M.I.T. ELECTROSTATIC STORAGE TUBE

by

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Project Whirlwind, Sponsored by the
Office of Naval Research

American Institute of Electrical Engineers
North Eastern District Meeting
Providence, Rhode Island
April 27, 1950

Report R-183

CONTENTS

FOREWORD

This report by S. H. Dodd, H. Klemperer and P. Youtz is the combined material on the M.I.T. electrostatic storage tube which was presented by P. Youtz at the 1950 National Convention of the Institute of Radio Engineers and by S. H. Dodd at the 1950 North Eastern District Meeting of the American Institute of Electrical Engineers.

ABSTRACT

A beam-deflection electrostatic tube was developed to store binary-coded information at two stable potential levels, 100 volts apart, for digital computers or communications systems. A single 2000-volt electron beam writes or reads one of 400 binary digits on a four-inch target. A 100-volt electron flood replaces leakage and retains stored information indefinitely. The potential boundary stability on the storage surface is assured by a mosaic of conducting beryllium squares. Access time is 6 to 25 microseconds. Tubes are in pilot production for a digital computer. Future developments should increase access speed to 6 microseconds and reliable operating storage density to 1024 binary digits.

1. INTRODUCTION

The M.I.T. electrostatic storage tube has been developed by the Servomechanisms Laboratory at the Massachusetts Institute of Technology under the sponsorship of the Office of Naval Research.

The need for information storage methods exists in many fields. For example, electronic storage is found in a radar MTI system where storage of radar information at different times is compared and the differences in the stored information are indicative of moving radar targets. Electronic computors must have storage of data available under the direction of the computing system.

The M.I.T. storage tube was developed specifically as a reliable high-speed memory device for a parallel-type digital computer. However, the tube is well suited for high-speed reliable storage of any binary-coded information.

The memory device for these applications must have the following characteristics:

(1) Since each bit of information to be remembered has a binary representation the device is required to store just two possible values for each digit -- either a zero or a one. This requires two stable storage levels -- one representing a zero, the other representing a one.

(2) The device must be able to place a number in any of its storage positions quickly and without errors. This is called writing.

(3) The device must be able to remove any number from any storage position quickly and without errors. This is called reading.

(4) The device must hold the numbers in storage permanently without errors as long as power is supplied to the tube. This is called holding.

(5) Some applications have a fifth requirement. For instance the parallel-type computer requires that the memory device be operable in a parallel transmission system. For example, in the parallel transmission of a 16-digit number the 16 digits are transmitted simultaneously over 16 separate channels. In this parallel transmission system the 16 digits of a number are stored simultaneously, one digit in each of 16 separate storage tubes, with all 16 storage tubes having their positioning units connected in parallel.

Recapitulating, these memory devices must be able to write and read quickly, hold two stable storage levels reliably and operate in a parallel system.

2. CHARACTERISTICS OF THE TUBE

2.1 Physical Appearance and Description

Figure 1 shows the installation of storage tubes and their associated circuitry in the storage tube row of a digital computer. Two tubes are mounted on each rack inside of mu-metal boxes to shield them from stray magnetic fields. To the right you see both lids in one rack removed. In addition, the inner shield of one tube is removed to show the tube itself.

Figure 2 shows a picture of the tube itself. It is a special cathode-ray tube in which both zeros and ones are stored as charges on a dielectric surface located at this end. Two electron guns are mounted at the other end. One of these is used to read and write, the other to maintain the information. The electron guns were mounted in separate necks during the development work to keep their operations carefully isolated. This isolation of the guns aided our test program.

An exploded view of the three major components of the storage tube is shown in Figure 3. The three components shown in this figure are: a cut-away view of the storage assembly, the write and read gun, and the holding gun. The write-read gun is an ordinary cathode-ray gun which is electrostatically focused and deflected. The deflection plates position a 50-microampere beam to a desired spot on the surface. Then the beam is used to charge the spot to one of the two desired charge levels. The holding gun, which is a triode structure, provides the holding action in the tube and permits permanent storage of information.

The storage assembly can be seen better in Figure 4. This cut-away view of the 100-mesh wire collector screen and the 4-inch diameter dielectric plate shows the parts in their true relative sizes.

In Figure 5 a partial section of this storage assembly shows the location of the collector screen and the dielectric plate, which is spaced .015 of an inch below the collector. The storage surface consists of a mosaic of small squares of conducting material on the dielectric plate. A backing plate supports the dielectric and makes electric contact with the silver film on its back surface. Two mica spacers insulate and locate these components within a frame. Tungsten springs were used to insure adequate screen tension.

2.2 Performance

2.21 Speed and Capacity

Information in the form of negative or positive signals is stored on this surface and read out at any desired moment. The time during which such writing and reading out can be performed is called the access time. The access time includes positioning the read-write beam to the desired storage location, turning on the beam, picking up capacitively the readout signal from the signal plate, checking and rewriting the stored signal when necessary. At present the access time of the tubes, including all these operations, ranges from 6 to 20 microseconds. At present a tube stores between 400 and 1024 binary digits in the form of discrete positive or negative charges. The access time and density depend on the type of tube and the mode of operation. However, the relatively low number of stored points on the target invites an explanation. It is true that many thousands of points can be stored in the present tube, as has been seen when a static charge distribution on the storage surface is read out with a television scan. However, the density figure of 400 to 1024 points is for tubes operating dynamically in a parallel system and remembering the information for a day without an error.

2.22 Tube Life

Tube life tests have been made in special life racks under both dynamic and static conditions. These tests indicate that the cathodes of the electron guns are the limiting factor in the life of the tubes. It is possible to replace the guns when they are deteriorated and reprocess the tubes. By this method we should be able to extend the useful life to several thousand hours. Six tubes have already been life tested between 5 and 8 thousand hours with static patterns stored on them.

3. OPERATION

3.1 Introduction

Before the operation of the tube is discussed, let us examine a pictorial schematic of the components in Figure 6.

The storage assembly consists of the following:

1st element is a collector made of 100-mesh per inch wire screen. This collector is held .015 of an inch in front of the storage surface. It serves as the collector and as the voltage reference level for the secondary emitted electrons from the storage surface.

2nd element is the storage surface, which is a beryllium mosaic on mica. We are interested in a mosaic of conducting islands which are carefully insulated from each other and which have a high secondary emission yield. Further, these elements must be small enough so that the writing beam charges a number of them to write one spot. We have used 3 mosaic sizes -- 40, 60, and 100 squares per linear inch. The secondary emission properties of beryllium with a thin film of oxide make this material well suited for our application.

3rd element is the dielectric, which is a 4-inch diameter mica sheet -- .005 of an inch thick.

4th element is the signal plate, which is a film of silver on the back side of the mica plate.

These 4 components are held rigidly in an assembly which was illustrated in the two previous figures. It should be noted that the collector is always at ground potential. The signal plate is gated positive during two operations -- in writing minus and in one method of reading.

Writing is simply the storing of a 0 or 1 on the storage surface at the selected spot. The ones are stored at the level of the collector potential and the zeros are stored at the level of the holding-gun-cathode potential.

Reading is the examination of any selected spot and the production of a signal representing the 0 or 1 digit which is stored.

Holding is the replenishing or depleting of the stored electrons to maintain each spot at the original value which was stored. This is accomplished by flooding the storage surface with a uniform beam of low velocity electrons. Holding is required to control the leakage effects and the stray secondary electrons, and in some cases to renew the charge of the stored signal which was partially removed by reading.

Now let us examine the detailed operations of the tube.

3.2 Writing

In order to write on the storage surface, the high-velocity-gun deflection-plate voltages are established so that when the beam is turned on it will select the desired spot. The high velocity beam covers 10 to 25 mosaic squares and always charges them to the collector potential.

Writing positive is illustrated in Figure 7. In order to write a positive spot, the high velocity beam is simply turned on until it charges the spot to collector potential. If the area was at collector potential before writing positive, it stays at collector potential. If the area was at holding-gun-cathode potential before writing, it is charged to collector potential during writing. This is so because there will be more secondary electrons from the area than primaries to it, and the excess secondaries leaving the area will charge it positive until it reaches collector potential.

Writing negative is shown in Figure 8. When a negative spot is written, a positive gate of 100V is applied to the signal plate. This capacitively raises the level of the whole storage surface by almost 100V during the gate. The high velocity beam is turned on while the surface is still 100V above normal and brings the storage spot to collector potential. (The writing beam always charges an area to collector potential.) Thus the selected spot is established at ground regardless of its previous potential. The gate to the signal plate then terminates and this spot on the surface drops 100V below ground. All other spots on the surface drop back to the potentials they held before gating the signal plate.

Thus, if the high velocity beam is turned on without gating the signal plate, the selected spot is written at ground potential; if the high velocity beam is turned on while the signal plate is gated, the selected spot again is written at ground potential but then assumes holding-gun-cathode potential when the gate ends. This action is not dependent on the potential of the spot before the writing operation and therefore no erasure is required to store new information.

3.3 Reading

Let us now consider the method of reading. The writing operations produce an array of spots on the surface representing zeros and ones. The zeros are spots at ground potential; the ones are 100V below ground potential at the holding gun cathode.

During the reading operation the high velocity beam is deflected to the desired spot to be read and is used to discharge the spot. The change in charge during the reading operation is capacitively coupled to the signal plate, and the displacement current is detected as an output signal. One mode of reading detects only negative areas. In this operation, when a positive spot is read, no change in charge occurs at the spot since a positive spot is already at collector potential. However, when a negative spot which is at -100V is read, it charges up to collector potential, and this change in charge is detected as an output signal.

Another mode of reading detects both positive and negative areas. It requires gating the signal plate to a level intermediate between the two stable charge levels. A spot when read then charges or discharges to this intermediate level and produces a positive or negative output signal accordingly. This method is being used in the M.I.T. computer application.

In the computer operation the high velocity beam is radio-frequency intensity modulated at 10 megacycles during the reading so that a radio-frequency signal can be easily separated from the signal plate gate. The radio-frequency signal is then amplified and detected, giving video output pulses of both polarities, which are well-suited for checking purposes.

3.4 Holding

3.41 Introduction

Various factors can cause a change in charge of the stored areas. One of these is leakage. To minimize this, the best possible dielectric is used and kept very clean during all handling and processing.

There are three other factors which disturb the charge stored on the surface:

1. The secondary electrons from bombardment of other spots on the storage surface.

2. The secondary electrons from the primary electrons striking the collector grid.

3. The reading beam itself.

Therefore, we need to compensate for these disturbances and restore leaked charge. Regenerative holding is employed in some types of memory tubes. This was described by F. C. Williams in England. In these types, provision is made for rewriting every stored signal at frequent enough intervals so that the decay is not enough to destroy the identity of the stored signal. However, in the M.I.T. tube we use static holding. Once a digit is written, it will be held indefinitely without rewriting. This static holding has been described in the literature of a number of authors, particularly Rajchman and Haeff. Rajchman used it in a memory tube which does not use a deflection system. Haeff used it in a beam-deflection electrostatic picture storage tube. In the M.I.T. tube, the holding gun floods the storage surface with a spray of 100V electrons to maintain the stored signals at two stable potentials. The two stable potentials are the collector potential and the holding-gun-cathode potential.

3.42 Explanation of Holding Action

Figure 9 shows a typical secondary emission curve. When electrons from the holding gun strike the target surface, they release electrons from the target material which are emitted at low velocity toward the collector screen. The secondary emission curve is the ratio of secondary to primary current. It shows that incoming electrons at low velocities release few secondaries but the ratio soon increases to the point where more secondaries than primaries are emitted. Only the low velocity range is of interest in determining holding gun action.

Figure 15 shows how the electrons behave when an area on the storage surface is near the negative stability point. To show that actual stability exists, we will consider what happens when the surface is below and above the stability point. The figure on the left shows a surface below the holding gun cathode potential. The holding gun electrons arrive at the plane of the collector with 100 volts energy but will never reach the surface since it is more than 100 volts negative. Thus no holding current flows to the surface. Small leakage currents to surrounding positive electrodes cause the surface to charge positive.

On the other hand, the figure on the right shows a surface slightly above cathode potential. The holding-gun electrons strike the surface with a few volts velocity. The secondary emission is much less than 1 so there are more primary electrons arriving at the surface than there are secondaries leaving. The resulting accumulation of electrons charges the surface in a negative direction until it reaches holding-gun-cathode potential.

At holding-gun-cathode potential, only enough primary electrons strike the surface to supply the leakage current. Thus, we have shown that if the surface differs from the negative stability point by a few volts in either direction, a restoring current returns the surface to the stable potential.

Figure 16 shows how the electrons behave when an area on the storage surface is near the positive stability point. The positive stability point is at collector potential so the holding gun electrons strike the surface with approximately 100 volts velocity. Therefore the secondary emission ratio is about 2. The figure on the left shows a surface slightly below collector potential. The secondary electrons are attracted to the collector and the net loss of electrons charges the area in a positive direction toward the collector.

The figure on the right shows a surface above collector potential. It is true that the secondary emission ratio is about 2, but the positive surface attracts secondaries. Thus both primary and secondary electrons accumulate at the surface and charge it negative toward collector. A positive area is thus kept at collector potential and a disturbance of a few volts in either direction results in a restoring current.

The important points of the holding gun operation are:

(1) A stable negative spot cannot move positive because low energy holding electrons accumulate and few secondaries exist.

(2) A stable positive spot stays positive because the excess of secondary electrons over primaries charges the surface positive to collector.

3.5 Mosaic Improves Stability

The mosaic improves the stability of the stored patterns by making more effective the action of the holding gun. These conducting islands of beryllium on mica provide definite boundaries for the charged areas and prevent them from creeping. The holding-beam current, falling uniformly over a conducting mosaic element, is able to counteract leakage from the edges of one island to a neighboring island. Therefore, larger mosaic islands give larger stabilizing current and higher storage stability. However, the mosaic size must be small enough so that the surface is essentially continuous with respect to the definition of the writing and reading gun. Then the deflection system need only be constructed to aim the beam during reading at the written spot rather than at a previously determined physical area. Therefore, the mosaic size is compromised to get high stability and high density of spot storage. These beryllium mosaics are prepared in very high vacuum by sublimation through a wire mesh mask held tightly against the mica. This masking screen is not used in a storage tube. The surface is removed and put into a clean assembly.

4. AVAILABLE M.I.T. TUBES

At present these tubes are in laboratory pilot production, and a sufficient stock has been accumulated and tested for initial digital computer installation. Figure 11 shows our present stock of tubes. We also keep on the shelf a stock of mosaics under vacuum for the storage tubes. Any application which requires high-speed and reliable storage of binary coded information for either parallel or serial transmission would find the M.I.T. tube useful.

5. TESTING METHODS

We have now covered the characteristics and operation of the storage tube. Figure 10 shows the block diagram of a test station designed to give a visual display of target potential distribution in a storage tube.

The sweep generator provides a television-type scan for both a monitor tube and the write-read gun of the storage tube. The beams in both tubes are deflected simultaneously.

A radio-frequency signal generator intensity-modulates a weak reading beam at 10 megacycles. The holding gun restores the charge lost during reading. The output signal, after amplification and phase detection, is used to intensity modulate the monitor tube. Thus negatively stored areas give a strong readout signal resulting in a bright area on the monitor tube while positively stored areas result in dark areas on the monitor tube.

If we reduce the accelerating voltage of the holding electrons below a critical value, the whole surface can be forced to the negative potential, thus giving a uniform area on which to store spots.

An array of positive spots can be stored in the storage tube by the following steps:

(1) The removal of the television scan from the deflection plates.

(2) Deflection of the beam to the desired spot on which the writing operation is to take place

(3) Writing a positive spot

(4) Repeat for each spot

After these operations are completed and the television scan reapplied, the readout circuit will again show a picture of the storage tube with a 20 x 20 array of positive spots stored on the surface. Of course, in normal computer operation all the spots will not necessarily be positive; we will probably have some random combination of positive and negative spots on the surface.

We have just discussed a test method which gives a static display of the storage surface charge distribution. Figure 12 shows a special test setup which has been built for testing the tubes dynamically. This installation provides facilities for operation of one to five storage tubes under conditions simulating as closely as possible, those which are encountered in a high-speed computer.

Figure 13 shows a block diagram of the dynamic tester. The usual mode of operation of the dynamic tester is cycling. This consists of counting through an array of spots and storing each piece of information in the next adjacent spot. Thus, inserted information is continuously cycled through the storage tube. In this test setup, the deflection circuits position the beam to one of 400 spots until a count pulse causes a deflection to the next spot. Temporary storage units 1 and 2 are circuits capable of storage of one piece of binary information..

Let us now consider the steps necessary for cycling. First the radio-frequency pulser drives the write-read gun, which gives a pulse of 10 mc modulated current. The resulting readout signal is stored in temporary storage #1 and also pulses the monitor tube.

The second operation senses the information in temporary storage #2 and thus decides whether to apply a gate to the signal plate for writing a negative spot. At the same time the write-read gun is gated on for the writing operation.

The third step transfers the information from temporary storage #1 to temporary storage #2 so that it will be available for writing in the next spot.

Fourth, the deflection generator is made to count to the next spot.

The sequence of operation is then repeated. Thus each sequence reads out from a spot, writes the information from the previous spot and then continues on to the next spot.

When the deflection generator has counted through a complete array, each piece of information has been advanced one position. The deflection generator then continues to count through the array again.

Information read out of the last spot on the tube is rewritten on the first spot so that instead of cycling off the end of the tube, the pattern is seen to continue to cycle inside of the tube. Normal operation of the dynamic tester cycles the spots with an interval of 40 microseconds between each count of the deflection generator.

A difficult test is to store and cycle a checkerboard array of spots. This is an array in which alternate spots are positive and negative. This means that as each spot is read out, the information to be written in its place must be of the opposite polarity, and therefore requires constant changing of the potential of the storage spots.

It is, however, more difficult to determine when a mistake is made when a checkerboard pattern is being cycled at high speeds. The dynamic tester has therefore been equipped with a sensing circuit which automatically stops the cycling whenever a single mistake is made.

6. APPLICATION IN COMMUNICATION

The field of communication is finding that a limit to the number of channels for both wire and wireless information is being approached. More efficient use of present transmission facilities could be made by a bandwidth reduction or by reducing the required time of data transmission.

A generalized memory system consisting of two M.I.T. storage tubes has been set up under the direction of Prof. Wiesner of M.I.T. to experiment with this communication application. One storage tube, with its associated deflection system, can accept incoming binary-coded information at a random time and will store this information until a complete array of information is available. Then the information in the storage tube can be rapidly read out and transmitted to a receiver while the second storage tube, with its associated circuits, takes over the role of receiving the incoming information. The system thus accepts information at a random time while giving an output in concentrated bursts.

This memory system was designed and constructed by Prof. Wiesner's group. Operation has been shown to be adequate by reading out all the information in one tube and storing this information in the second tube. The information from the second tube is then retransmitted to the first tube. This cycling of the information between tubes has been done at high speeds for periods of several hours without mistakes.

The capabilities of the storage tube just described are adequate for many other applications which can use binary-coded information.

7. FUTURE RESEARCH AND DEVELOPMENTS

A more compact design has been made as indicated in Figure 11. In this model both guns are mounted in one neck. This will be simplified further for production. Future improvements on this tube are expected to result in decreasing access time to 6 microseconds and increasing storage density for reliable operating storage to 1024 binary digits.

DRAWING LIST

Figure #	Title
1 (F959)	Storage Installation
2 (F916)	Storage Tube
3 (F918)	Major Storage Tube Components
4 (F919)	Storage Assembly
5 (F969)	Storage Assembly Section
6 (F968) (B-35535)	Storage Tube Schematic
7 (F978) (A-35392)	Write +
8 (F977) (A-35393)	Write -
9 (A-35613)	Typical Secondary Emission Curve
10 (B-35376)	Television Test Method
11 (F958)	Storage Tube Inventory
12 (F871)	Dynamic Tester
13 (B-35594)	Block Diagram - Dynamic Tester
14 (F924)	New Design of Storage Tube
15 (F1011) (A-35635)	Holding Gun Operation Near Negative Stability
16 (F1012) (A-35635)	Holding Gun Operation Near Positive Stability

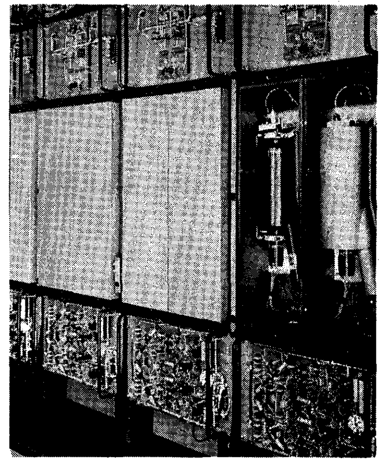

Fig. 1. Storage installation

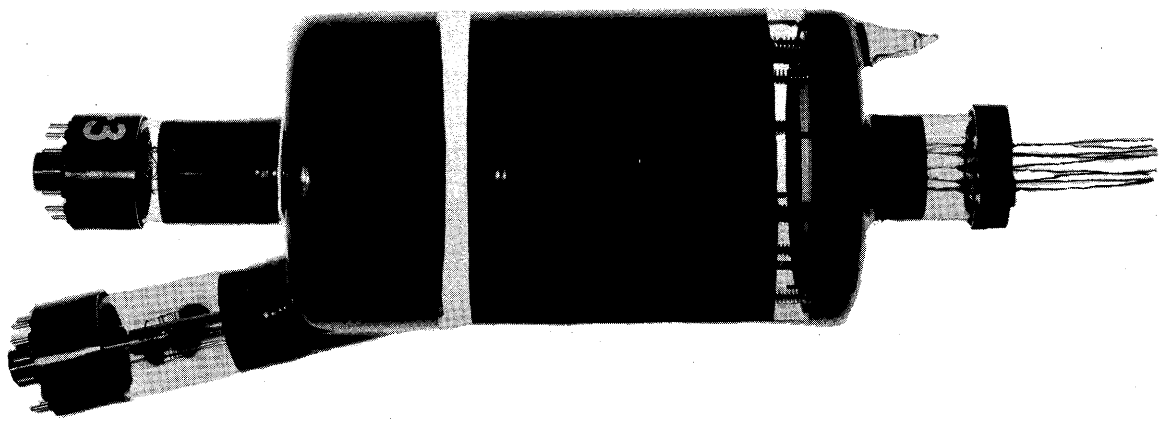

Fig. 2. Storage tube

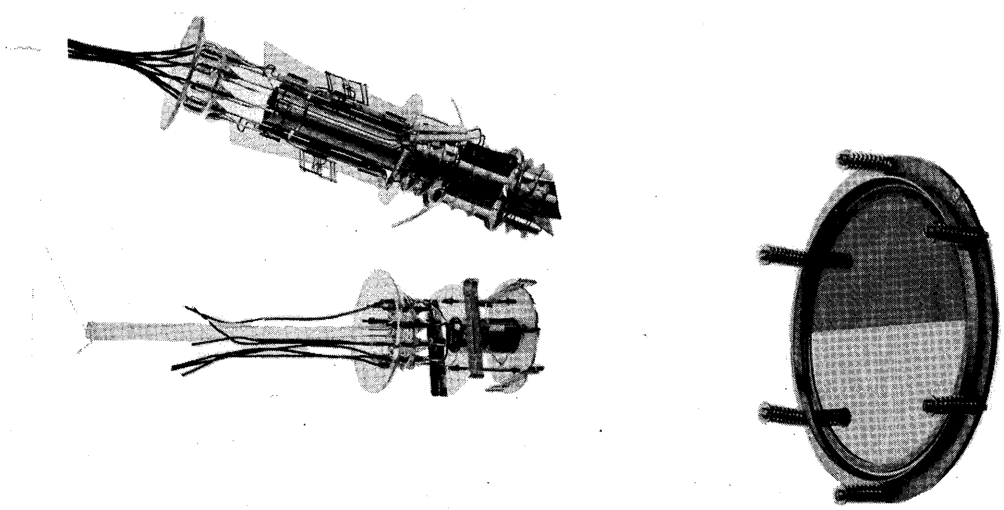

Fig. 3. Major storage tube components

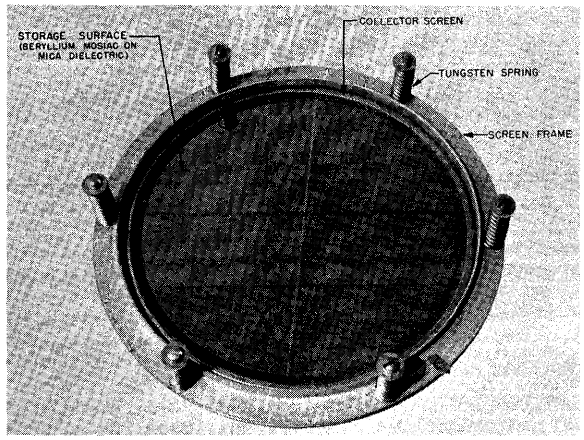

Fig. 4. Storage assembly

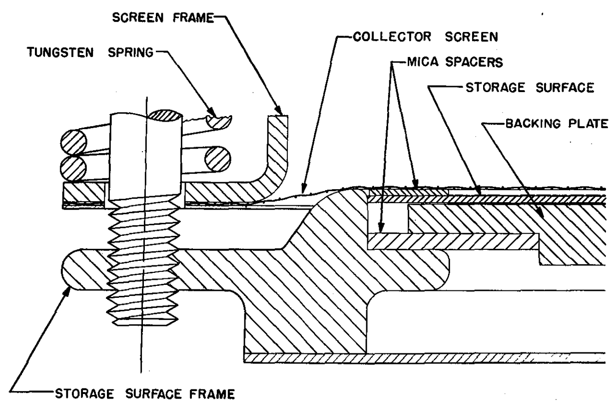

Fig. 5. Storage assembly section

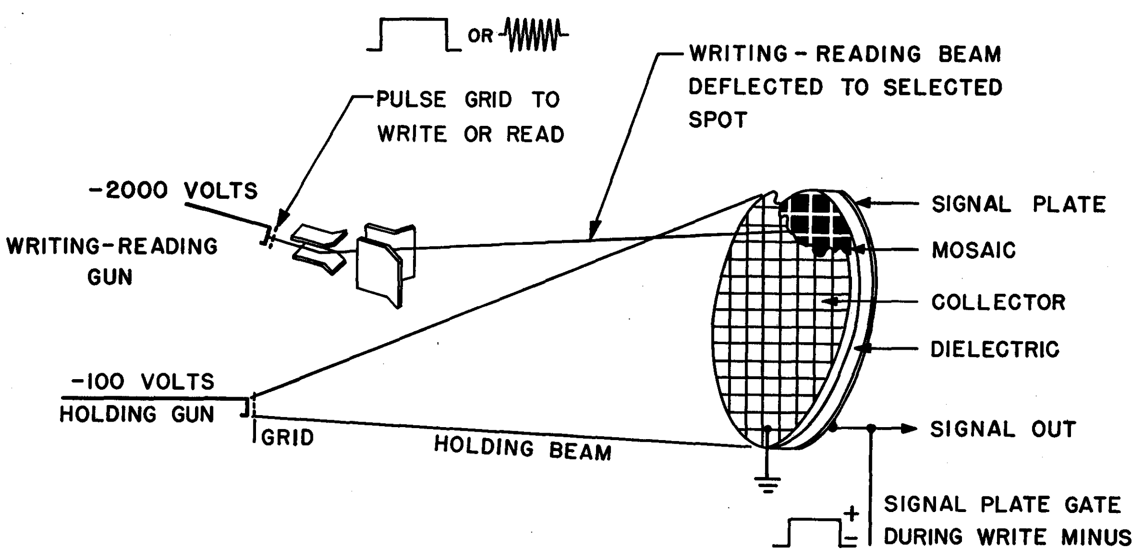

Fig. 6. Storage tube schematic

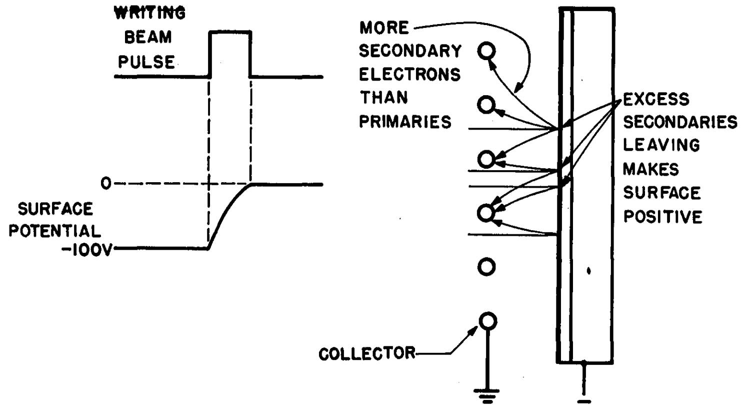

Fig. 7. Write +

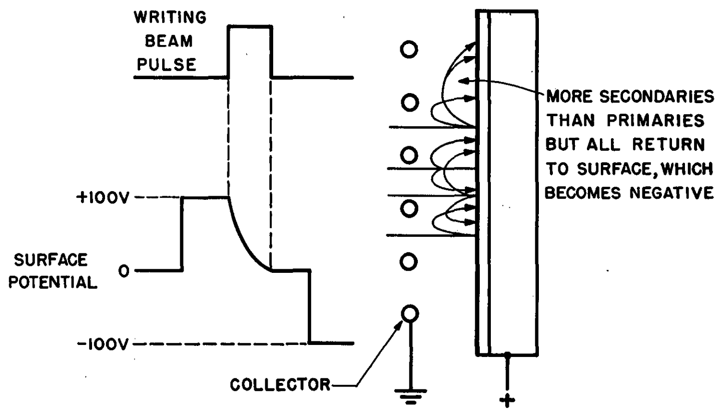

Fig. 8. Write -

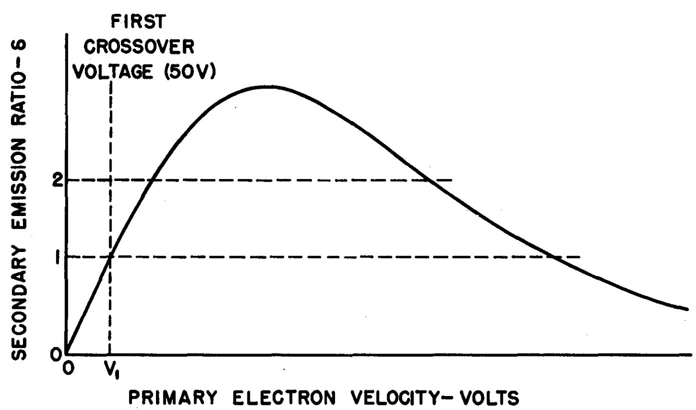

Fig. 9. Typical secondary emission curve

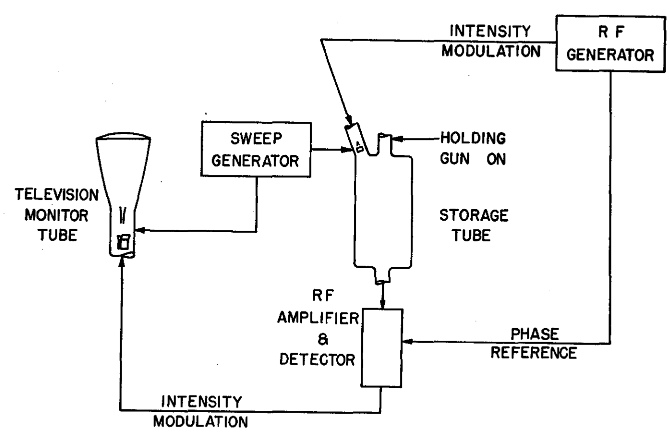

Fig. 10. Television test method

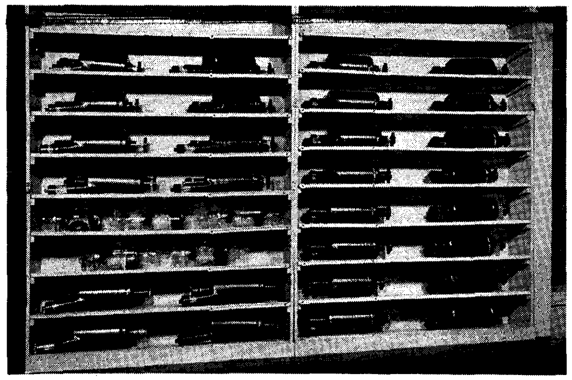

Fig. 11. Storage tube inventory

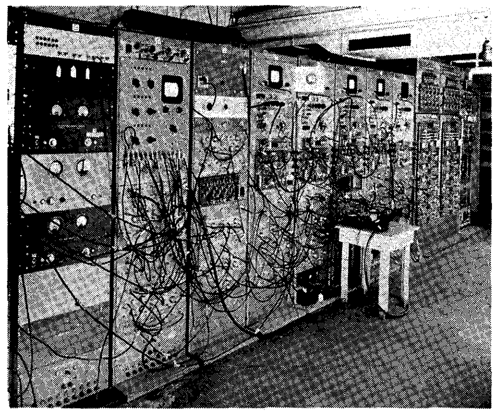

Fig. 12. Dynamic tester

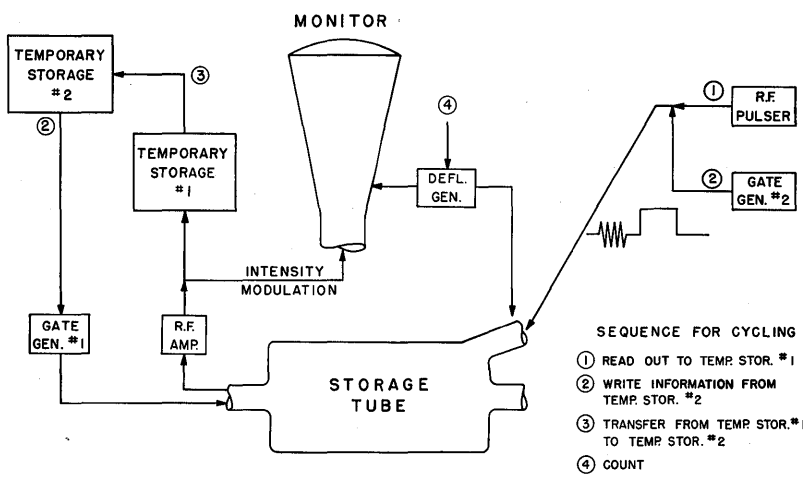

Fig. 13. Block diagram of dynamic tester

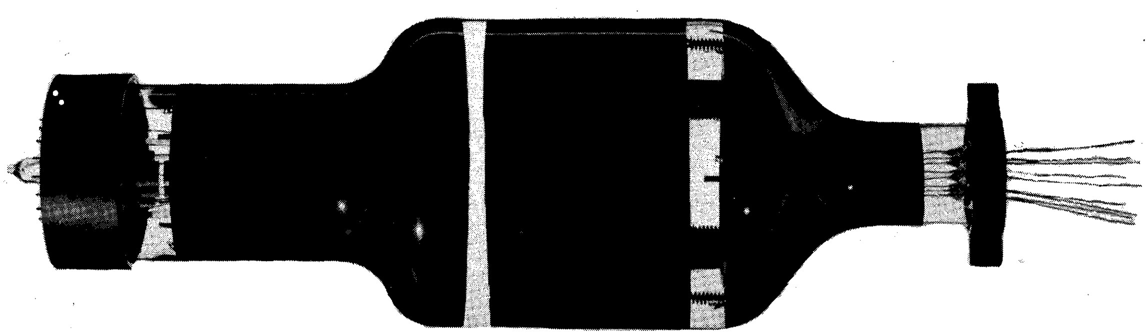

Fig. 14. New design of storage tube

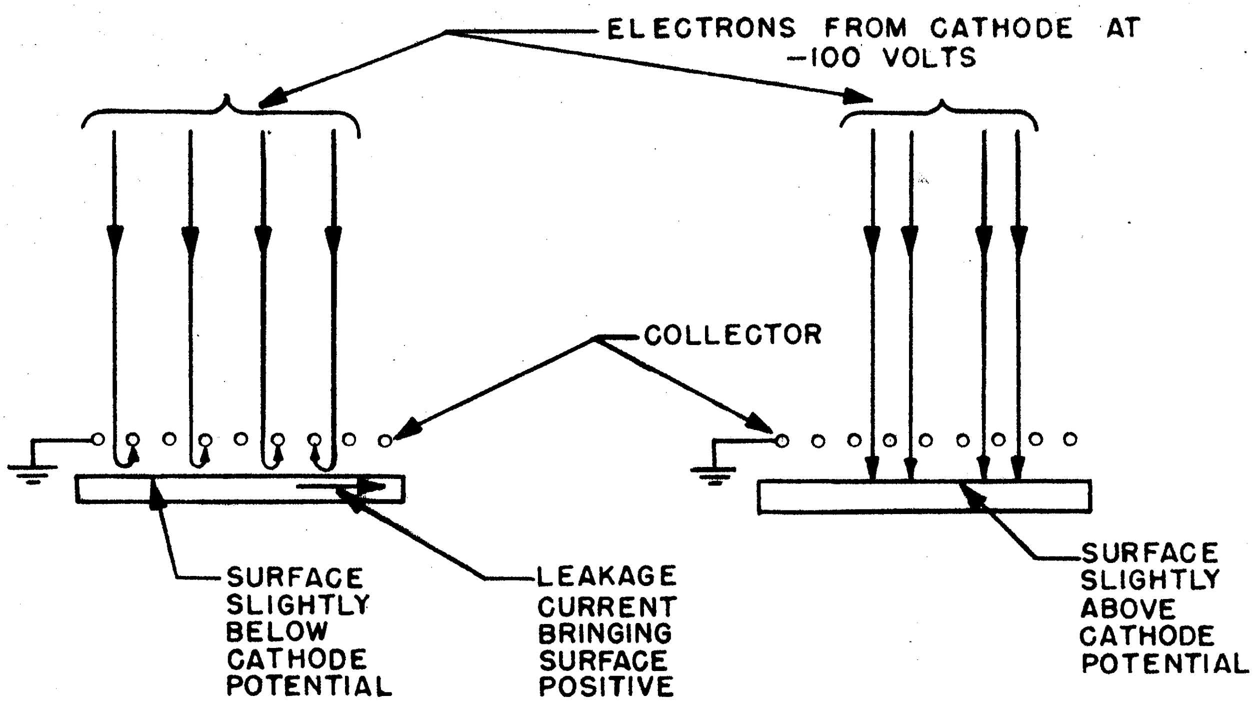

FIG. 15
HOLDING GUN OPERATION
NEAR NEGATIVE STABILITY

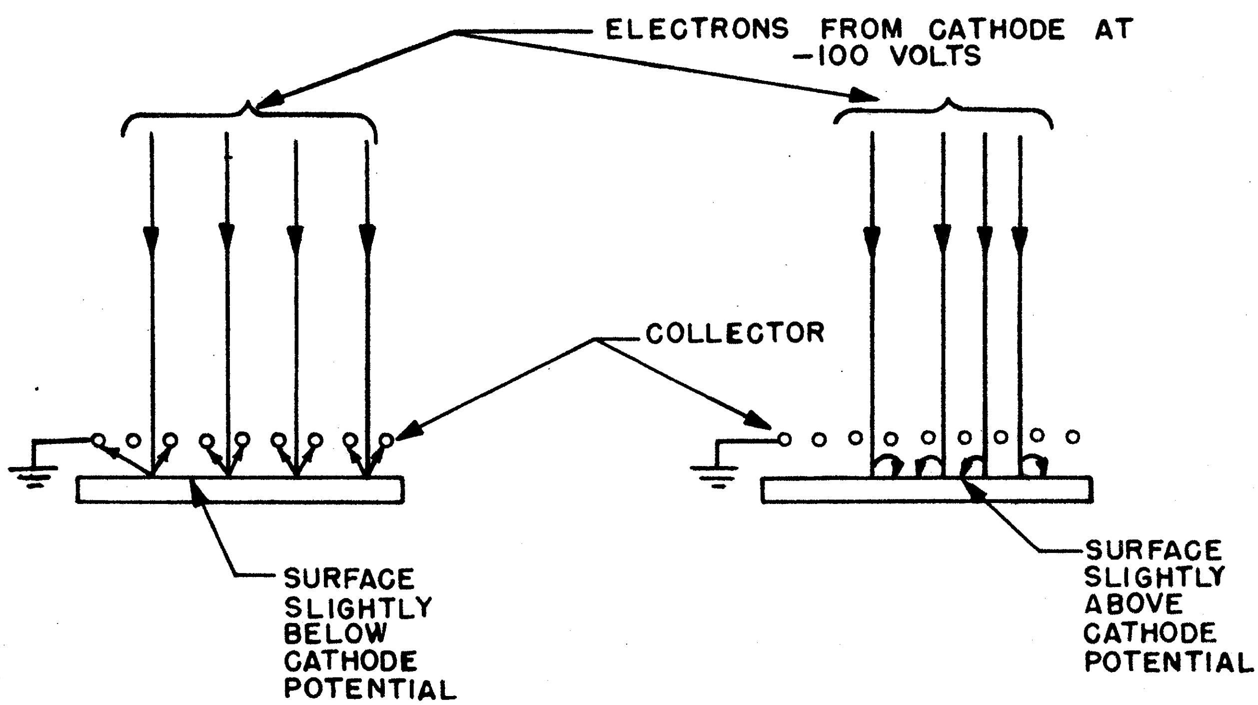

FIG. 16
HOLDING GUN OPERATION
NEAR POSITIVE STABILITY

A-35635