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# A NEW COMPUTER STORAGE TUBE

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Storage tubes used in digital computers store information by the charging of spots on a target to one of two stable states. By a proper code combination of a number of spots, both decimal digits and alphabetic characters can be stored. Consequently, a cathode-ray tube can store information if a number of spots can be charged to one of two distinguishable levels.

The new tube is called the IBM-93 Cathode-Ray Storage Tube. One of the binary states required to store information is the normal potential of a spot hit by the beam. To obtain the second state, the beam is turned on, and an electrode which is capacitively coupled to the target surface is pulsed negatively. The entire target area is driven negative and the beam restores a spot to the normal potential which is positive with respect to the rest of the target. This method of operation does not require secondary redistribution of electrons.

Secondary redistribution is essential in the operation of the Williams system. (1) In this method of storing information on the phosphor of a cathode-ray tube, one binary state, called a dot, is the equilibrium potential of a spot under the beam. The second binary state, called a dash, is obtained by moving the beam in a line adjacent to the storage location and allowing the splash of secondary electrons to charge the storage location to a more negative potential. This splash, or secondary redistribution, may also change neighboring storage locations and becomes especially serious when the information at one location is referred to many times. In the Williams tube the very effect used in the storage process is the same effect which limits the storage capacity.

The new tube uses an accelerating field at the target surface to inhibit secondary redistribution. The accelerating field is established between a fine wire mesh lying on the target surface and a collector grid located a short distance in front of the mesh. The wire mesh also serves as a barrier so that secondary electrons cannot travel from one storage location to another in paths close to the target surface.

## TUBE CONSTRUCTION

The IBM-93, shown in the photograph, consists of a reëntrant (recessed face) glass bulb containing an electrostatically deflected electron gun and a target structure. The final seal of the bulb is made at the reëntrant end, which allows the target to be mounted in the open, where it is accessible. The reëntrant bulb structure has the additional advantage of allowing the seal to be made away from the target without having it in the coated portion. Keeping the seal away from the target reduces the heating of the target and the possibility of distortion when the seal is made.

The major gun requirements are a small spot size and a minimum of deflection defocusing. The target area containing a binary digit (abbreviated "bit") is proportional to spot size or beam diameter at the target. It is obvious that as the target area used to store a single bit is made smaller the storage capacity of the tube is increased. As the beam is deflected from the axis of the tube, the spot increases in size due to deflection defocusing. Sufficient beam current to produce a usable signal is not a problem. A recently-developed gun is capable of meeting the strict requirements (2) and therefore is used in the IBM-93.

The target consists of a dielectric having a fine mesh on its surface, a collector grid located a short distance in front of the mesh, and a metallic coating called the backplate on the other side of the dielectric. Fig. 1 is a schematic diagram of the target.

Since this target construction is rather unique, it will be described in some detail. The lower ceramic frame is held on a mandrel and placed in a grid winding machine as shown in the photograph. A square piece of mica having an evaporated metal coating on one side is placed on the frame with the metallic side down. The machine winds 0.0004-inch diameter tungsten wire over the mica and frame with a winding pitch of 300 turns per inch. A low-inertia tensioning device maintains a tension of one-half breaking strength in the wire as it is wound. A second winding is placed on top of the first at right angles to it forming the mesh. The wires are secured to the frame with a ceramic cement. The frame has the same temperature coefficient of expansion as the tungsten wire to prevent breaking of wires when the tube is heated during processing. The collector grid is wound on a second frame with wires running at an angle of $45^\circ$ with respect to the frame sides. The two frames are cemented together with ceramic cement, spacers being used to keep the mesh and the collector grid 0.010-inch apart.

The collector grid and mesh have been designed so that any portion of the target surface may be used to store a bit. The wires in both are very fine and spaced sufficiently close together so that as the storage location is moved over the target, the storage signal changes less than ten percent.

## READING AND WRITING

As has been mentioned before, there are two states of charge which the writing process establishes on the dielectric surface. The binary state called a zero is the equilibrium potential of the target surface under the beam. Assume that the tube is connected as shown in Fig. 2. The pentode is cut off, putting the backplate and mesh at ground potential. When the beam is turned on, the secondary electron current exceeds the primary beam current. This secondary current is a result of the secondary emission characteristics of the mica. If the spot is negative with respect to the effective collector, all the secondary electrons leave the spot. Since electrons are leaving at a greater rate than are arriving, the spot becomes charged positively. On the other hand, if the spot is positive with respect to the collector, most of the secondaries are returned to the spot, and the beam electrons charge the spot in a negative direction. As the spot potential swings toward that of the collector by being charged either positive or negative, the field between the collector and the spot diminishes. This change in the field causes the secondary electron current to approach the primary beam current. When the two currents are equal, the spot is at the equilibrium potential.

The other binary state, called a plus, is obtained by applying a negative pulse to the backplate while the beam is on and turning the beam off before the end of the backplate pulse. These conditions and the changes in potential of a spot beneath the beam are shown in Fig. 3. The mica surface swings negative with the backplate because of the capacitive coupling through the mica. The action of the beam tends to restore the spot to the equilibrium potential with respect to the effective collector. This restoring action makes the spot under bombardment positive with respect to the surrounding area. After the beam is turned off, all the target surface, except the spot that was under the beam goes back to the original potential when the backplate pulse ends. The spot that was under the beam is left positive with respect to the surrounding area.

Reading is accomplished by applying voltages to the deflecting plates that will direct the beam to the bit in question, and then applying a voltage pulse to the gun grid to turn the beam on. If the bit is a zero, there will be no output since the spot is at equilibrium potential. If the bit is a plus, few secondaries will leave the spot, and the primary beam electrons make the spot swing negative until the equilibrium potential is reached. This negative potential change of the spot beneath the beam is capacitively coupled to the backplate and amplifier input.

Although the backplate pulse is 100 volts, the output signal is only about a millivolt. Because the mica is thicker than the spacing between mesh wires, an element of the mica area has more coupling to the mesh than to the backplate. The diode conducts during the backplate pulse and clamps the mesh to ground potential. Consequently, the target surface swings only a few volts at most. Moreover, all of the target surface does not swing by the same amount, since the capacitance between an element of area and the mesh wires varies with the location of the element inside the square of the mesh. The portion of the target area that is directly beneath the mesh wires does not swing at all. This reduction in the potential change of the target surface is one effect which reduces the signal magnitude.

The shunt capacitance between the backplate and ground also reduces the signal magnitude as does the amplifier input capacitance. These capacitances must be driven through the capacitance between the spot on the target surface being bombarded and the backplate. This capacitance is several orders of magnitude smaller than the shunt capacitances. As a result, the output signal is a small fraction of the potential change on the spot.

The signal magnitude is increased considerably by the use of a diode between the mesh and ground. This diode does not conduct at signal time but allows the mesh and backplate to act together so the signal does not have to charge the large backplate-to-mesh capacitance. Otherwise, this capacitance would be in parallel with the tube output. This reduction in output capacitance of the tube makes it possible to use a larger load resistance for the tube, and maintain the same output circuit bandwidth. Because the storage tube may be considered to have a constant current output, increasing the load resistance increases the signal output of the tube. Another advantage of the diode is that it reduces the amount of the backplate pulse at the amplifier input.

Since reading is destructive, time is provided for both reading and writing in the same deflection cycle. Three microseconds of the cycle is used for setting up the deflection voltages and four microseconds is allowed for reading and writing the information. An extra microsecond serves as a safety margin and provides additional time for the amplifier to recover. The total length of the cycle is 8 microseconds.

Only two types of operating cycles are required; the timing for these cycles is shown in Fig. 4. These cycles are called plus and zero in conformity with the binary state of the bit at the end of the cycle. The interrogate interval "a," of one microsecond duration, is the same in both cycles and occurs after the beam is positioned. The beam bombards the bit in question and the output from the target is amplified and time sampled with a strobe pulse in a coincidence circuit. The coincidence circuit also provides level discrimination. It is followed by a trigger circuit which stores the information read from the tube until it is required later in the cycle. The beam is left on during the next time interval "b" in both cycles. A positive one-microsecond pulse is applied to the pentode grid which causes this tube and the diode to conduct heavily. A negative 100-volt pulse is developed across a 250-ohm resistor connected between the mesh and backplate. This pulse causes the dielectric surface to swing negative and the spot beneath the beam is charged positively as has been discussed. If the bit is to be a plus, the beam is turned off before the end of the backplate pulse. If a zero is to be written, the beam is left on for two microseconds ("c" Fig. 4) after the end of the backplate pulse and the plus is erased. The time at which the beam is turned off is the only difference between plus and zero cycles.

## RESET OPERATION

The beam-on time in the zero cycle has been extended through intervals "b" and "c" to provide resetting. At the end of the interrogation interval ("a") a previous plus would have been erased and the bit returned to the normal zero potential. Hence the grid could be turned off at this time and a zero would be written. Such a cycle is called a non-reset zero.

Non-reset operation causes excessive interaction between neighboring bits. This interaction can be explained by considering the distribution of electrons in a beam. In a cathode-ray tube, the electron beam is considered to have a Gausian distribution of electrons along a cross section taken through the center of the beam. The mathematical expression for electron current density is: (3)

$$\rho = \rho_0 \epsilon^{-kr^2}$$

where $\rho_0$ is the density at the axis of the beam and r is the radial distance from the center of the beam. This expression is a bell shaped curve when plotted in linear coordinates.

The current flowing to a 0.010-inch diameter probe from the gun has been measured as a function of the distance between the beam and probe centers. Fig. 5 shows the results obtained. The ordinate scale is logarithmic and the abscissa is the square of the separation between beam and probe. A Gausian curve is a straight line in this coordinate system. The actual distribution of electrons in the beam is Gausian for several orders of magnitude and then appears to approach a constant value.

The nominal radius shown in the figure is taken as one-half the visible spot diameter when this gun is used in a tube having a fluorescent screen. The electrons to the right of the nominal radius are called fringe electrons. These electrons strike neighboring bits, and charge them in the same manner as the one beneath the beam but at a slower rate. This effect becomes of particular interest when repeated references consisting of non-reset cycles are made to a zero bit having one or more adjacent plus bits. During interval "b," with both the beam and backplate pulse on, the fringe electrons striking neighboring bits will reset them in the plus direction. Interval "c" is necessary to erase the plus that was written during "b" and leave the bit at the normal zero potential. Complete resetting is not possible but a substantial improvement can be obtained.

The value of resetting has been studied in equipment which determines the interaction between two adjacent spots. In this equipment, only two bits are stored on the target. A predetermined number of references may be made to one of the bits, and then the output signal of the second spot is examined to determine the change in signal magnitude caused by the references to the first spot. Both the number of references and the distance between the two spots may be varied. Fig. 6 shows the number of references to a zero bit which will reduce the plus signal of an adjacent bit to 50% of its original value as a function of the spacing between the two bits. Curves for both reset and non-reset operation are shown. They show that reset operation allows a considerable reduction in spacing at the higher references.

Reset operation requires a backplate pulse every cycle, but an even more important reason for having the backplate pulse periodic is to alleviate the amplifier recovery problem. The voltage developed across the diode during the backplate pulse is over 1000 times the signal output of the tube. This voltage is impressed on the amplifier input and blocks several stages. The time available for recovery is from the end of the backplate pulse of one cycle to the interrogate pulse of the next. This time is six microseconds. The amplifier interstage coupling capacitors are charged during the backplate pulse and their discharge is the main cause of amplifier blocking. Because the discharge time constant is much longer than the six microseconds available for recovery it is a difficult problem to obtain amplifier recovery in the time available. If the backplate pulse occurs every cycle, complete recovery is not necessary to give a constant plus signal output. Under this condition, the amplifier need recover only to the point where a usable signal output is obtained.

## AMPLIFIER CIRCUIT

In order to obtain sufficient amplifier recovery, several non-inverting amplifier stages are used to amplify the signal to a level of a few volts. A positive backplate pulse from an inverting type stage would cause the following grid to conduct. While the grid is conducting, it will have a low impedance and the coupling capacitor will charge rapidly through this impedance. The capacitor discharge will bias the grid negatively, blocking the stage. The negative bias will also increase the input impedance of the tube and cause the capacitor to discharge more slowly. The non-inverting stages have the advantage that the backplate pulse is always negative and the grid of the following stage is cut off instead of being driven into conduction.

The amplifier uses four cathode-coupled grounded-grid stages feeding into a pentode followed by a cathode follower. The amplifier schematic diagram is shown in Fig. 7. Each of the first three stages has a gain of seven. The fourth stage is modified by a regenerative feedback loop from the plate of the first tube to the grid of the second. This feedback doubles the gain of the stage. The output of the fourth stage is differentiated to reduce the duration of overshoots produced in previous interstage coupling networks and then inverted by the high gain pentode stage. The positive excursions produced by differentiating are clipped by the pentode grid. A cathode follower is provided to drive the output cable.

The amplifier output is shown in Fig. 8. This is a double exposure taken of the amplifier output displayed on an oscilloscope when the raster shown in the photograph is being stored. The backplate pulse is to the right of the signal. The upper signal occurs when a plus is stored at all 8192 locations in the raster and the lower signal is produced by a raster full of zeros.

## TEST EQUIPMENT

Storage capacity and reference number are the two major characteristics for a storage tube used in the memory of a digital computer. The number of references that may be made to a bit is a function of the distance between that bit and its nearest neighbors. Obviously, storage capacity is also a function of this distance. Consequently, it is possible to trade storage capacity for reference number in the design of a computer and the designer must know the relationship between reference number and spacing.

A tester has been designed which operates with rasters containing up to 8192 bits. With this equipment, the lowest reference number existing in the raster can be determined. Because the reference number varies over the target area, two-spot spill data do not give sufficient information to evaluate tube performance. The tester starts with a raster of either pluses or zeros, selects a bit, changes it to one of the opposite sign, reads it (with checking) a predetermined number of times and then rewrites the original binary state. All the bits in the raster are then checked to make sure that interaction has not caused one or more bits to change sign. The tester proceeds through the raster in this manner bit by bit and stops automatically if an error is made. After several passes have been made without errors, the raster is manually reset to one of the opposite sign and the process is repeated. In this way, the effects caused by pounding a zero on a field of pluses and those caused by pounding a plus on a field of zeros are checked. The level-discriminating circuit following the amplifier is set so that the same number of references is obtained in both directions and this number is used as an index of performance.

## EVALUATION

Reference number may be obtained for various spacings by adjusting the gain of the deflection amplifiers in the tester. Fig. 9

shows the test results of seven tubes produced in one lot. The reference number of three tubes, "A," "B" and "C" is plotted as a function of the spacing between bits and the reference number of four other tubes, "D," "E," "F" and "G," is shown with a spacing of 0.010-and 0.022-inch. The data indicate the amount of spread that may be expected between tubes.

The applications for a storage tube of this type may be divided into two classes with respect to the number of references required. A computer buffer storage application requires only a few references to a bit before neighboring locations are regenerated. The other application is in the working memory of a computer where a large number of references is required. In the latter application, as the storage capacity is increased, the time required to regenerate all the bits in the tube also increases. Consequently, the number of references required also increases directly with the storage capacity unless more time is allowed for regeneration.

The high-reference storage capacity of this tube may be evaluated by comparison with the IBM-85, which is used in the Williams-type memory system of the Type 701 Electronic Data Processing Machines. The IBM-85 stores 1024 bits spaced 0.052-inch with a reference number of 342. The target area of the new tube was made 25% less to keep the bulb diameter the same. If one stores three times as many bits on the new tube and the same time is allotted for regeneration, the spacing will be 0.023-inch and the required reference number will be about 1000 (i.e. 3 x 342). Fig. 9 shows that the worst tube has 2000 references at 0.023-inch spacing, which allows for a reasonable safety factor. Thus, in a high-reference application, the IBM-93 can store 3000 bits.

The curves showing the reference number variations with spacing may also be used to determine the storage capacity for low reference applications. With a smaller spacing, 10,000 bits may be stored on the target with a reference number of 100.

Consideration will now be given to an evaluation of the new tube with respect to some of the other factors which must be considered in applying cathode-ray tubes to the Williams system.

The IBM-93 requires the same deflection stability as a tube used in the Williams dot-dash system. At interrogation time the beam must be positioned on the storage location within about one-tenth of a beam diameter to prevent an appreciable reduction in stored signal. The stability required is independent of the number of bits stored and depends only on the beam diameter. This requirement is the same for the IBM-93 as for the IBM-85 since both tubes use the same gun and have the same beam diameter. Measurements on a 701 memory show a drift of the order of one-tenth of a beam diameter in an eight-hour day, which is entirely adequate.

Foreign materials on the target surface having a secondary emission coefficient, or a resistivity, less than the surrounding area, will cause spots which will not store the proper charge. This problem is quite similar to the blemish problem in cathode-ray tubes for Williams systems.

With the latter tubes, the problem has been solved by cleanliness in the preparation of the screen and in subsequent processing of the tube. Of a lot of 692 IBM-85 tubes made in the IBM plant, 92 percent of the tubes were completely free of bad spots.

Another factor which can limit capacity of a Williams system has been called "gentle rain." Gentle rain causes an interaction between bits which are too far apart to be attributed to secondary redistribution from the spot being bombarded. It may be caused by secondary electrons from some source other than the screen, or secondaries dislodged by fringe electrons of the primary beam.

This effect causes the reference number at large spacing to increase less as the spacing is increased than it does at small spacings. It limits the maximum number of references between regenerations irrespective of how these references are spread over the storage locations in the tube. Splash, on the other hand, limits the number of references which may be made to one bit before the adjacent storage locations are regenerated.

Gentle rain has been studied in the IBM-93 by referring to a section of the raster a number of times before regenerating the rest of the raster and then noting if any bits outside the splash range have been affected. In this case, the figure of merit used is the product of the number of references made to the section and the number of bits in the section. Tubes tested in this manner yield a product of 1,600,000 references without adverse effects from gentle rain. The significance of this result can be understood if one realizes that the tube is operating nearly a quarter of a minute without regeneration. Therefore, the storage capacity of the IBM-93 should not be limited by gentle rain.

A peculiar phenomenon called mudhole has been observed in the application of the Williams system. (4) Mudhole is apparently caused by an increase in phosphor conductivity produced by beam bombardment. This conductivity results in a loss of dot charge and a reduced signal when the dot is interrogated. A test for mudhole consists of writing a one-microsecond dot 1024 times with 12 microseconds between each writing pulse, waiting 20 milliseconds, and comparing the amplitude of the dot signal at the end of this time with a normal dot signal. The specification allows a 50 percent reduction in dot signal magnitude. The signal magnitude decreases with increasing references or wait time. In order to detect mudhole in the IBM-93, both the number of references and the wait time must be increased by a factor of 10 and, in addition, the beam current must also be increased by a factor of 5 over the normal operating current. Consequently the mudhole effect is not significant in the application of this tube.

The IBM-93 is the result of a program to develop a tube specifically for digital computer storage. The new tube can store 3000 bits in a high reference application and 10,000 bits in a buffer storage application without the adverse effects of gentle rain or mudhole. These improvements indicate that the cathode-ray tube is still a very attractive storage means.

D. R. Young of this laboratory did the initial development work on the project and it has been continued by a large group of people. Although it is not possible to mention all their names here, the author would like to acknowledge their contributions.

(1). A. W. Holt and W. W. Davis, Computer-Memory uses Conventional C-R Tubes, Electronics, p 178, December, 1953.

(2). W. E. Mutter, Improved Cathode-Ray Tube for Application in Williams Memory System, Electrical Engineering, p 352, April, 1952.

(3). H. Moss, The Electron Gun of the Cathode-Ray Tube - Part I, Journal Brit. IRE, p 10, January, 1945.

(4). J. C. Logue, A. E. Brennemann and A. C. Koelsch, Engineering Experience in the Design and Operation of a Large Scale Electrostatic Memory, Convention Record of the IRE VII p 21, 1953.

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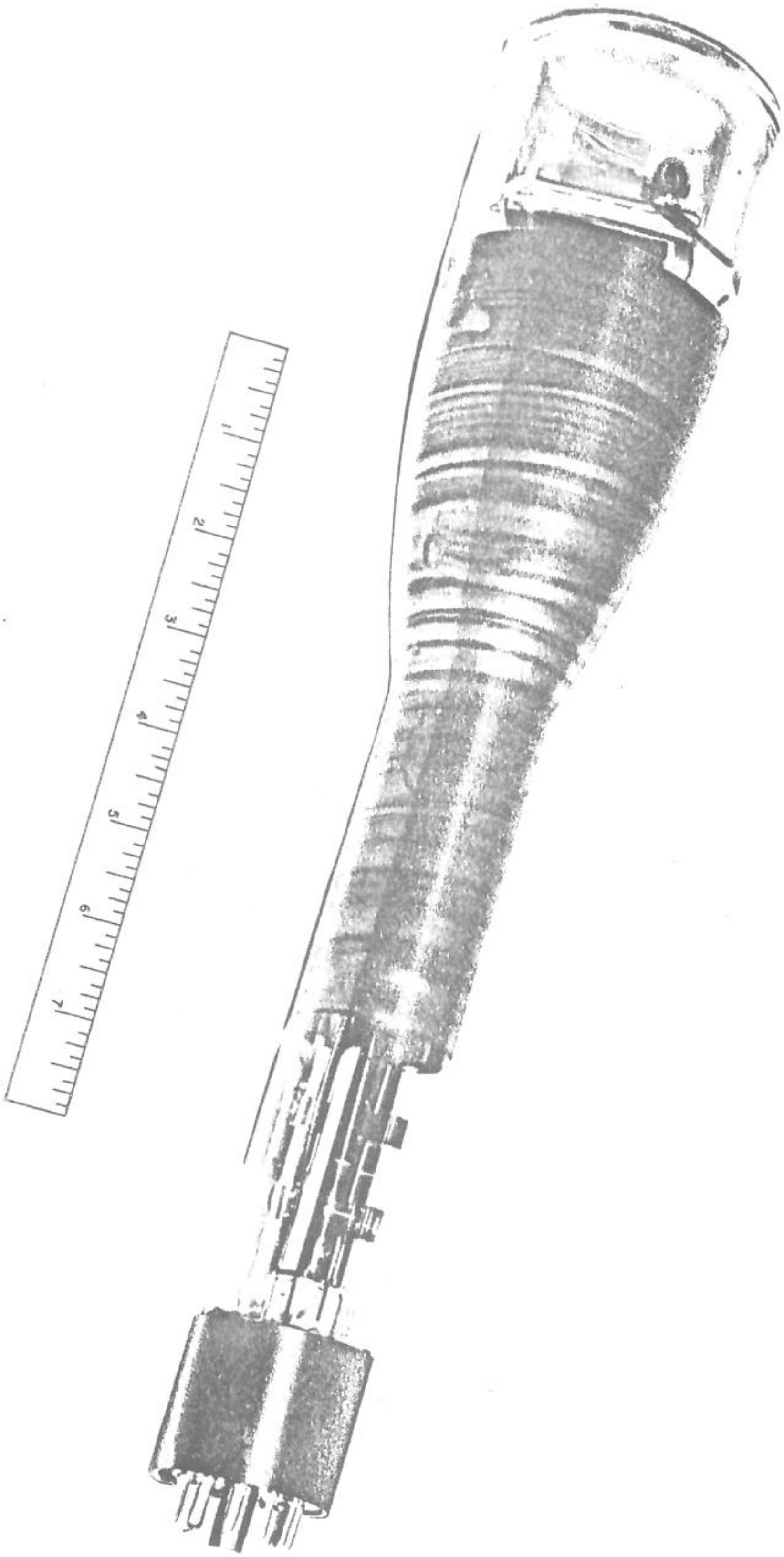
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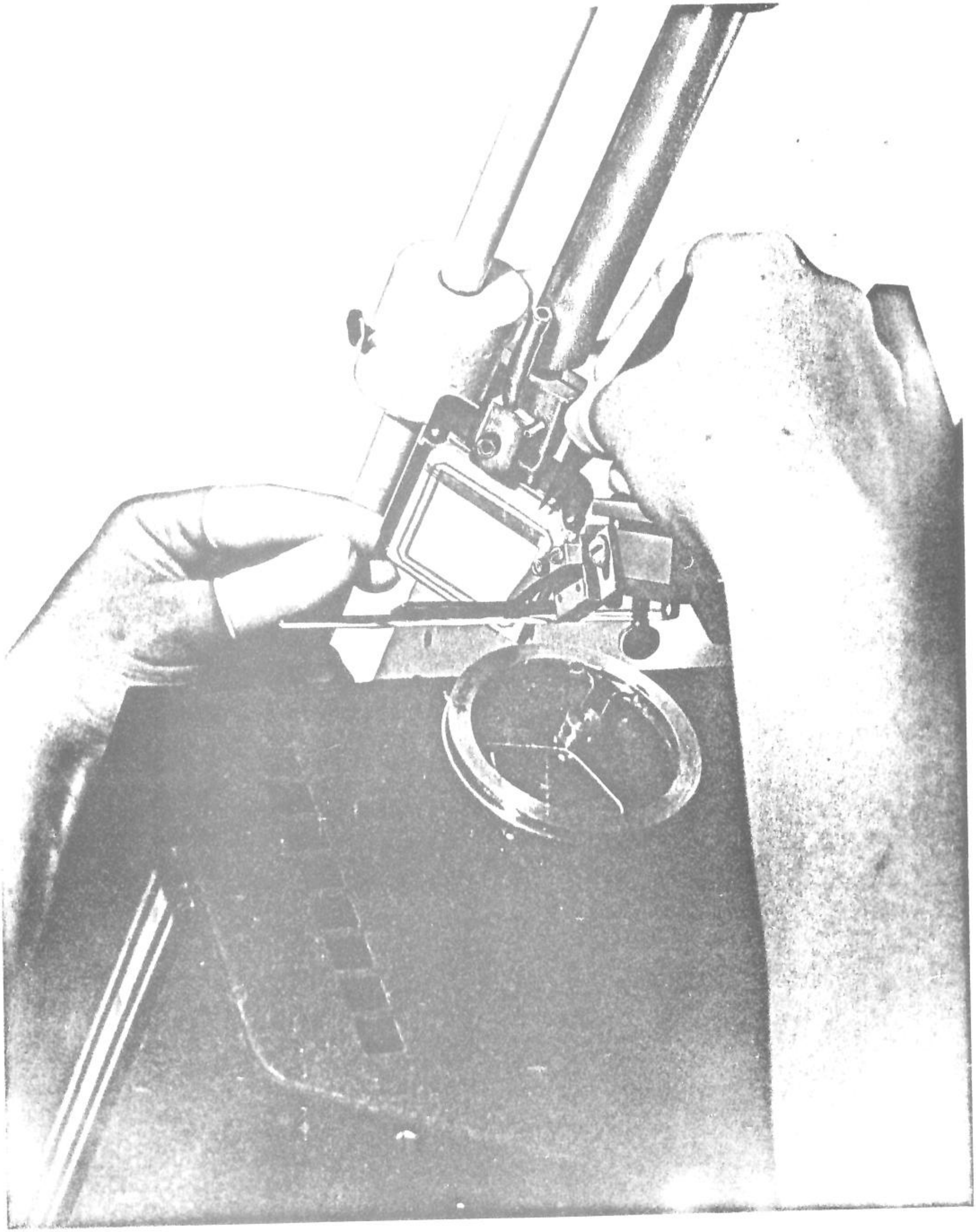
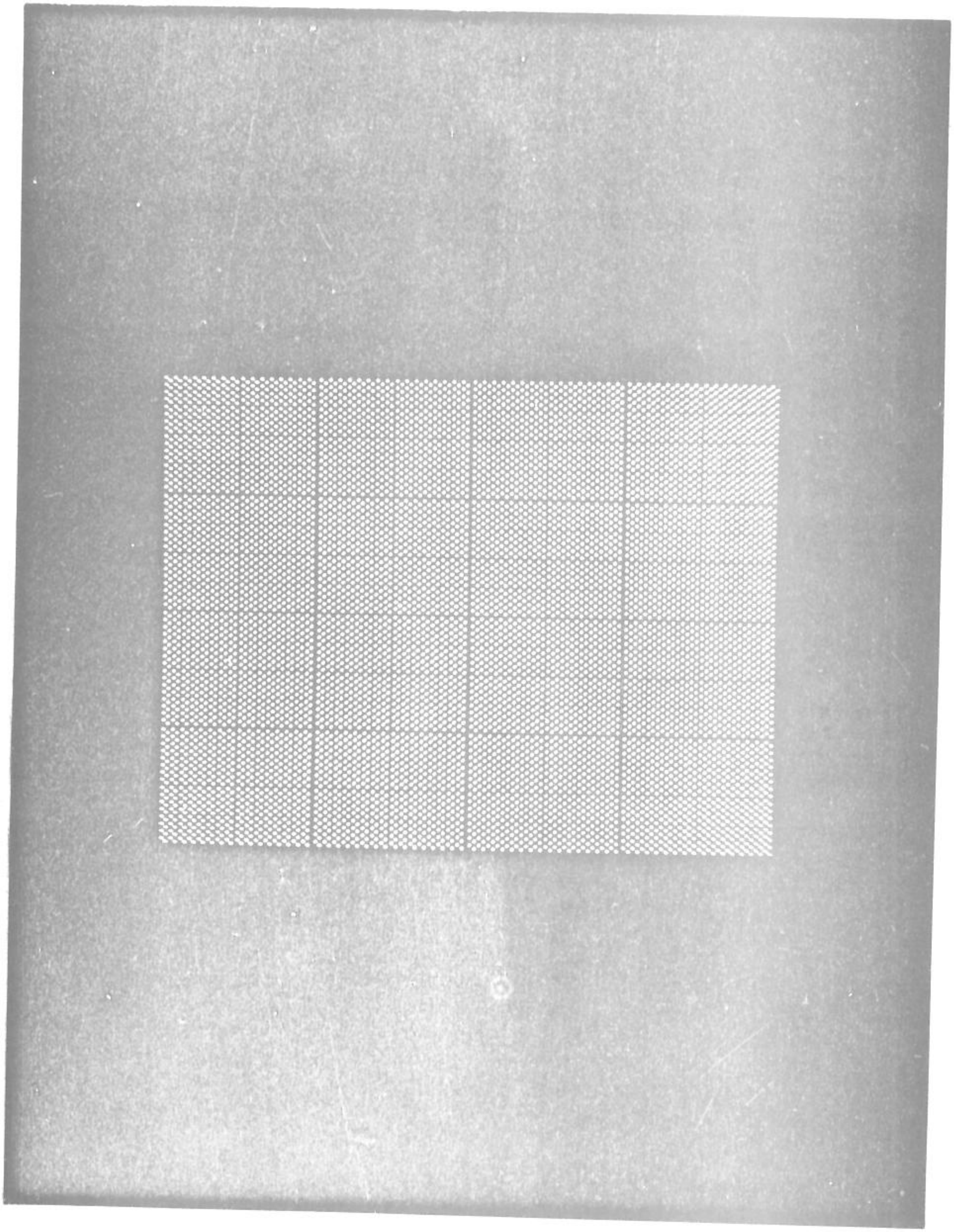
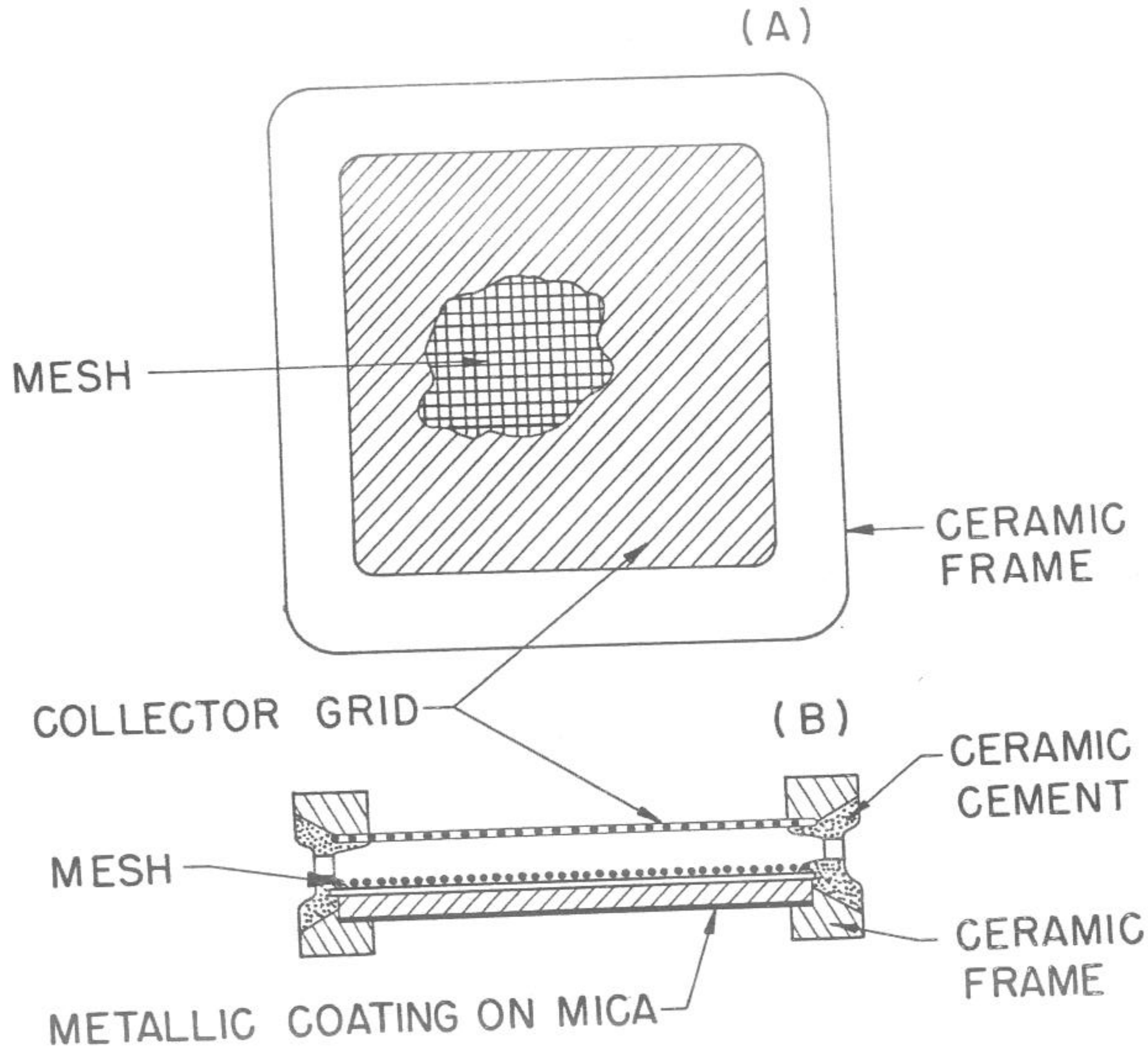






TARGET ELEMENTS AS SEEN FROM THE GUN SIDE WITH COLLECTOR GRID PARTIALLY CUT AWAY (A) AND CROSS SECTION OF THE TARGET (B)

FIGURE 1

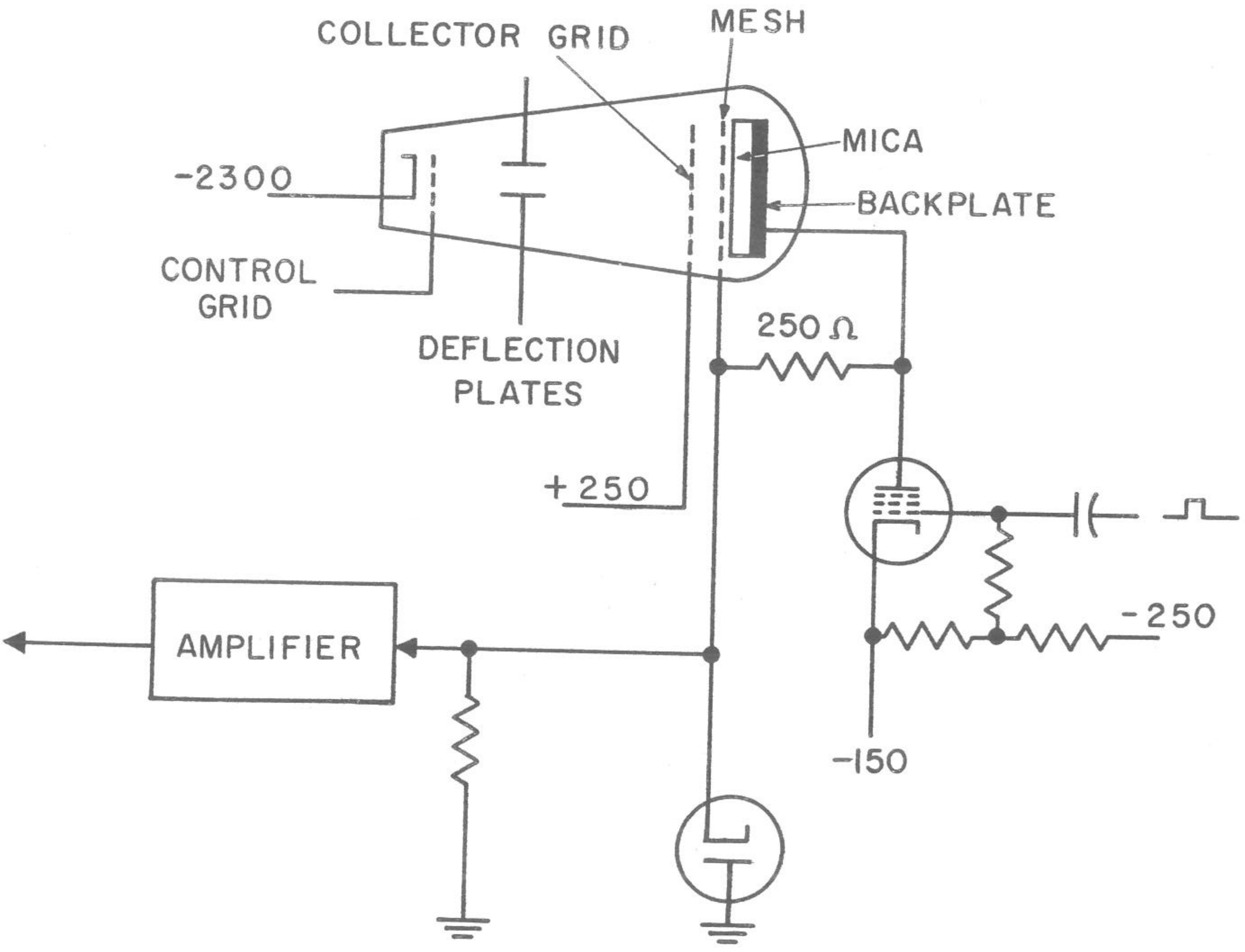


FIG. 2 OUTPUT CIRCUIT OF STORAGE TUBE

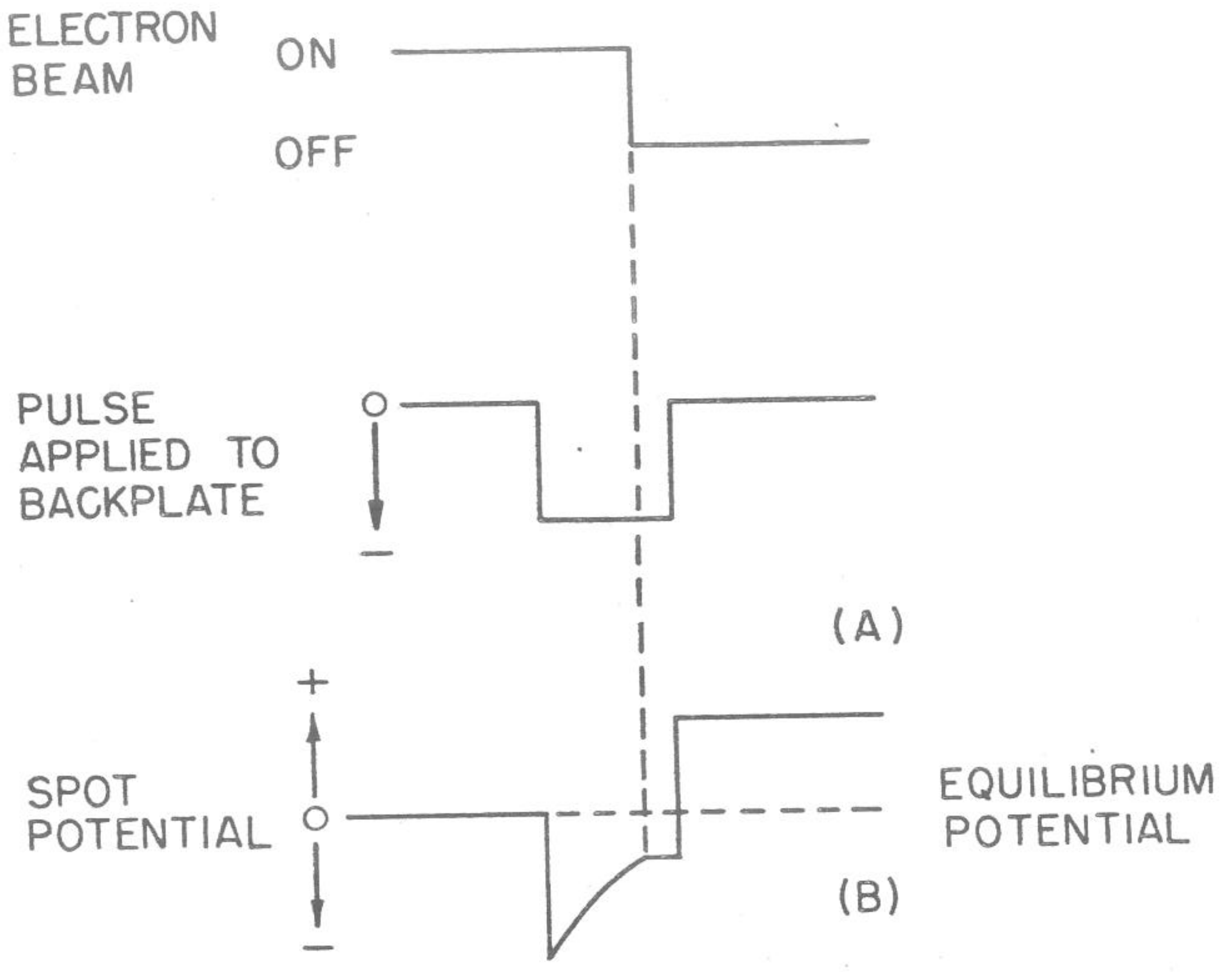


FIG. 3 WAVEFORMS FOR ESTABLISHING PLUS CHARGE (A) AND CHARGE IN POTENTIAL AT STORAGE LOCATION (B)

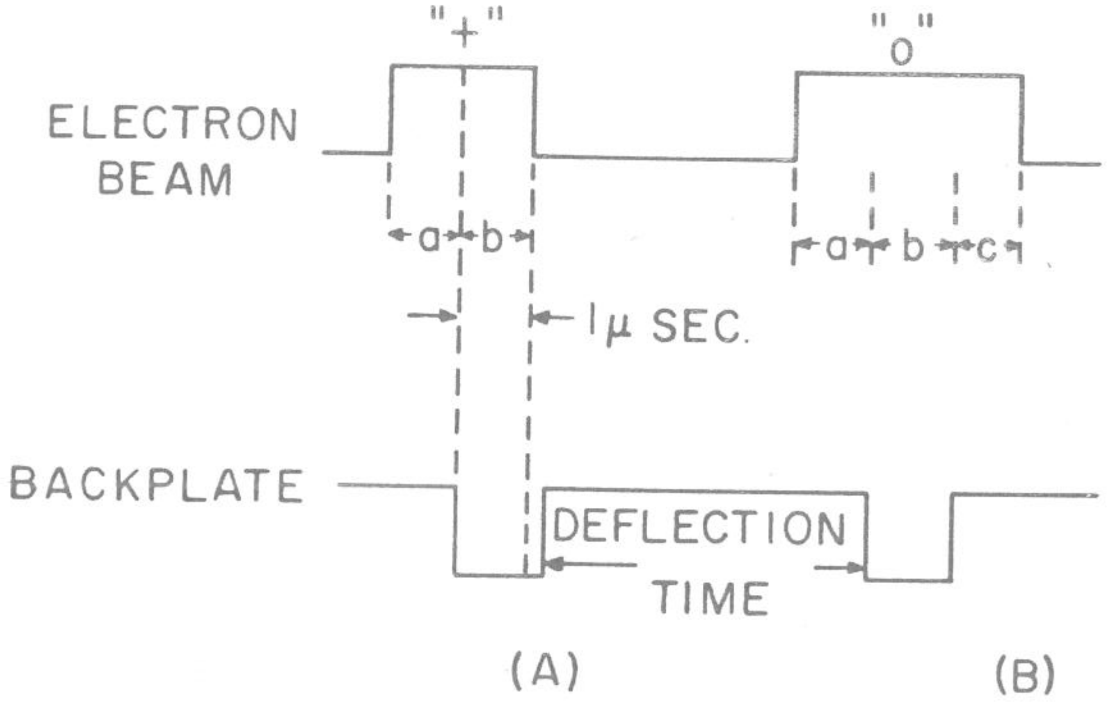


FIG. 4 TIMING OF ELECTRON GUN GRID AND BACKPLATE PULSES USED IN RECORDING AND WRITING A PLUS (A) AND A RESET ZERO (B)

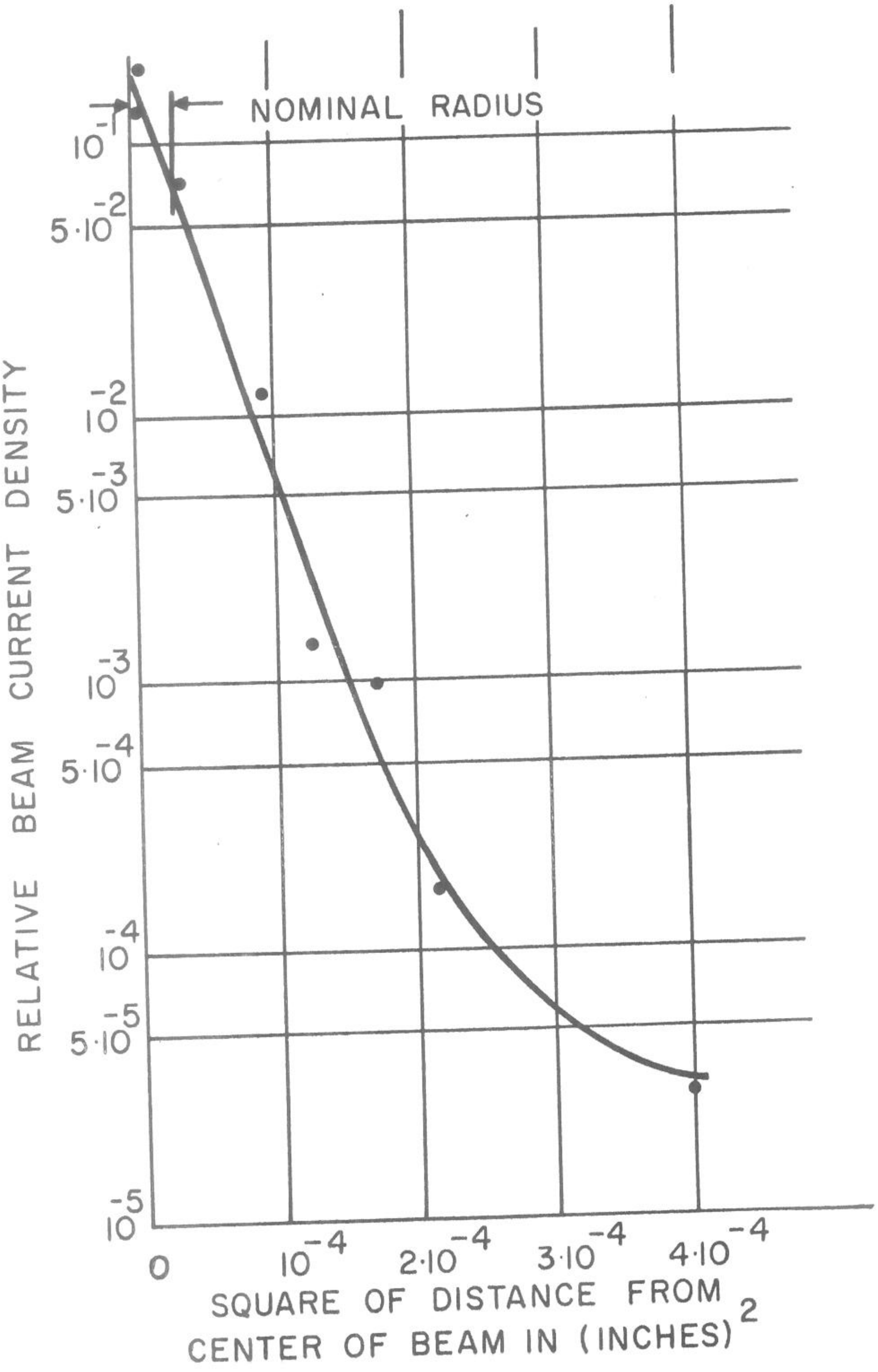
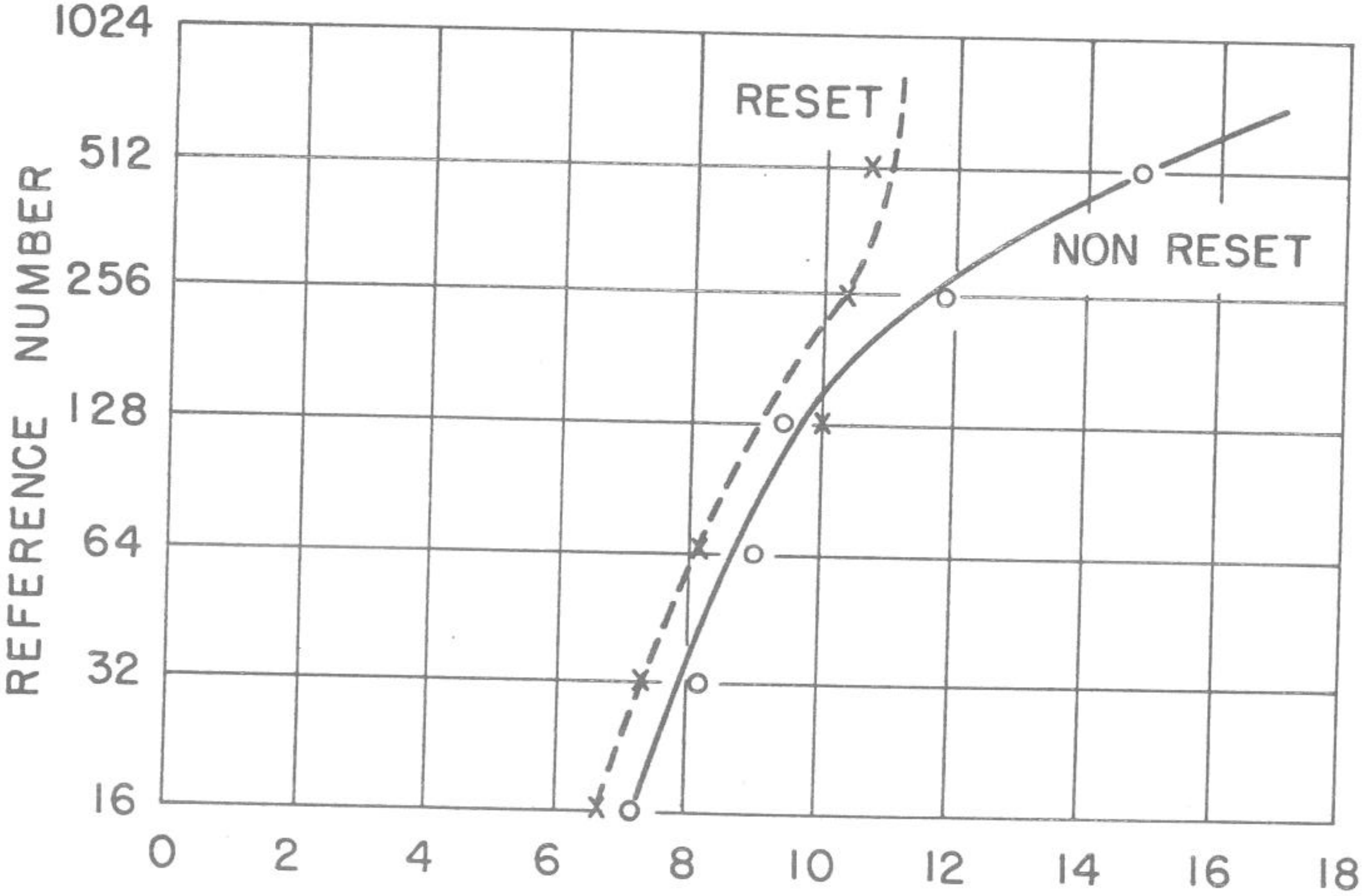


FIG. 5 TYPICAL DISTRIBUTION OF ELECTRONS IN A BEAM



TWO SPOT SPILL CURVES SHOWING IMPROVEMENT OBTAINED BY RESETTING

FIGURE 6

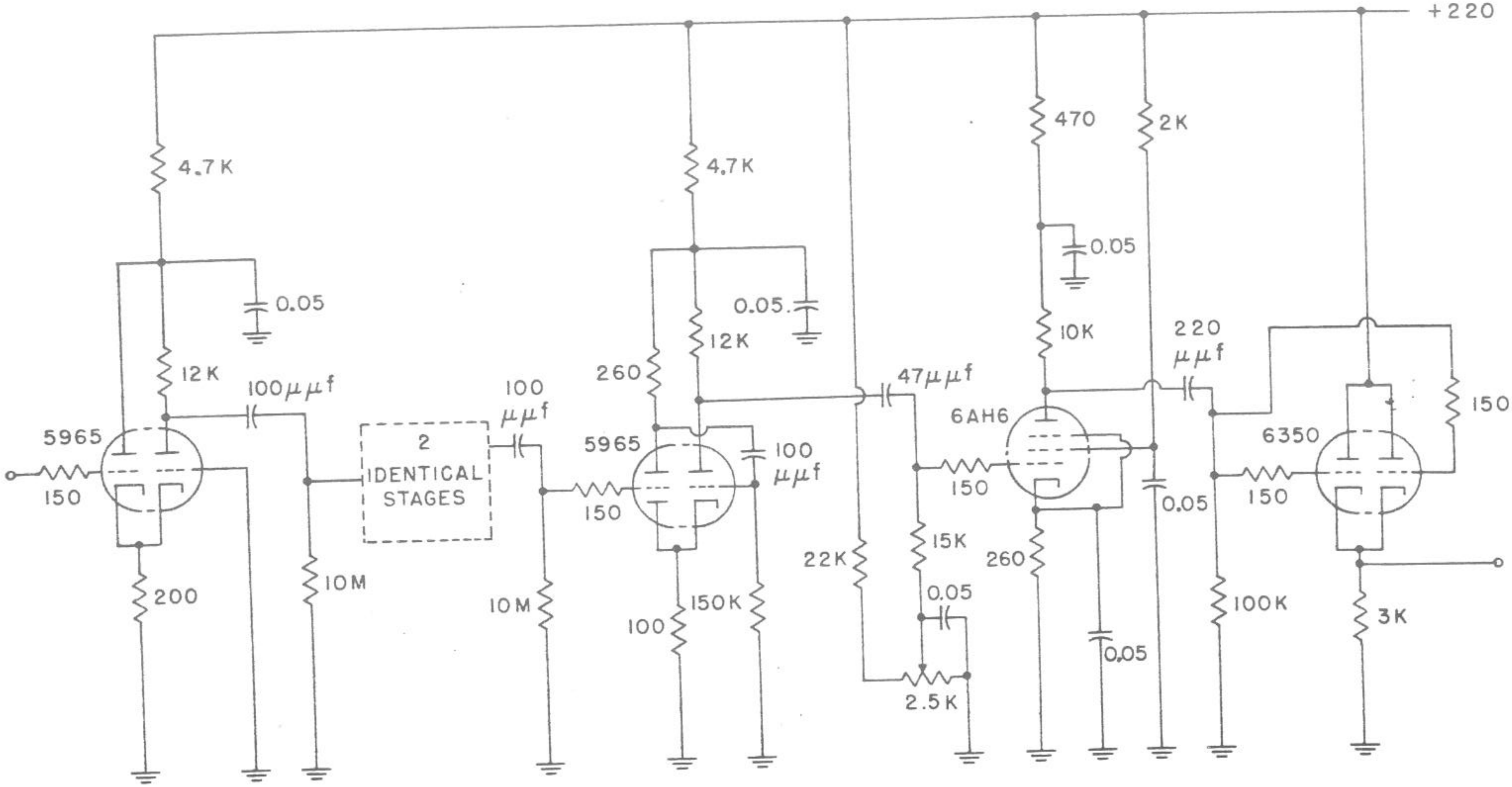
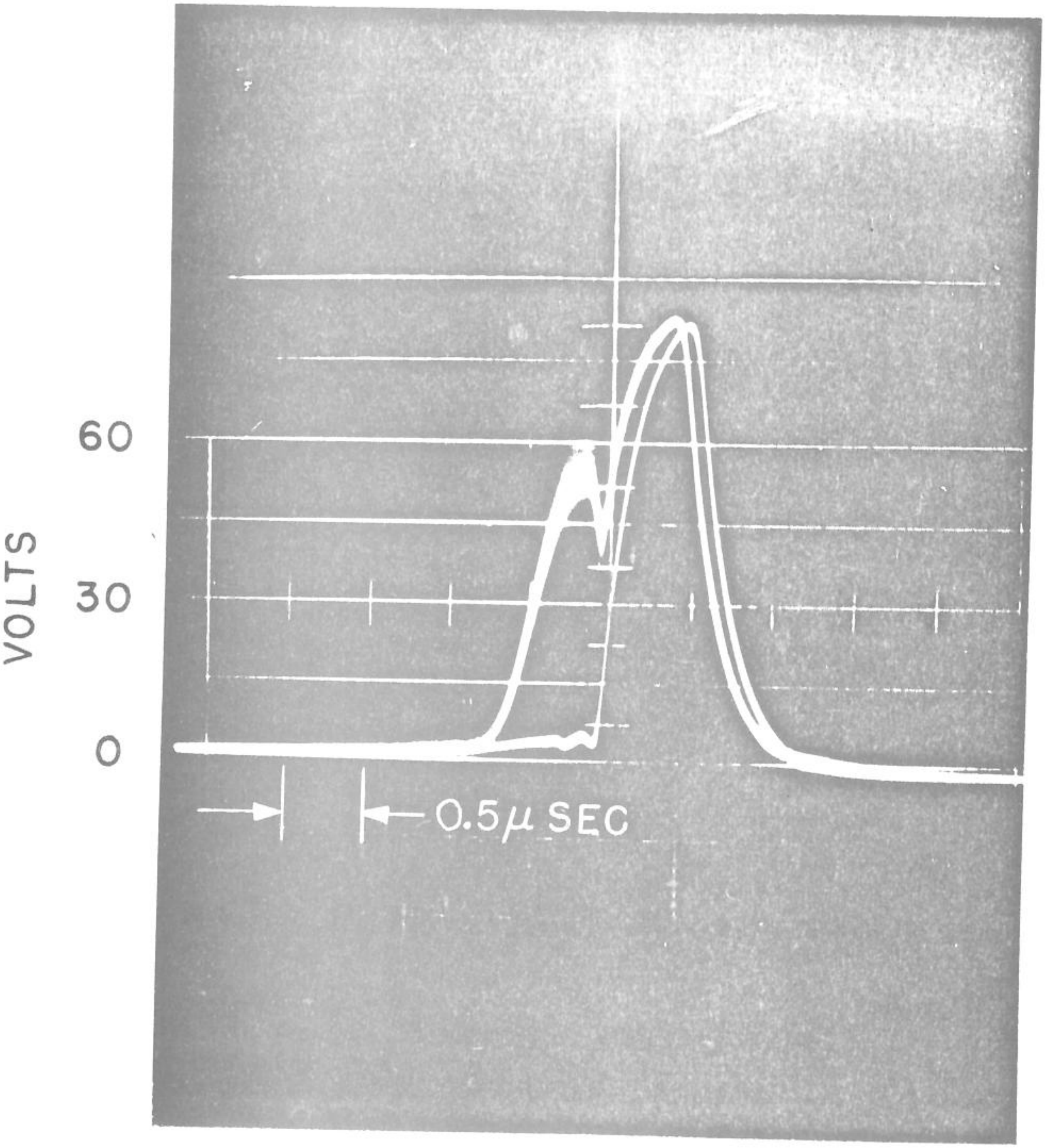
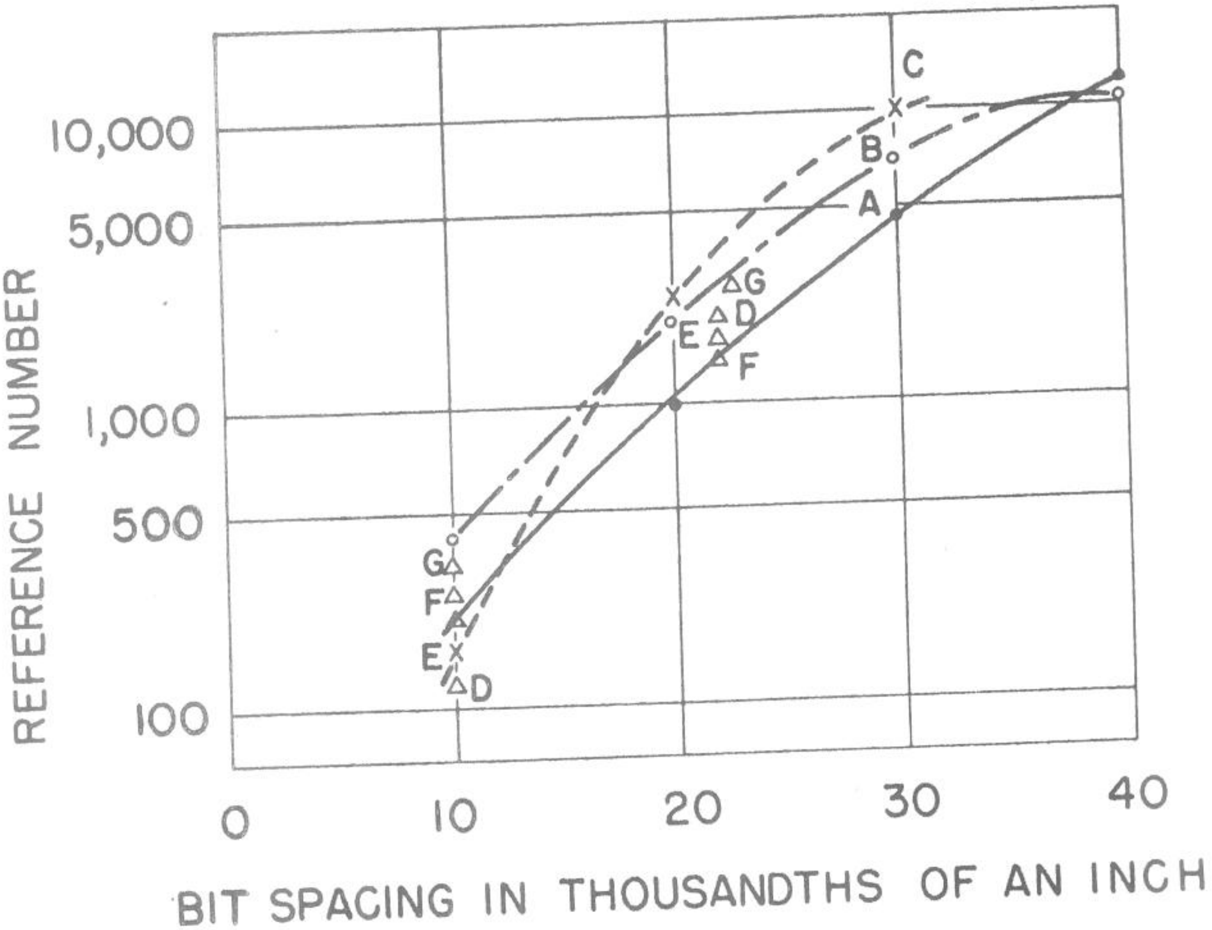


FIG. 7 SCHEMATIC OF SIGNAL AMPLIFIER USING ONLY ONE INVERTING STAGE



OUTPUT SIGNALS

FIGURE 8



REFERENCE NUMBER AS A FUNCTION OF SPACING FOR SEVERAL TUBES.

FIGURE 9