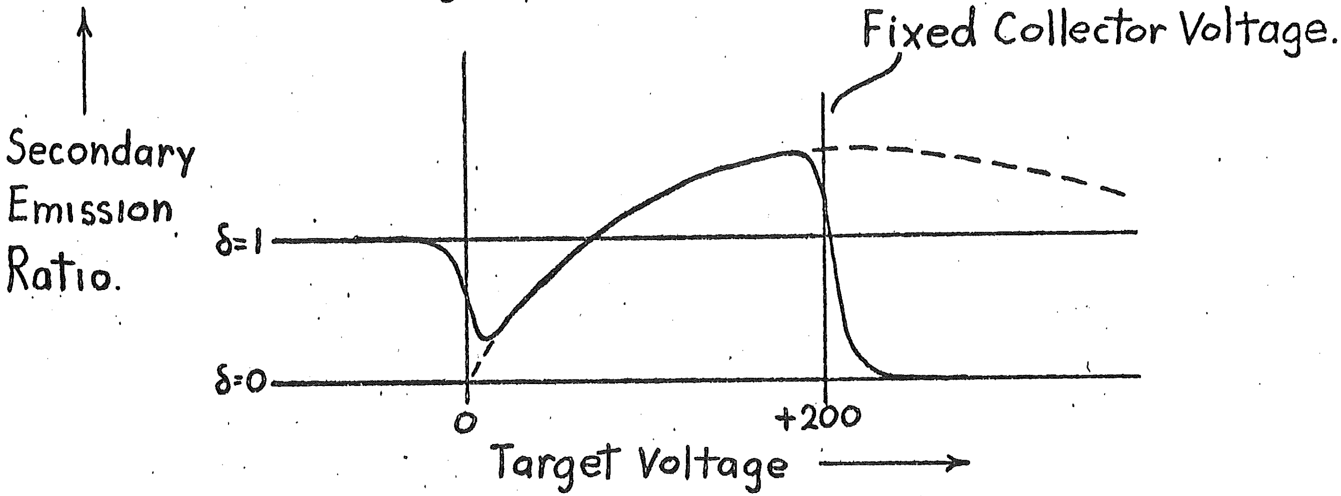
The tube of Figure 2 is then modified by fixing the collector voltage at +200 volts, as in Figure 6.

Figure 6.



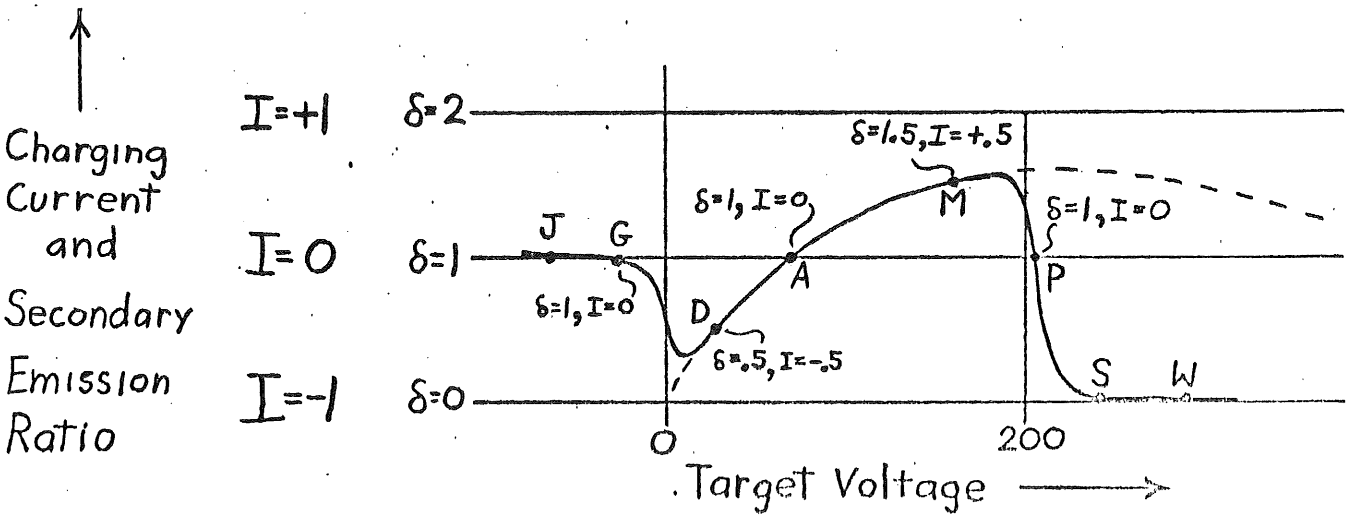
This causes a change in the secondary emission curve, due to reflection of secondary electrons by the collector. This 'apparatus effect' appears in Figure 7 at voltages above the fixed collector voltage.

Figure 7.



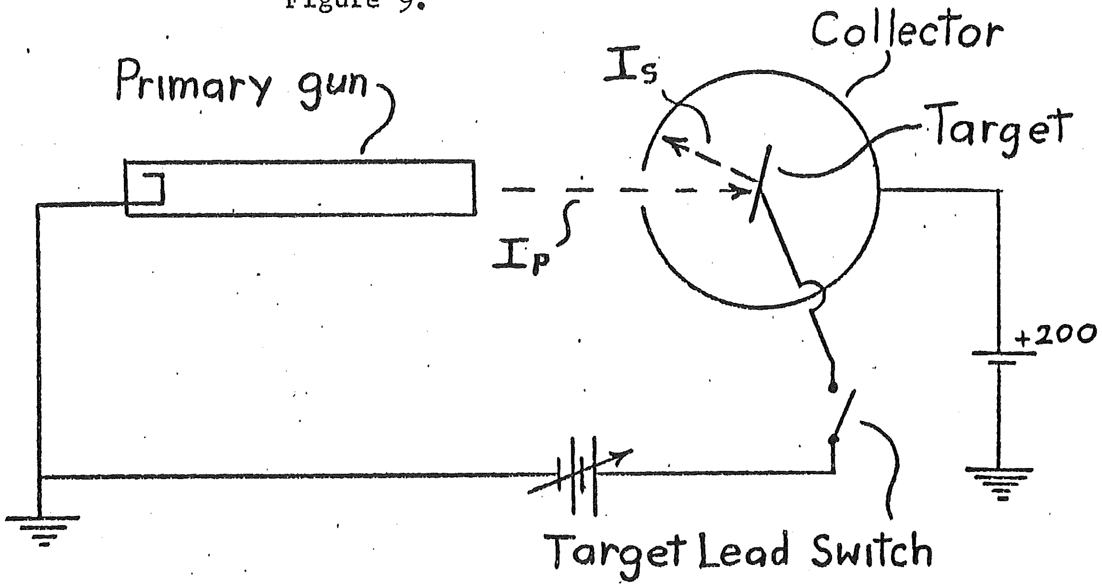
The ratio of the secondary and primary currents is converted into a current difference, to determine target charging current for different target voltages. An additional ordinate scale is added in Figure 8, and charging currents in the target lead-wire are discussed for several points on the curve.

Figure 8.



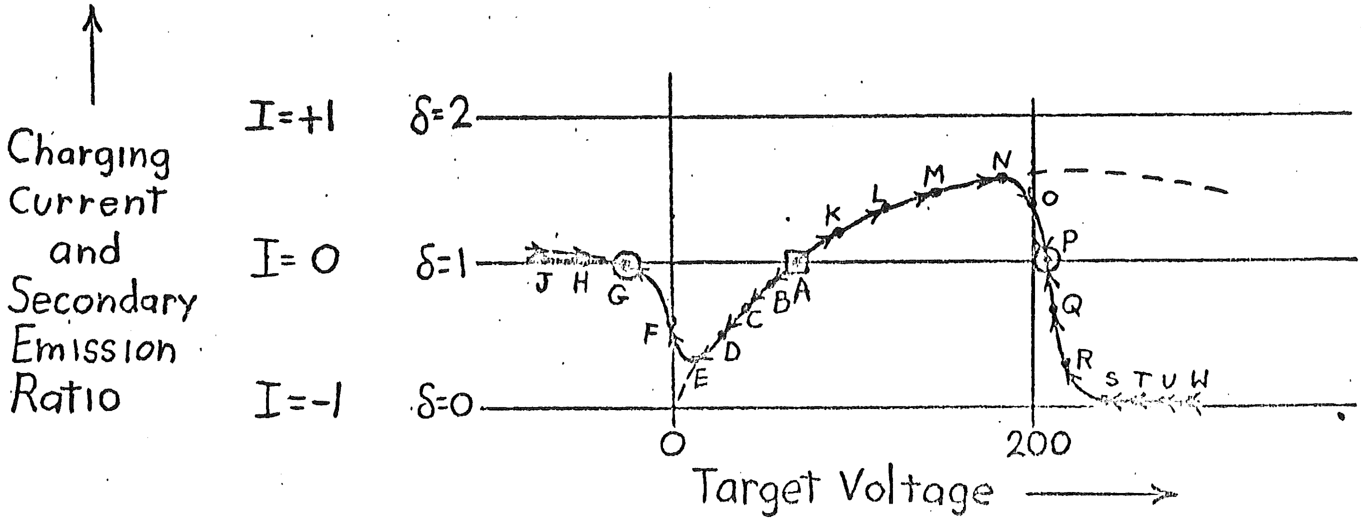
The tube is again modified, as in Figure 9, by the addition of a switch in the target lead-wire. The target may be set at some selected voltage and associated charging current, before opening the switch.

Figure 9.



The direction in which the target charges when the switch is opened is shown over the range of useful target voltages in Figure 10. Two stable voltage points occur because restoring forces of charging occur when the target is not at either stable point. This tube exhibits simple storage, capable of electrical measurement of one stored 'bit' of information from outside of the tube.

Figure 10.



The effect of various fixed collector voltages on the existance of the two stable points is explored in Figure 11. A simple concept of the 'stable range' of collector voltage is defined and its limits discussed.

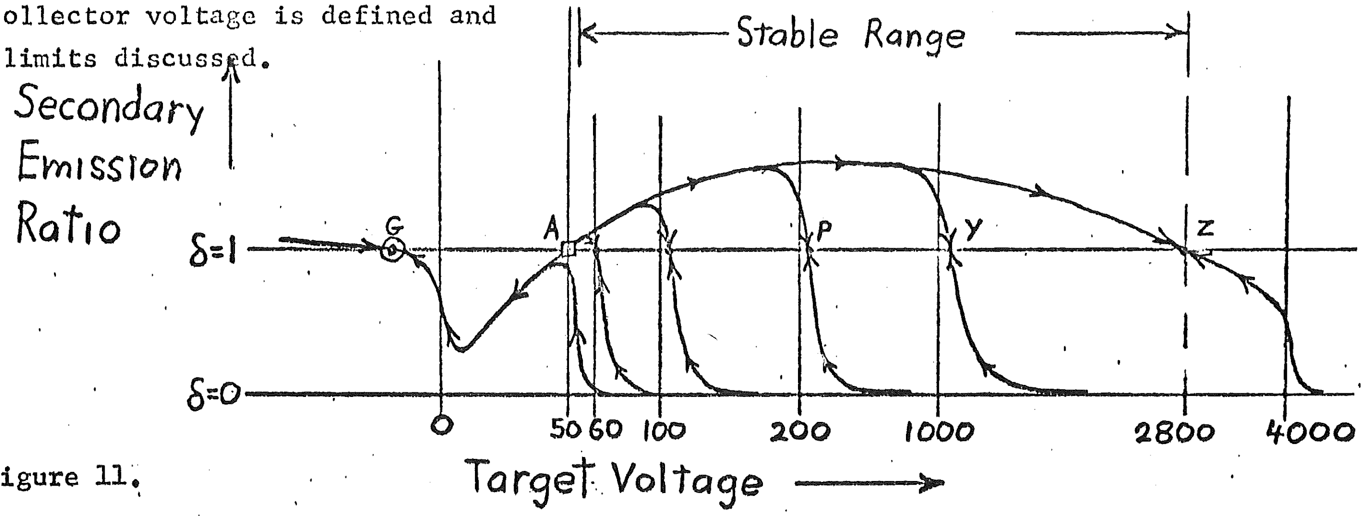


Figure 11.

A mechanical 'rolling ball' analogy of stability is shown in Figures 12 and 13. The direction and amount of restoring forces on a rolling ball and on a floating target are compared.

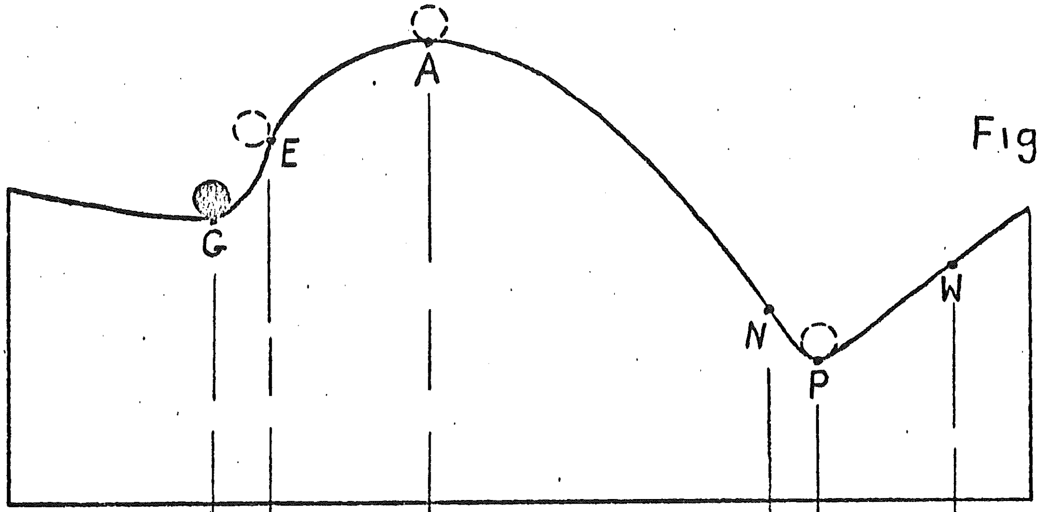


Figure 12.

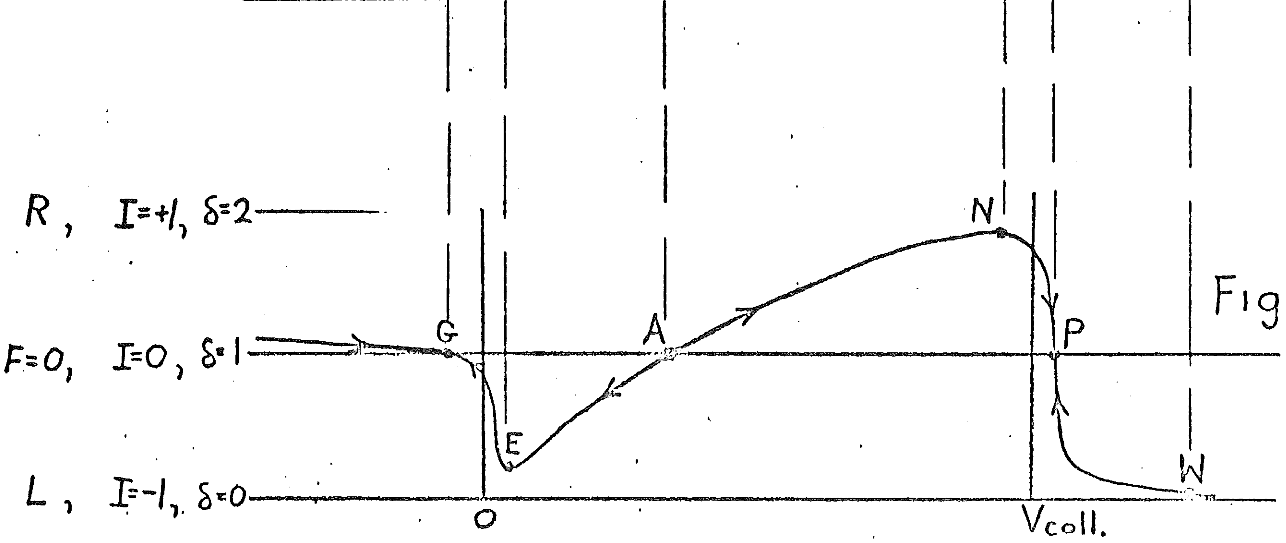
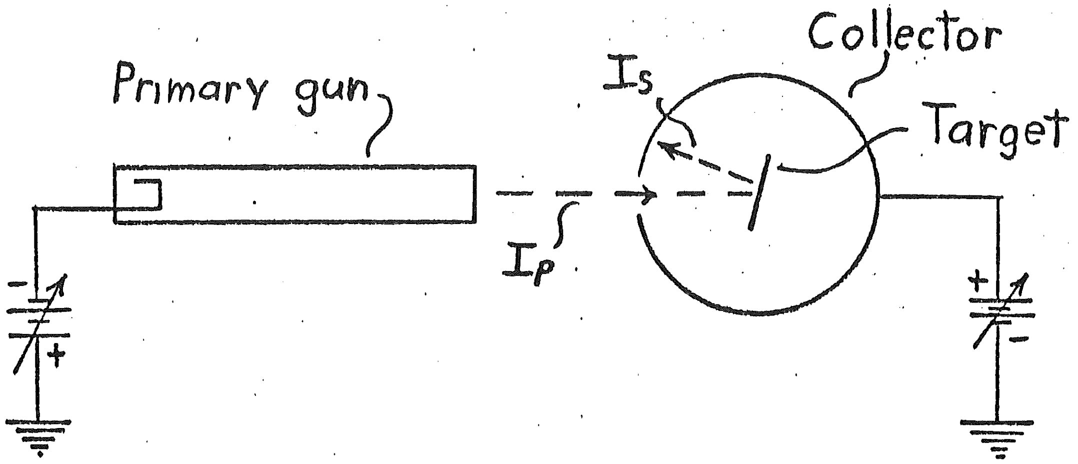


Figure 13

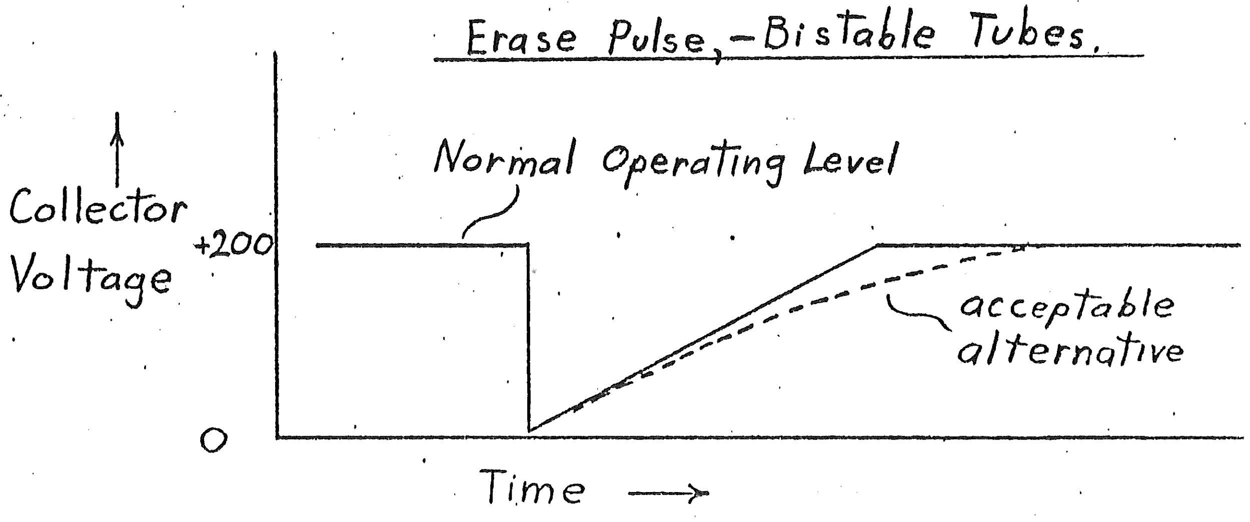
The tube is again modified by changing to a floating target having no external connections, as in Figure 14. This is the first tube described here which writes, stores, and erases by controlling a floating target.

Figure 14.



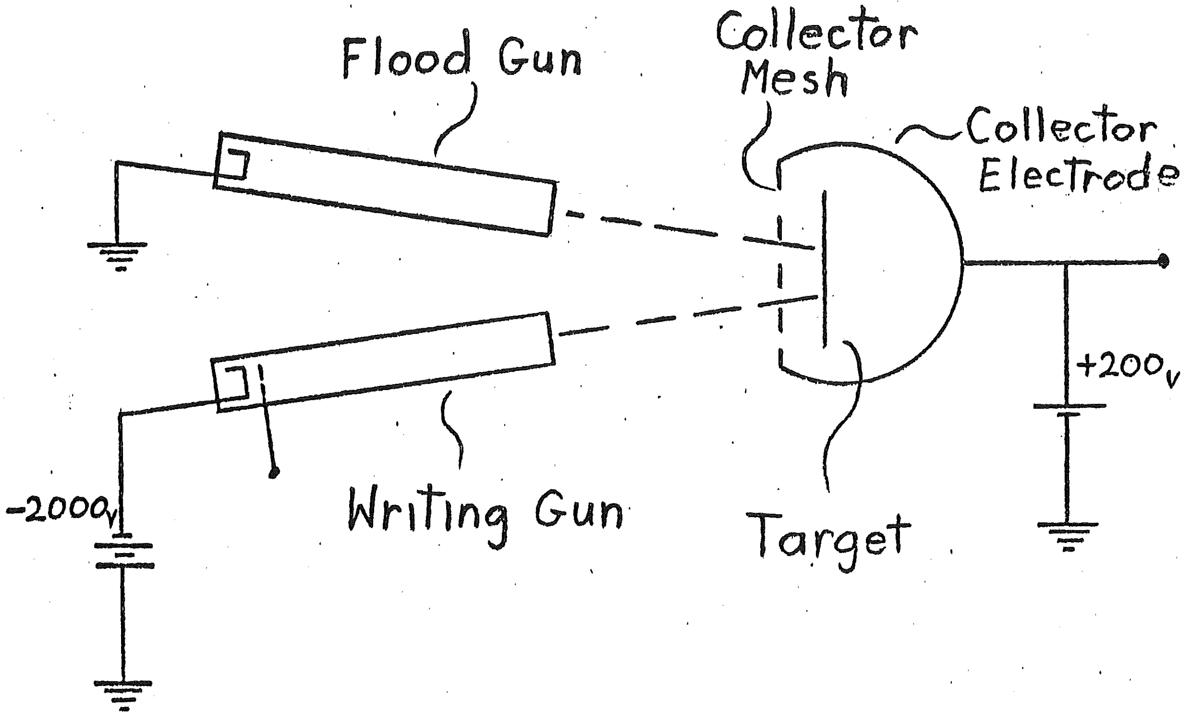
Control of a floating target with a single electron gun is described, where the effect depends on shifting the relative cathode-to-target voltage, by shifting the cathode voltage. Writing and erasing with the collector are described. These two descriptions are for background in the writing and erase effects to be used in commercial storage tube structures. Figure 15 shows the erase pulse.

Figure 15.



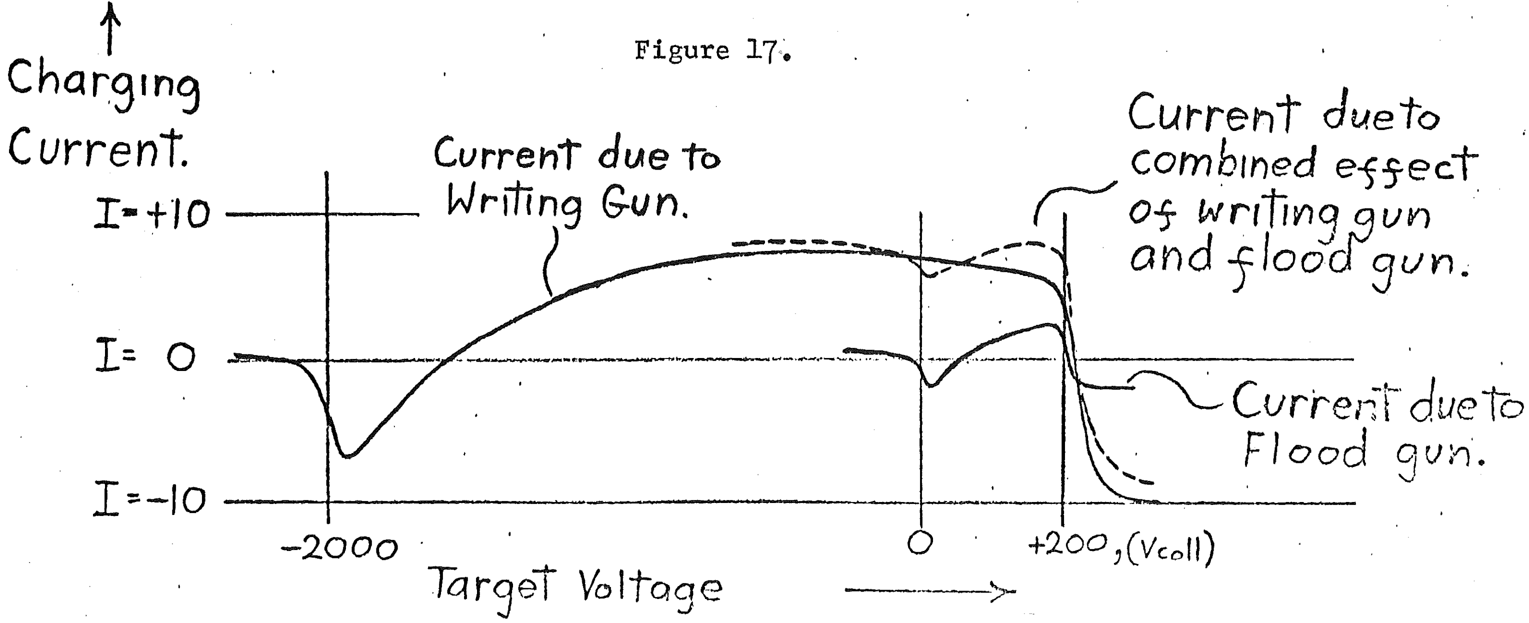
The tube is modified by the addition of a second electron gun, as shown in Figure 16, below. Bi-stability occurs due to the flood gun current, as in preceding tubes. Charging by the writing gun is in the positive direction. Opposition of writing by the flood gun and completion of writing by the flood gun is discussed. This is the first tube here which controls a floating target with guns at <u>fixed</u> voltages.

Figure 16.



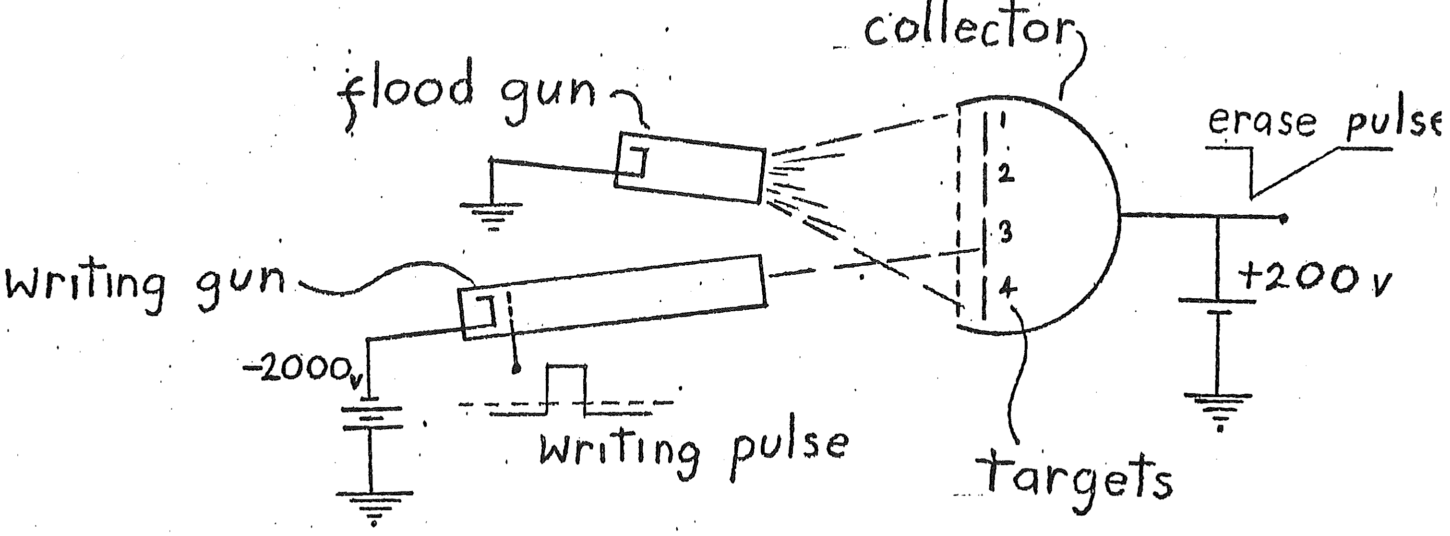
Practical control of a target with two guns is described in Figure 17 by showing the addition of two charging curves of different amplitude, displaced from each other on the voltage axis.

Figure 17.



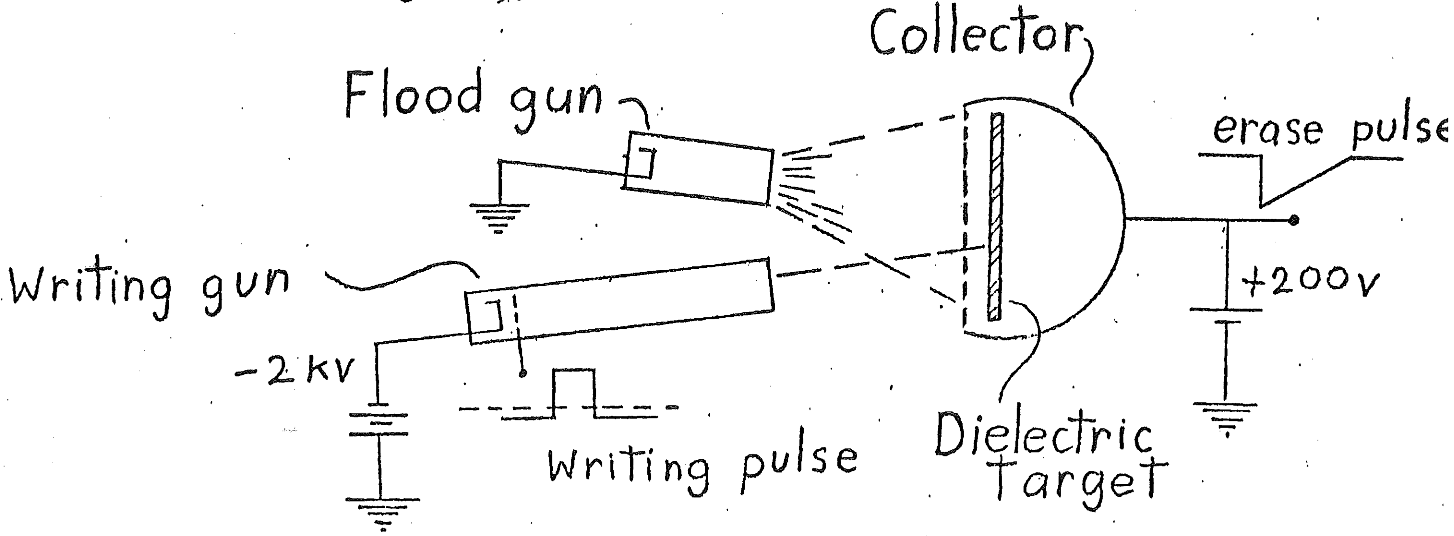
The tube is again modified in Figure 18 by introducing multiple targets and then a two-dimensional array of targets. The ability of the flood gun to hold some targets 'erased' while others are held 'written' is shown to require different areas of coverage of the targets by current from the two guns. The storage of a coarse four-line, two-dimensional charge-image is achieved in this tube, which is the first, in this report, to have a two-dimensional charge-image.

Figure 18.



The tube is modified again in Figure 19 by the introduction of a continuous dielectric sheet target, in place of multiple conductive targets. The array of individual targets is allowed to approach a limit in target size and number, as an evolution into the area-elements of a continuous dielectric sheet.

Figure 19.



The charging and written pattern resulting from fixed and swept spots are described in terms of time integrated charge at an area element of target surface, in Figures 20 and 21. This tube has now evolved into a structure capable of writing, storage, and erasure of a high-resolution, two-dimensional bi-stable charge image, and is the first one described here to have a <u>high resolution</u> charge image. The next step is a visible light image.

Figure 20

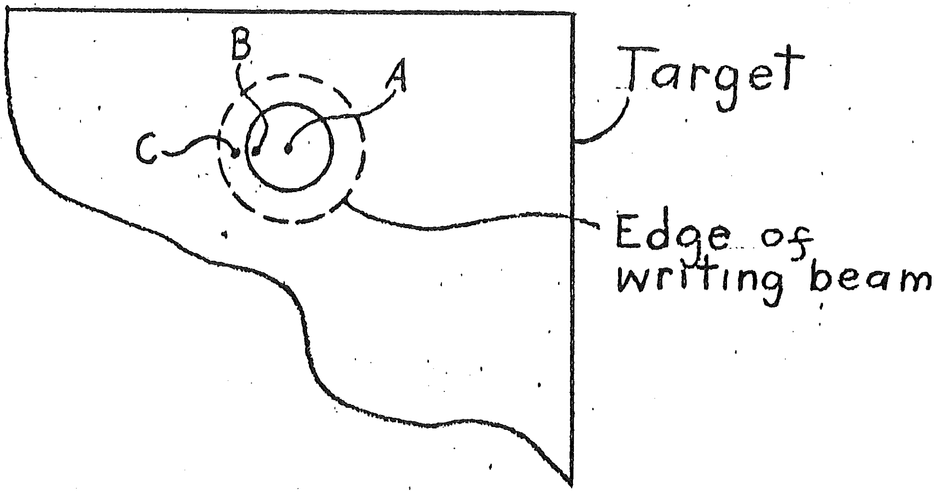
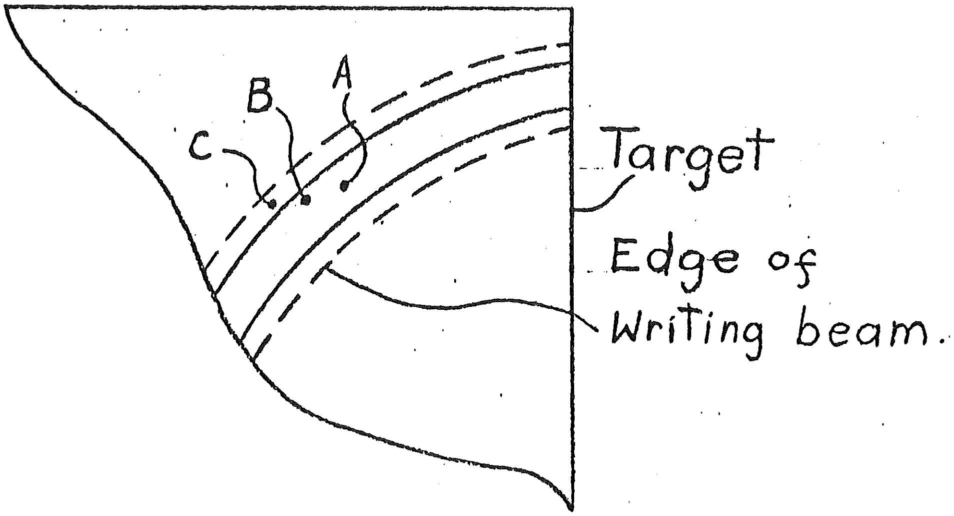
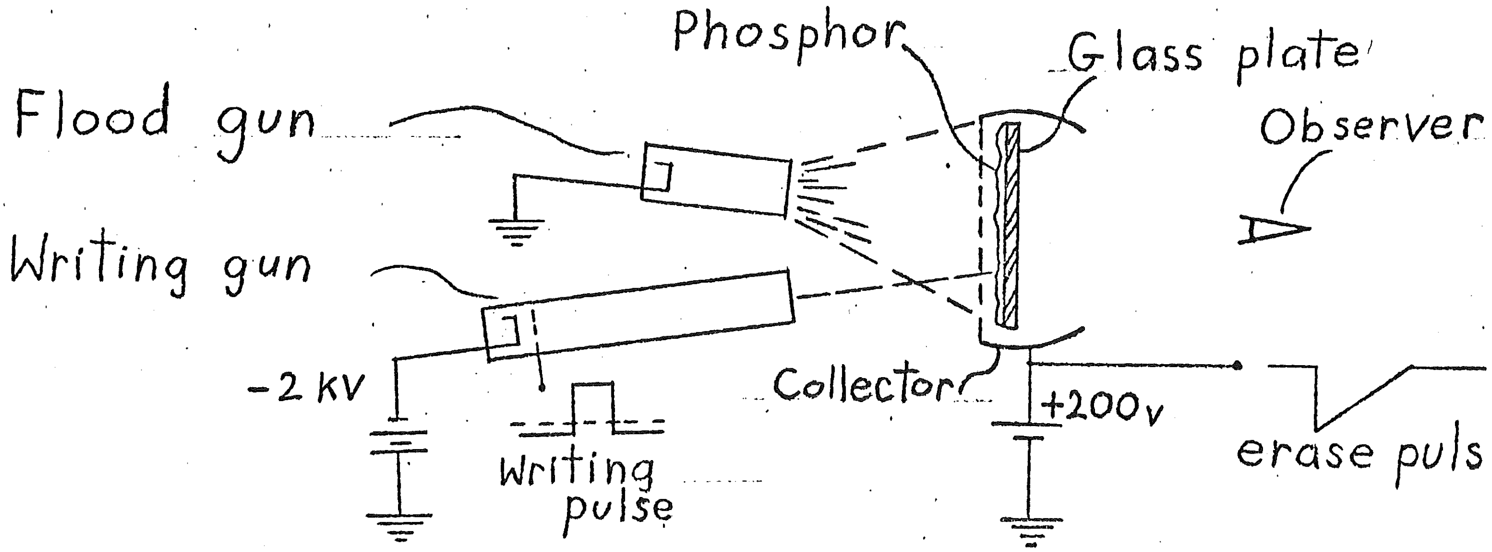


Figure 21



The transition from a stored charge-image to a visible image is made by using a fluorescent phosphor for a bi-stable target dielectric. This is a significant early type reported by A. Haeff in 'Electronics', and shown in Figure 22. Limited brighfness in this tube is discussed, and this leads to discussion of increased collector voltage, to gain brightness by increasing the bombarding energy in written areas. The collector voltage increase is limited by loss of the image due to image boundary migration. The cause of image boundary migration is described in terms of conductivity and restoring currents at adjacent areas on the target. The upper and lower collector voltages at which the onset of boundary migration occurs, either toward or away from written areas, narrows the stable range of collector voltages, by defining a 'retention threshold' and 'fade-positive' point.

Figure 22.



A sequence of illustrative tubes is described in Figures 23 and 24, introducing the idea of grid-control of flood electrons by the targets in a simple low-resolution multiple-target tube. Then, high brightness is obtained in Figure 25 by acceleration of the electrons transmitted through the target and bombardment of a separate high voltage phosphor screen.

Figure 23

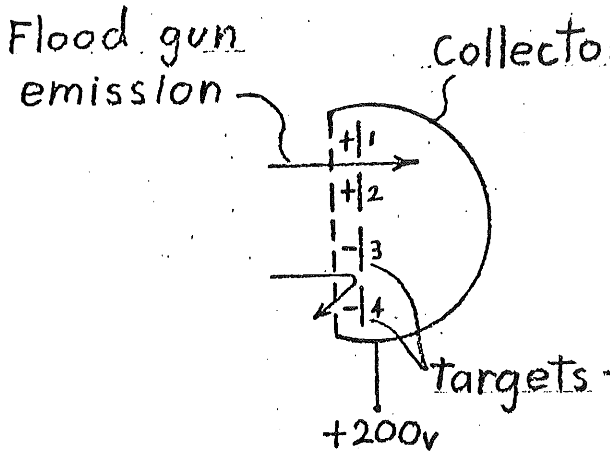


Figure 24

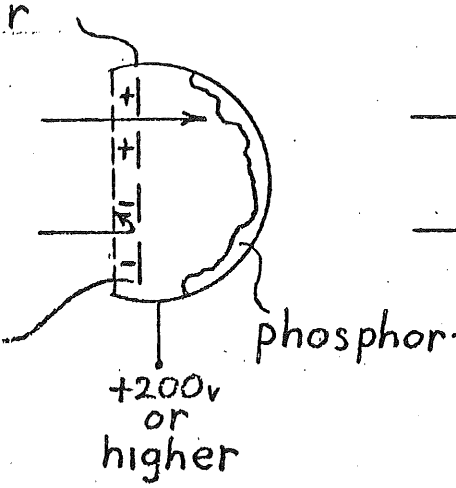
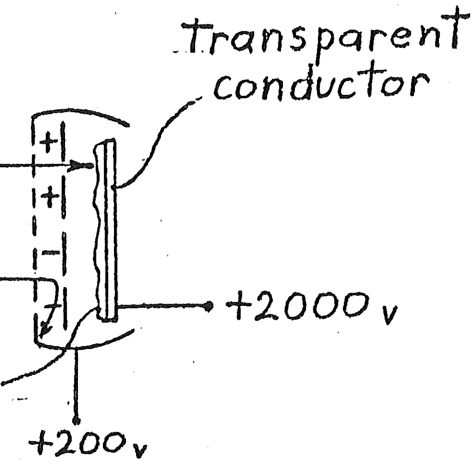


Figure 25



This system is then extended to high resolution tubes in Figures 26 and 27 using an apertured dielectric sheet having its collector voltage limited by image boundary migration. High brightness is again achieved by using acceleration of transmitted flood electrons to a separate high voltage phosphor screen, in Figure 28.

Figure 26

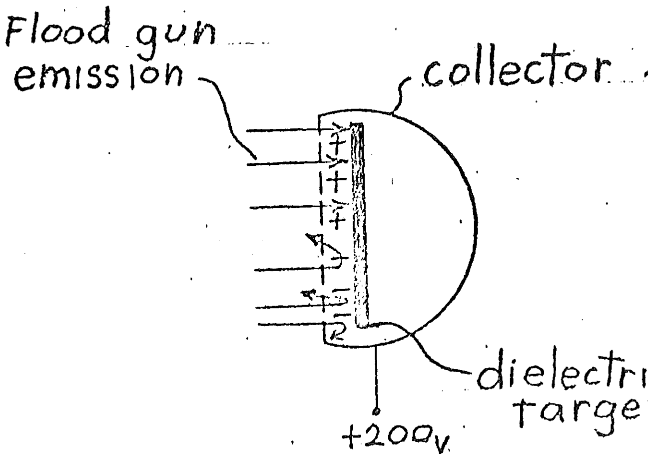


Figure 27

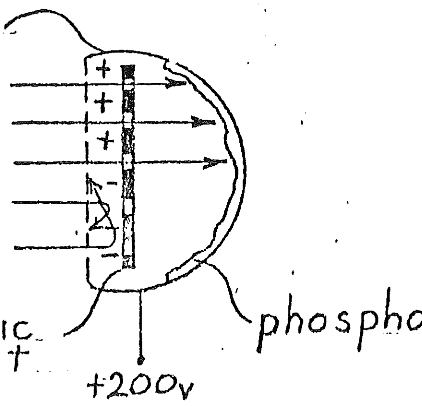
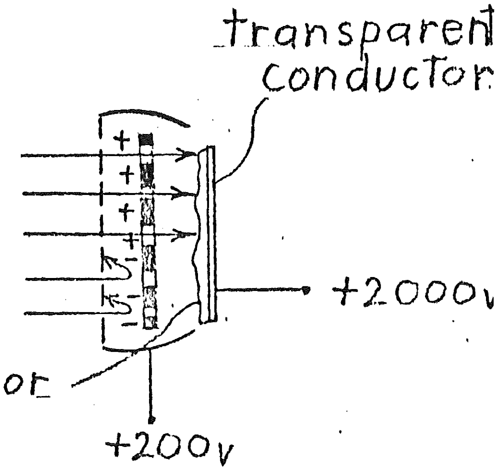
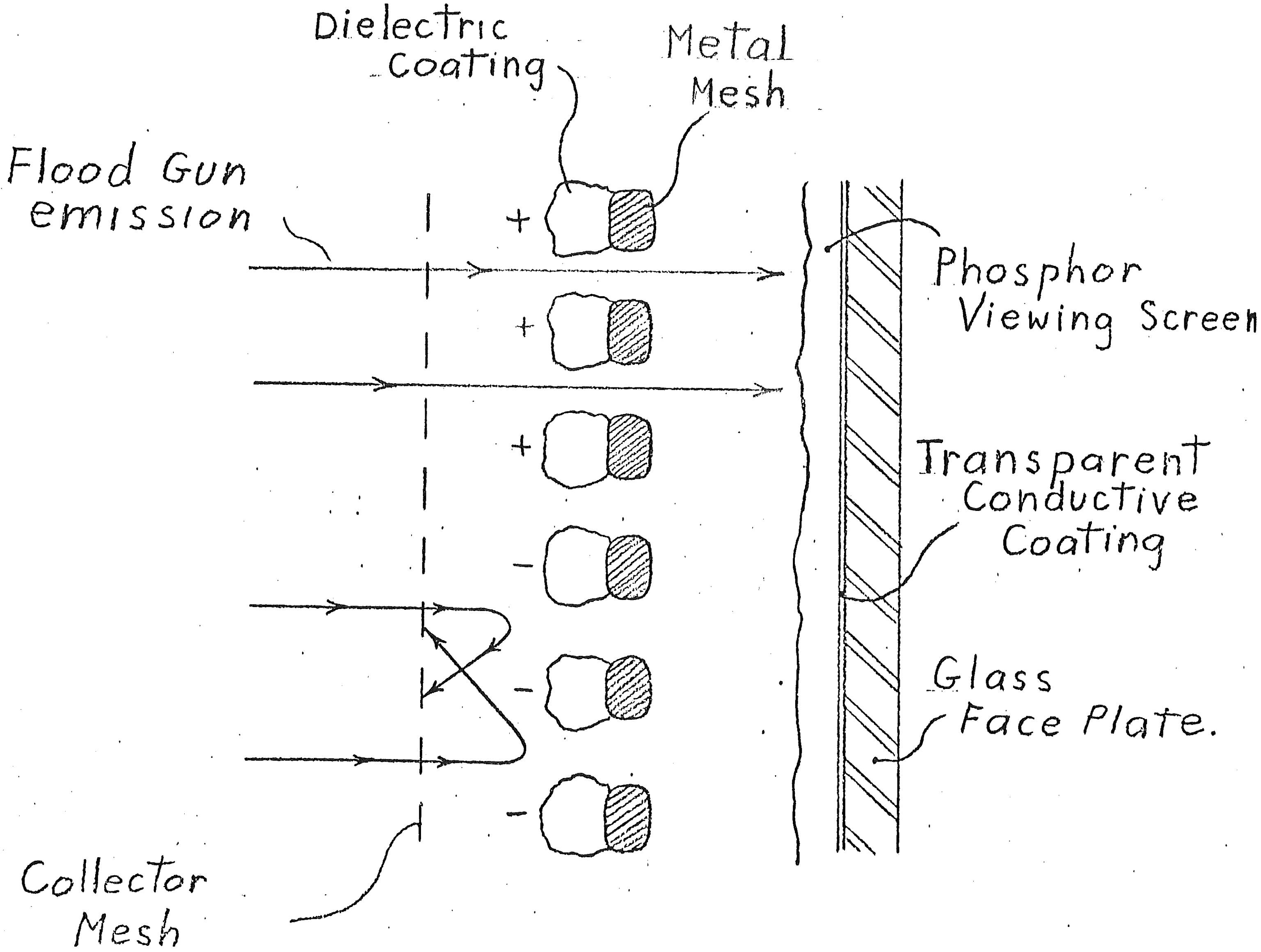


Figure 28



The tube is then modified again in Figure 29 to arrive at a practically realizable target structure, by supporting the dielectric layer on a metal supporting mesh.

Figure 29.



The field in the apertures of the target is shown in Figures 30 and 31, and is described in some detail, to show how controllable target transmission occurs in the composite structure combining a dielectric and a conductor.

Figure 30 (unwritten)

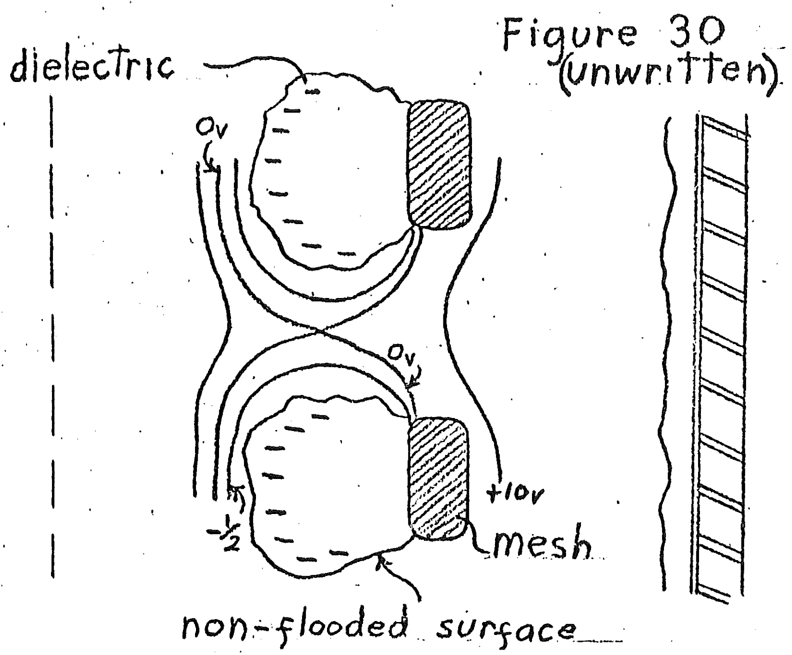
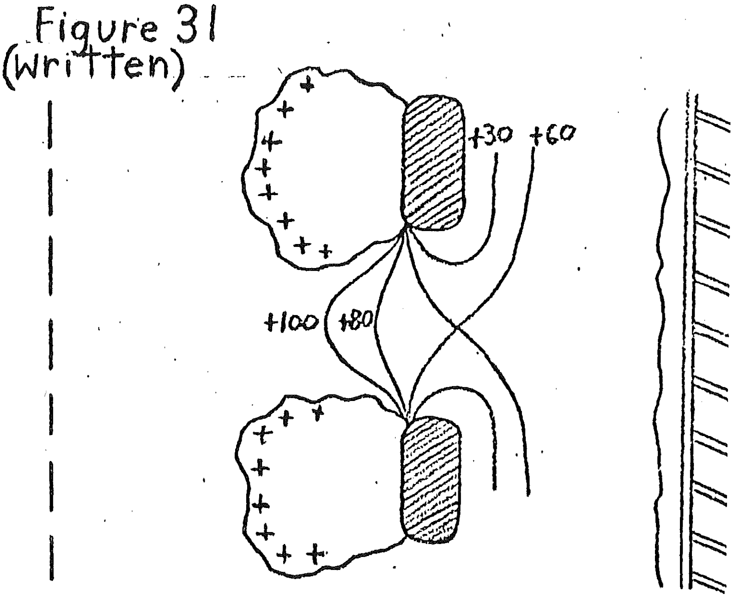
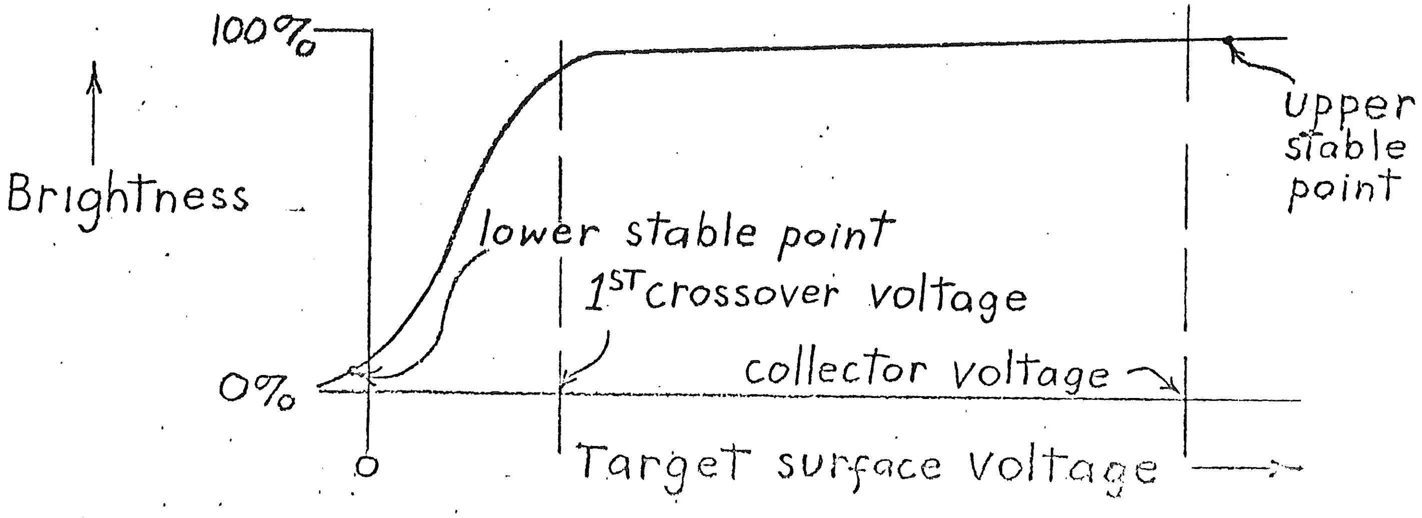


Figure 31 (written)



The resulting brightness-transmission curve is shown in Figure 32 and the stable points noted on the curve.

Figure 32.



With the description of the ion-repeller mesh and the contacting collector shown in Figures 33 and 34, the evolution of a bi-stable tube is complete, and this is the structure of the bi-stable storage target used in tubes which are commercially available from Hughes and Machlett. One of these tubes, the Hughes' 'Memotron' is shown in Figure 35.

Figure 33

Figure 34

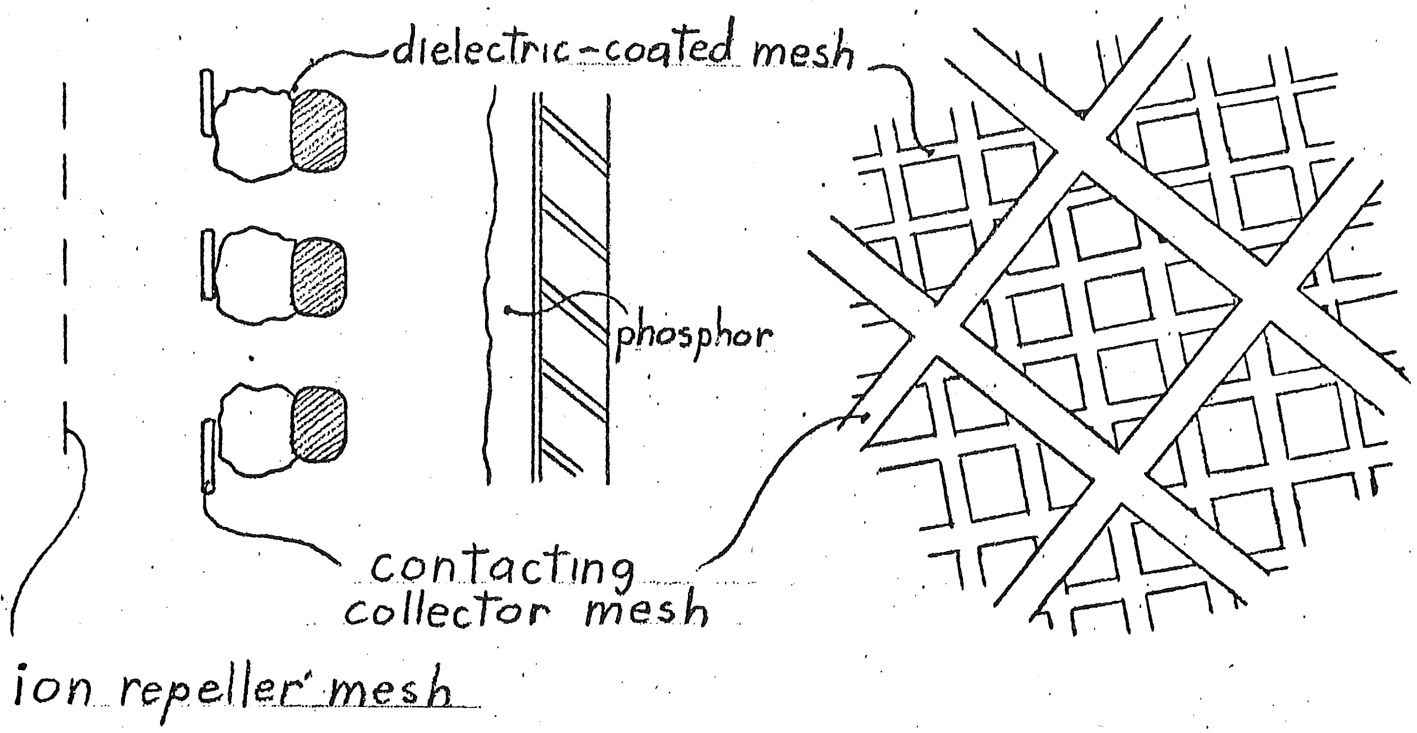
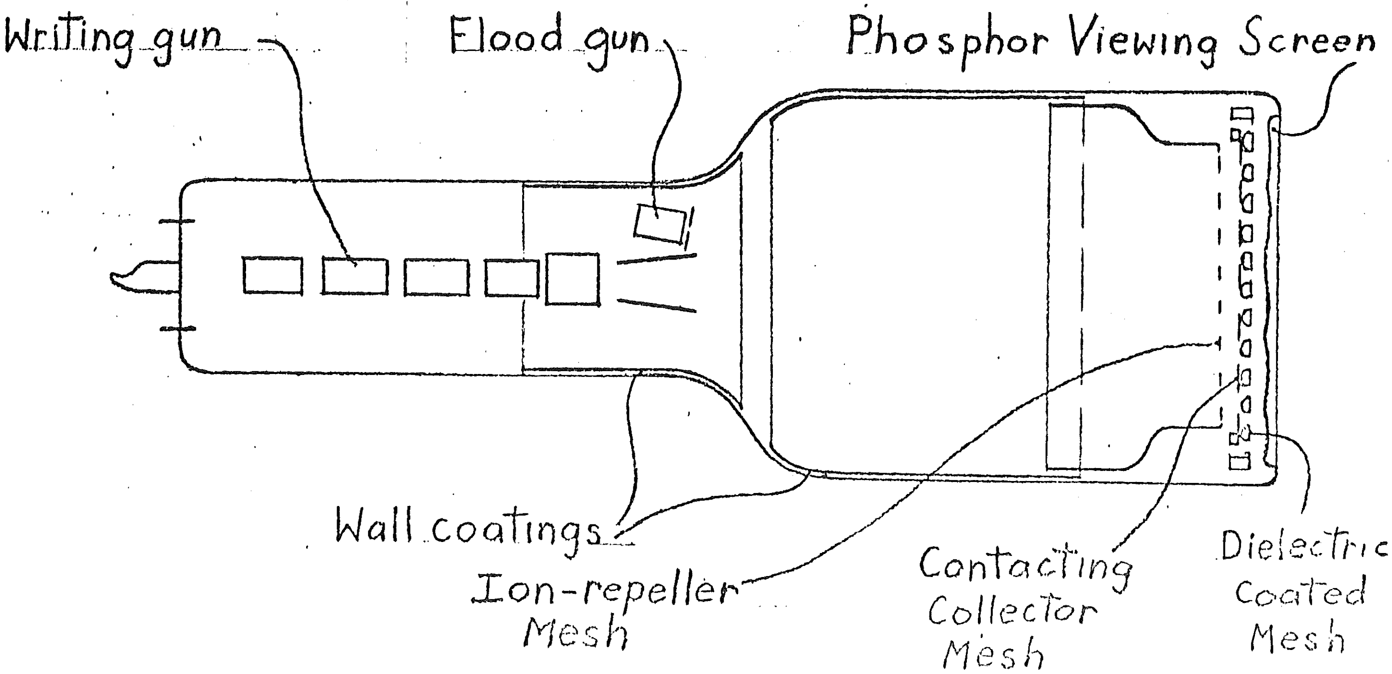
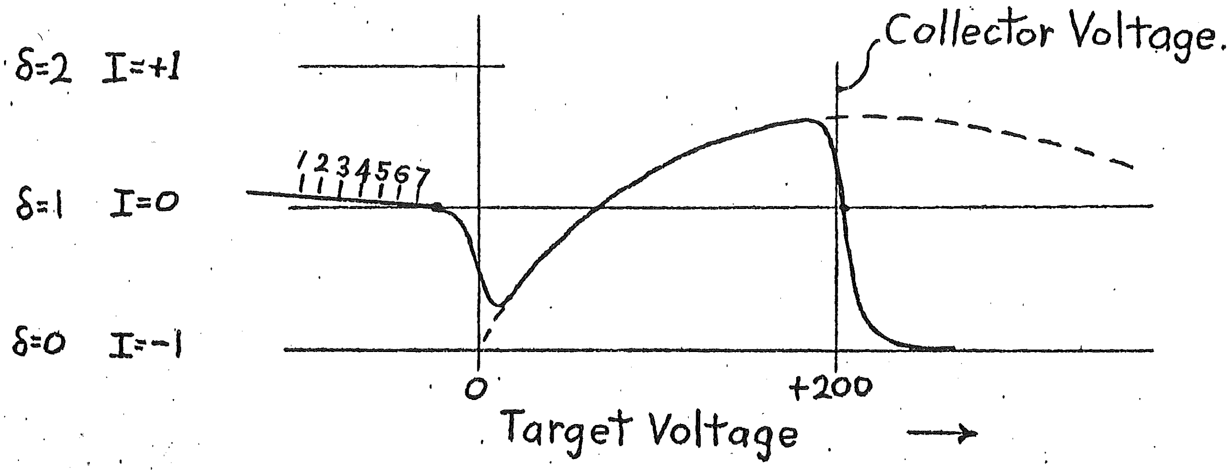


Figure 35



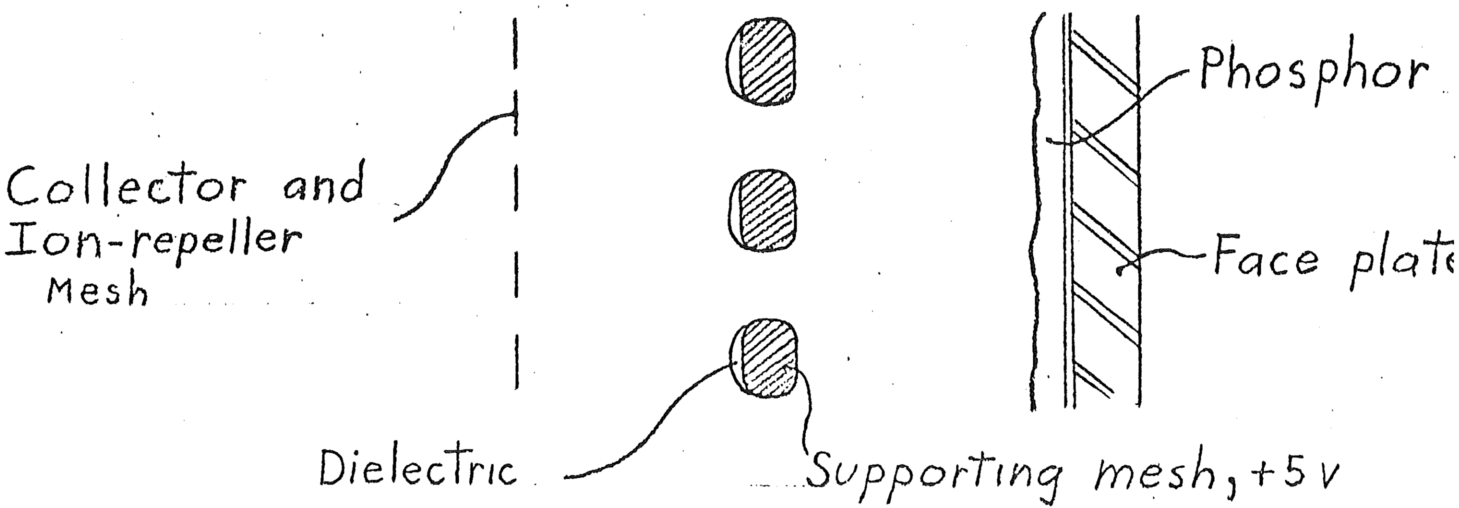
Half-tone tubes are introduced by describing the storage of a half tone charge-image on a bi-stable target, without a visible image. In Figure 36, the half-tone range of target voltage on the secondary emission curve is below the lower 'quasi-stable' target voltage, where positive ion bombardment is a weak restoring force. Loss of the image by fading in the positive, 'bright' direction is discussed and the mechanism of erase is described.

Figure 36



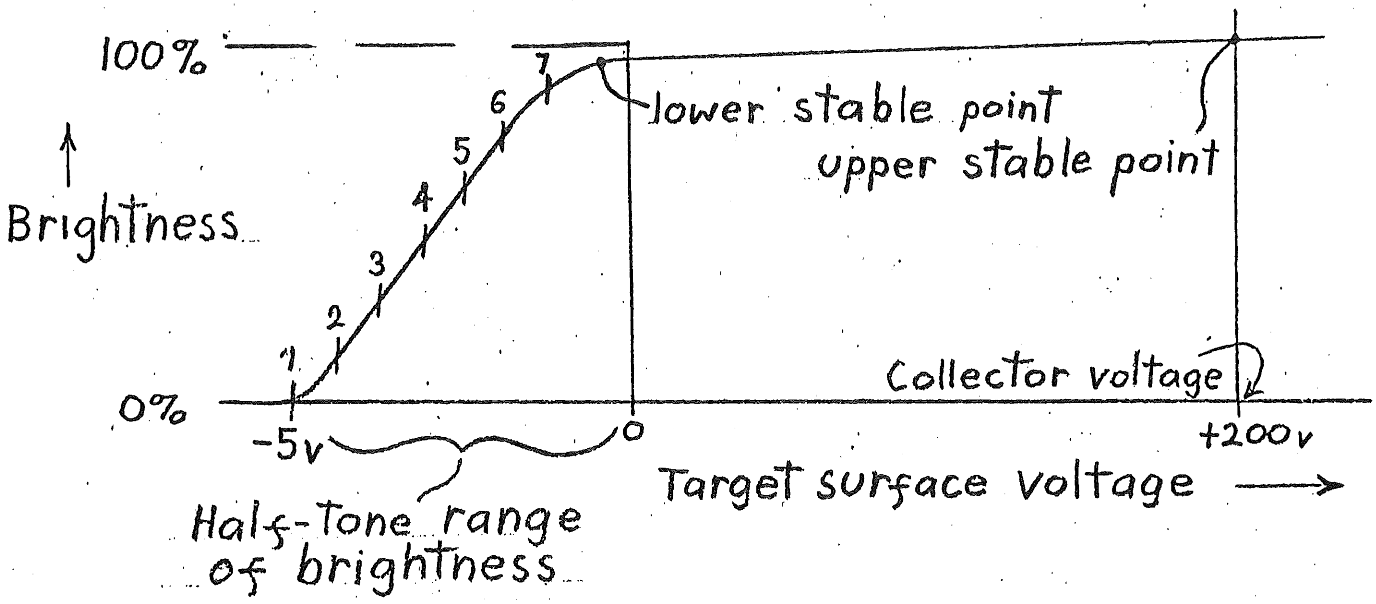
The actual half-tone tube is shown in Figure 37 and both the charge-image and visible image are produced. The structure of this target is described, especially the thin evaporated dielectric and the non-contacting collector. The display mechanism differs from that of the bi-stable tube in that flood electrons do not reach the dielectric surface during display.

Figure 37.



In Figure 38, the half-tone brightness-transmission curve goes from cut-off to saturation in only about a 3 volt range of target surface voltage. The ability of both the bi-stable and half-tone tubes to store charge-images of both bi-stable and half-tone modes is illustrative of fundamental similarity between the tubes. Similarities and differences between the tubes are outlined.

Figure 38.



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1. "Storage Tubes", Knoll and Kazan, Wiley, 1952.
2. "A Memory Tube", A. V. Haeff, Electronics, September, 1947.
3. "Secondary Electron Emission", Bruining, McGraw-Hill, 1954.