THE SELECTIVE ELECTROSTATIC STORAGE TUBE*

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Summary—*This paper describes an electrostatic storage tube developed for high speed registry and read-out of digital information consisting of bivalued signals. It has storage capacity for 256 signals.*

The selection of the internal address of the stored signals is by means of a fixed matrix formed by two orthogonal sets of spaced parallel bars. A uniform, electron emission, available in all windows of the matrix, is suppressed everywhere except in a particular window, by applying appropriate control voltages to the bars. A novel system of connections between the bars allows control of many windows by relatively few external leads. Bivalued address signals are applied to these leads. This does not require circuits having an accurate amplitude response.

The storage is obtained by the two stable potentials which tiny floating metallic elements, located in register with the windows, assume under continuous electron bombardment. The signal to be stored is applied by capacitive coupling to all elements and brings the selected one to the desired stable potential. The reading signals are sizeable electron currents passing through a hole in the storing elements under the control of the element's potential. A visual display of the stored information is obtained also.

The tube has many ideal characteristics: indefinitely long storage time; random access to any element for writing and reading in a few microseconds; no erasure needed before registry; and possibility of indefinitely repeated readings from any element.

The characteristics of the tube and requirements of the associated circuits are given. A theory of the connections of parallel bars for combinatorial selection is included.

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INTRODUCTION

Some ten years ago electronic circuits were developed to perform arithmetical computations accurately at tremendous speeds by operating on bivalued or "on-off" signals which express the numbers in digital form, either in the binary or some coded decimal numeration system. It became possible to perform extremely long sequences of accurate computations in short enough times to attack by numerical methods many scientific, technical and military problems which could not, in practice, be solved by former methods. Several successful machines have already been built in this country and abroad, and many are under construction. In fact, electronic computation has been in introduced to business machines and, to believe some prophets, is likely to produce a revolution in clerical work.

The inner memory of an electronic digital computing machine is a storage device into which bivalued signals can be registered in a very short time, stored for an indefinite period and read off on very short notice. It is the essential component required for automatic operation because numbers resulting from one computation can be stored to serve as a basis for a subsequent one, and thereby make possible long sequences without undue waste of time for handling intermediary results. The memory can also store coded instructions describing the arithmetical operations to be performed for a particular problem and enable the machine to execute them in a fixed sequence, or one which is conditioned by the progress of the computation. In this way a machine consisting of an input device, an inner memory, a control, a single arithmetical unit and an output device, is essentially universal because it can solve a great variety of problems by merely inserting a proper program of instructions in it. These instructions, or orders, will contain in general the location or address within the memory of the numbers to be operated on, the desired operation, and the address to which the result is to be stored.

The usefulness of a computing machine depends, evidently, on the storage capacity of its memory, as this limits the size of the program and the number of possible intermediary results. Access to the desired address of the storage should take a time shorter than, or comparable to, that taken by the most frequent arithmetical operation in order to avoid wasting most of the time in mere "filings" and "look-ups." The requirements of large capacity and short access time are mutually contrary in storage devices in which access to all bits of information is in time series, such as in a moving magnetic tape, rotating drum or sonic delay line. With area (or volume) storage, this is not generally the case as it is possible to have direct access to any point without motion of the entire pattern of information. In short, the essential component of an information handling machine is a large capacity memory with rapid random access to its elements.

The storage of electric charges on a multitude of small areas of a surface has been utilized for years in television pickup tubes, such as the iconoscope, and other beam deflected storage tubes and is one of the fastest storage systems known. The electrostatic storage tube described in this paper is based on a novel conception of area selection. It is by the means of a fixed matrix formed by two orthogonal sets of parallel wires rather than by the deflection of a beam. Electrons bombard the matrix uniformly and are stopped in all windows except a particular one, as illustrated in Figure 1. This is accomplished by applying proper control voltages to the selecting bars. It is obvious that such a go, no-go, control of positions materially fixed by the matrix provides a greater certainty of selection than is possible by controlling precisely the deflection of a beam. Moreover, the bivalued signals coding the address of the information are directly convertible to the control voltages of the tube without resorting to accurate amplitude conversion, unnatural to digital computation which deals with quantized quantities only. These advantages are obtained by the use of a large number of control bars which would be impractical if it were not for the possibility of connecting them into a relatively small number of groups. This possibility arises from the fact that a quadruple coincidence of positive voltages on the bars making up a window is necessary to let electrons pass through that window. The number of elements

Fig. 1 -- Principle of selection

is, therefore, proportional to the 4th power of the number of controlling leads. The resulting economy of control leads may be appreciated by considering that about a million elements can be controlled by one hundred leads.

The storage mechanism, like the selection, is inherently quantized in this tube. The storage is obtained by the two naturally stable potentials which electrically floating metallic storing elements assume under constant electron bombardment: the potential at which electrons are repelled from the element and one of the potentials for which the bombarding primary electrons produce an equal number of secondaries. The storage time is indefinite, because the constant current holds forcefully the equilibrium potential in spite of the leakage due to the imperfections of the insulation of the element's supports. The signals to be stored are applied by capacitive coupling to all elements and bring the selected ones to the desired stable potentials. The reading currents are sizeable electron currents obtained by the "grid-action" of the storing elements. These currents are either present or absent, so that readings are bivalued also and require no amplitude discrimination. These currents produce incidentally a monitoring visual display.

The selection principle and early results of the research work were described in several patents[1] and reported by the author at several meetings[2,3] and in one brief published note.[5] Later results were briefly reported at several conferences.[6,8] Several geometrical arrangements with larger storage capacities were tried at first. The present paper is confined to the description of the latest tube with a capacity of 256 elements which has been developed to practical usefulness. It includes, in the appendix, a theory of connections of parallel bars for combinatorial selection, as this aspect of the tube is the most novel.

It is believed that this tube — the only truly random access storage device operating with bivalued inputs and outputs — will be very useful for the inner memory of computing machines. It may also have use in the broader field of automatic handling of coded information where temporary storage with rapid access to a moderate amount of information is required.

[1] U. S. Patents 2,442,985, 2,494,670 and 2,519,172. Other patents pending.

[2] Jan Rajchman, "The Selectron — A Tube for Selective Electrostatic Storage", Symposium for Large Scale Computing Machinery, Harvard University, January 8, 1947. The Proceedings of this Symposium have been published by the Harvard University Press.

[3] Jan Rajchman, "The Selectron — A Tube for Selective Electrostatic Storage". Several talks were made on this subject but not published: Society of Sigma Xi, Princeton Section, February 13, 1947; I.R.E. National Convention, New York City, March 4, 1947; I.R.E. Tube Conference, Syracuse, New York, June, 1947.

[4] A. V. Haeff, "A Memory Tube", *Electronics,* Vol. 20, No. 9, p. 80, September, 1947.

[5] Jan Rajchman, "The Selectron — A Tube for Selective Electrostatic Storage", *Mathematical Tables and Other Aids to Computation,* p. 359-361, Vol. II, No. 20, October, 1947.

[6] Jan Rajchman, "Recent Progress on the Selectron", oral progress reports presented at Association for Computing Machinery, Oak Ridge, Tennessee, April 19, 1949; I.R.E. Tube Conference, Princeton University, June 20, 1949; Second Symposium on Large Scale Computing Machines, Harvard University, September, 1949.

[7] S. H. Dodd, H. Klemperer and P. Youtz, "Electrostatic Storage Tube", *Electrical Engineering,* Vol. 69, No. 11, p. 990-995, November, 1950.

[8] Jan Rajchman, "Recent Experiences with the Selective Electrostatic Memory Tube", Conference on Electron Tubes for Computers, Atlantic City, December 11, 1950.

DESCRIPTION OF THE TUBE

The present model of the selective electrostatic storage tube has 256 storing elements. Figure 2 is a photograph of the tube. It is 3 inches in diameter and 8 inches long. The diametral and axial cross sections of the tube are shown in Figures 3 and 4.

Eight elongated cathodes of rectangular cross-section (.020 X .040 inch) are located in a diametral plane of the tube. Between and parallel to the cathodes are a set of nine nickel-coated copper bars of square cross-section (approximately .1 X .1 inch), referred to as vertical bars, the axis of the tube being vertical in normal operation. The vertical selecting bars are connected into 6 groups VI, V2, V3, V4 and V'I, V'2 as shown in Figure 5. On either side of the plane of the cathodes and V-bars there is a set of 18 parallel nickel bars of square cross-section (approximately .05 X .05 inch) at right angles to the V set. These two sets of horizontal selecting bars sandwich the cathodes and V bars as do all other electrodes of the tube, the tube being symmetrical with respect to the plane of the cathodes. The 36 H bars are connected into 12 groups: HI to H4 and H'l to H'8, as shown in Figure 5. The spaces between the V or H bars are gates for the flow of electrons which can be selectively opened or closed. Since there is one more bar than intervals between bars, 9 vertical bars are required to form 8 gates. The two sets of horizontal bars are divided by the central cathode supports, making it necessary to have 36 bars for 32 gates.

On either side beyond the horizontal bars there is a collector made of two flat metal plates perforated with round holes in register with the windows formed by the V and H bars. The collector mask plate, with relatively small holes (.040 inch), is backed by the collector spacer plate with larger holes (.120 inch). (See details in Figure 6.) Adjacent to the collector plates there are two mica sheets, the front and back micas, perforated to match the collector holes. These mica sheets hold between them 128 metallic storing elements which are insulated from all electrodes, i.e. electrically floating. These elements are tiny bodies of revolution made out of steel on an automatic screw machine and nickel plated. The conical heads of these elements protrude in the holes of the collector spacer plate which shields them completely from one another. The heads have, a .020-inch hole in the center. The enlarged diameter in the middle allows the elements to be held with out individual riveting. Adjacent to the back mica is a metal plate, the writing plate, with matching holes into which protrude the tails of the storing elements.

Fig. 2 -- Photograph of Selective Electrostatic Storage Tube

Beyond the writing plate is another plate, the reading plate, with the same pattern. Still beyond, is a Faraday cage made of two perforated plates spaced .300 inch apart and closed on all four sides by metallic strips. A glass coated with a fluorescent material, willemite, backs the outer plate of the Faraday cage. In the central plane of the cage there are 9 vertical wires located between the columns of holes of the plates. These reading wires are insulated from the cage by supporting mica strips and are connected together. The corresponding lead is shielded, even through the stem of the tube.

Fig. 3 -- Diametral cross section.

The construction of the tube is facilitated by several subassemblies: the cathode and V bars; the collector, storing elements and writing plate; the Faraday cages; and the side micas.

The cathodes and Vbars are supported by small ceramics, The ceramics are held in a row between pairs of U-shaped strips. The eight cathodes are mounted in three such rows of ceramics and are sprayed together to insure uniform emissivity. A hairpin heater wire and a reinforcing straight tungsten wire are inserted subsequently in each cathode.

Fig. 4 -- Axial cross section

The mask and spacer collector plates, the front and back mica plates holding 128 storing elements and the writing plate form a tight subassembly which is riveted together at the upper and lower ends and in the center. To insure insulation between the collector and writing plate, there are two separate sets of rivets engaging the back mica in different locations where appropriate clearance holes are provided in the plates not held. The back mica of one of the two sub-assemblies is longer and carries terminals for the heaters and cathodes. The side micas hold together two partial assemblies, each consisting of: 18 horizontal wires and their 6 connecting wires, one collector-writing plate subassembly, one reading plate and one Faraday cage.

Fig. 5 -- Connection of Selecting Bars

The two partial assemblies and the central cathode-V bars sub-assembly are tied together to produce the final mount. The cathode ceramics insure accurate equal spacings of the two halves of the collector on either side of the plane of the cathodes. Four rods connected to the two Faraday cages support the structure on the stem. The connections to the stem have been designed to be as direct as possible to avoid accidental short circuits. The stem has 34 pins: 22 on an outer circle comprising the 18 selecting leads and 4 for the supporting rods; and 12 on an inner circle including 2 coaxial output leads and all other 10 necessary connections.

The operation of the tube depends almost exclusively on the geometry of the electrodes, for while it depends also on reasonable thermionic and secondary emissions, it requires no exceptional emissivities or surface uniformity. The significant dimensions are shown in Figure 6 for a single electron optical channel. The clearances between parts and tolerances of dimensions are within reasonable shop practice. The mounting requires some precautions of cleanliness, particularly to avoid lint. No explicit activation of the secondary emission is necessary. The exhaust and cathode activation schedules are similar to those of a small transmitting tube.

Fig. 6 -- Detail of one electron channel.

HOLDING STATE

The operating condition is obtained by applying fixed direct-current potentials to the cathode, collector and Faraday cage and direct-current bias voltages to the selecting V and H bars, the writing and reading plates and the reading wires, as indicated in Figure 7. In the quiescent state of the tube, storing information previously written-in, all the selecting bars are at their more positive or opening potential which is the bias potential designed to be the zero potential of the cathode. In this condition electrons emitted from the cathodes are formed into 256 beams which are focused through the centers of the collector holes and are directed on the storing elements. Since these elements are not connected anywhere and are electrically floating, except for ohmic leakage of the mica supports, their potential will adjust itself so that the algebraic sum of currents to them is exactly zero. It turns out that, there are two naturally stable potentials for which this is the case.

Fig. 7 -- Principle of operation.

This can be understood by examining the actual current to the storing element as a function of a forced variation of its potential as shown in Figure 8. When the element is more negative than the cathode, it repels any incurring electrons and receives only small positive leakage currents through the micas in contact with the collector and writing plate as well as some ions, present however perfect the vacuum, as shown exaggeratedly by the load line of the figure. As the element is made more positive, the incurring electrons produce a negative current much greater than the ohmic and ionic contributions and the net current passing through zero near the cathode potential, becomes negative. The zero-current potential is about half-to-one volt negative with respect to the cathode potential, because there are enough electrons with sufficient initial thermal velocities to overcome the resulting retarding potential and compensate the leakage current. At more positive potentials, secondary emission from the storing element tends to cancel the bombarding primary current, being a loss of negative charge. The two become equal at the so-called first crossover. For still more positive potentials, the secondary emission becomes greater than the primary bombardment and a positive current is obtained. Finally when the element exceeds the collector potential, the secondary emission is suppressed, due to the retarding field between the element and the collector, and the full negative primary current is obtained. The current is zero at a potential of about one volt lower than the collector potential at which the resulting accelerating field opposes the retarding effect of the space charges due to the relatively large operating current density of the secondary electron current, to an extent just sufficient to obtain a secondary emission ratio of one. The zero-current potentials near the cathode and the collector are stable for a floating element because any deviation results in currents tending to restore equilibrium. The first crossover point, on the other hand, is unstable. The positive restoring current below cathode potential due to leakage and ions is usually negligibly small, so that for any potential up to the limiting half-to-one volt below cathode potential, there is essentially zero current. Consequently, the equilibrium potential may well be considerably below cathode potential in actual dynamic conditions prevailing during the operation of the tube.

Fig. 8 -- Current-voltage characteristic of storing element.

It is clear from the above that any pattern of stable potentials (conveniently referred to henceforth as cathode or negative, and collector or positive potentials), once established on the storing elements, will remain indefinitely, as long as power is on the tube, without any deterioration whatsoever, by virtue of the holding action of electron currents present on all elements which counteract detrimental ohmic or ionic currents.*

** This principle of storage has been adopted in beam deflected storage tubes, by A. V. Haeff in the Naval Research Laboratory tube, and by S. H. Dodd, H. Klemperer and P. Youtz in the Massachusetts Institute of Technology tube. See References 2, 4, 7, page 56. [page 5 this document]*

Fig. 9 -- Current-voltage characteristics for different collector voltages.

A family of current-voltage characteristics of the storing element was determined by direct measurement of a test element to which a lead was connected especially. Several remarks are of interest in connection with these curves shown in Figure 9 for different collector voltages. The negative current below first crossover, which has its greatest value at about 10 volts, insures the stability of the lower equilibrium potential (and could be used for charging the element as will be explained). The angle of the conical head of the element, designed to maximize this current, was chosen so as to force the low velocity electrons to approach the surface as normally as possible. The first cross-over potential is a sensitive measure of the secondary emissivity, and while for the particular test element it is 33 volts, it may be found to have any value between 30 and 100 volts. The maximum positive current flows at a potential considerably below collector potential, at which the secondary emissivity is higher, because an appreciable accelerating field is required to collect the space charge limited emission. The space charge accounts also for the lower-than-collector, zero current potential as mentioned above. While most secondary emission is suppressed for a retarding potential of 10 volts, the full negative current is obtained at 20 volts above collector. At higher voltages still, the primary current is practically independent of the potential of the element because this potential has no effect on the field near the cathode which is well shielded by the collector. These asymptotic values of the current to the storing element increase rapidly with collector voltage, not only on account of the enhanced space-charge-limited cathode emission, but also because the percentage of wasted current to the collector becomes smaller.

SELECTION

The registration of the incoming information into the tube or writing-in and the subsequent interrogation or reading from the tube, are made to a single or a few elements at a time and require the selection of the storing elements to which access is desired. This is accomplished by applying a negative pulse to all the V and H bars except one in each of the four groups V, V', H and H'. The bars are connected in such a way that one and only one gate in each of the V and H directions will have its two limiting bars remaining at the bias-cathode potential, while all other gates will have one or both limiting bars at the pulsed negative potential. This can be verified by examining Figure 5. For example, if the element defined by V3V2H4H5' is selected, there are gates such as V2V2' or H4H6' in which one bar is pulsed negatively and the other remains at zero, other gates such as V2V1' or H1H6' in which both bars are pulsed, but only in the selected gates V3V2' and H4H5' both limiting bars remain unpulsed. When a V or H bar is sufficiently negative, it cuts off almost entirely the emission from the corresponding adjacent cathodes or cathode regions and the small remaining part is deflected and does not reach the hole in the collector. Of course when both sides of a gate are negative, the current is cut off even more because a negative potential barrier is formed through which no electrons can pass. It follows, therefore, that only the particular selected window, with its four bars at zero bias potential, will still have its original current while all others will be cut off.

Fig. 10 -- Cutoff characteristic of selecting bars.
Voltages shown are negative.

The actual cutoff characteristics of the selecting bars have been determined by measuring the current passing through a collector hole as a function of the potential of one selecting bar, the three other surrounding bars being at zero bias. The ratio of this current to the full operating current of the opened window is shown in Figure 10 for different collector voltages. The current to most unselected elements is reduced, of course, by a much greater proportion since two, three or four bars contribute to that reduction. It can be estimated, on the basis of the writing and reading mechanisms described below, that there is completely negligible cross coupling between elements when less than 1 per cent of the full operating current is the maximum reaching any unselected element. This occurs for a selecting pulse on the horizontal bars about equal to the collector voltage, and for a' quarter of that voltage on the vertical bars. For sake of uniformity of the driving circuits, equal selecting pulses may be used on all bars. A pulse amplitude of 200 volts will be adequate for a wide range of collector voltages. Since the bars are either at zero bias or negative, they draw no current. Their load is purely capacitive and varies from 14.5 to 28.5 micromicrofarads depending on the particular bar group. (See Table II, which lists capacities.)

Fig. 11 -- Effects of selecting bar bias.

The electron optical system formed by the cathode, selecting V and H bars, collector and storing element is reasonably efficient, as about 80 per cent of the electrons emitted from practically the entire length of the cathode are actually focused on the storing elements and only 20 per cent are wasted on the collector. It is designed to operate at zero bar bias voltage, which is not only most convenient for the selecting driving circuits, but results also in a two-electrode system in which the focus is independent of the magnitude of the collector voltage applied (except for some space charge effects). The effects of different bias voltages are shown in Figure 11. For negative biases, some saving in the required selecting cut-off pulse is obtained at the expense of writing and possibly reading currents. For positive bias, greater writing and reading currents are obtained, at the expense of increased selecting cut-off voltage and considerable currents to the vertical and horizontal bars. Since these currents differ greatly between bar groups, particularly well regulated driving circuits must be used to prevent bias dissymmetry to which the optics are very sensitive.

The principle of selection of this tube is based on the idea that both sides of a gate have control on the passage of electrons through it and that, therefore, combinatorial systems of connections are possible by connecting each side of the gate to appropriate sides of other gates. In fact, since this is done in both directions, a fourth power relation exists, in general, between the number of necessary connection groups and the number of controlled windows. Since a seal through the vacuum envelope and an external circuit is required for each connection group, the economy in the number of these groups is of great practical importance. In the present tube 18 leads control 256 windows, but a more spectacular result of the fourth power relation would be a tube with 128 leads controlling 1,048,576 windows. The combinatorial principles of area selection, the chief novel characteristic of this tube, are analyzed at some length in the appendix.

WRITING

To register an incoming information bit* into a particular storage element, that element is first selected by interrupting the current to / all other elements except to it, as explained above. The selected storing element is then brought to the desired potential by a combination of the electronic current remaining on it—which may be keyed during the selection time—and the displacement current resulting from the pulsing of the writing plate to which all elements are capacitively coupled.

* *One bivalued signal.*

The writing method providing the shortest access time is as follows: (See Figure 12) At the instant at which the selecting pulse has reached its most negative value and the element is truly selected, a positive pulse is applied to the writing plate of sufficient rate of rise and amplitude to cause the corresponding positive displacement current, by overriding the electronic holding currents, to raise the storing element potential by an increment equal to the cathode-collector potential. This brings an element originally at cathode potential near the collector potential, and one originally at collector potential to nearly twice that potential. If positive registry is desired, the writing pulse is made to decay sufficiently slowly to cause the displacement current to the element to be smaller than the maximum positive net electron current from it. Therefore, an element, brought from cathode to collector potential by the pulse rise, will be charged positively during this decay and remain locked at collector potential. If negative registry is desired, the writing pulse is kept at its maximum value for a plateau time sufficiently long to allow an element, brought from collector potential to twice that potential, to be charged back to collector potential by the incident primary electrons. The writing pulse is then made to drop as sharply as it rose, resulting in a negative displacement current which overrides the holding positive electron current and brings the storing element to cathode potential where it remains locked. It is apparent that this writing procedure leaves unchanged the potential of the selected element which was originally at the potential to which it was driven. Therefore no erasure is necessary before writing, since the slowly decaying writing pulse will leave the element at collector potential, and the square pulse will leave it at cathode potential, regardless of the initial condition of the element.

Fig. 12 -- Writing by writing-plate modulation.

The minimum time *t* required to charge the storing element to the *V* volts between cathode and collector can be computed easily because the charging electronic current, *i,* is essentially constant. For negative charging, *i* is simply the constant value between *V* and *2V* (see Figure 8), while for positive charging it is the maximum positive current flowing at a potental slightly below *V* to which the element is driven by the decaying writing plate pulse. At the operating collector voltage of 175 volts, these currents are about equal, both approximately 350 microamperes, because the effective secondary emission ratio is near 2. The capacity *C* of the storing element is made up of .8 micromicrofarad to the collector and of .8 micromicrofarad to the writing plate, giving a total of 1.6 micromicrofarads to be charged. The simple relation $Q = CV = ti$ gives a minimum writing time of $t = .8$ microsecond. The actual charging time which is the length of the decay or of the plateau of the writing pulses must be made longer than this minimum to allow for variations in current and capacity between elements as well as a reasonable safety factor. Times of 2.5 microseconds were actually found satisfactory for prolonged operation.

The sharpness required in the rise of the writing plate pulse and in its decay when it is square, can be estimated by computing the duration for which the displacement current to the storing element is just equal to the opposing electronic holding current. For the decay, this is precisely the minimum charging time, .8 microsecond, computed above. For the rise, the positive writing-in to an element originally at cathode potential is the only critical case. Since the holding current for potentials below first crossover is at most a fifth the asymptotic charging current present above collector potential (see Figures 8 and 9), the limiting duration of the rise is 4 microseconds. The actual rise and decay of the writing plate pulse must occur in much shorter times than these limits in order to insure that the displacement current will be the controlling factor. Rise times of 1 microsecond and decay of .2 microsecond were actually found to be safe.

The power requirements of the circuits driving the writing plate so sharply are appreciable. The capacity division of the element between the collector and writing plate makes it necessary to use an amplitude of the writing pulse equal to about twice the cathode-to-collector potential, i.e., approximately 350 volts. Furthermore, each writing plate is a capacitive load of 112 micromicrofarads, or a total of 224 micromicrofarads with both plates in parallel. The driving power can be reduced considerably by keying-off the electron current to the selected element at the appropriate pulse decay (and rise) times in order to suppress the opposing holding action of this current, as shown in Figure 12. When this is done, these times may be lengthened at will. The consequent saving in writing plate power is obtained at the expense of additional keying circuits and some lengthening of the access time. The keying can be accomplished on any one of the four selecting bars surrounding the element, *V*, *V'*, *H* or *H'*, but most conveniently on the *V* bar, since there are only two families of *V* bars, *V'I* and *V'2*. The keying pulses, applied to both bars, will be effective on the selected one while the other carries the full length selecting pulse. A first keying pulse could be used during the rise of both positive and negative write-in pulses but is not very important because the negative current below first crossover is very small (omitted on the figure). A second pulse is really important during the decay of the negative writing-in pulse which otherwise must be so rapid. This second pulse is detrimental to the positive writing-in because it diminishes slightly the charging current, but this effect is so small that it is simpler to introduce no polarity differentiation and always have it present.

Fig. 13 -- Writing by selecting-bar current keying

Another writing method utilizes a standard shape writing plate pulse and keying of the current to the selected element to control the polarity of registration. The pulse has a rapid rise (or relatively slow one with power saving keying) followed by a plateau and a relatively slow decay equal respectively to the duration of the former square and decaying pulses (e.g., each 2.5 microseconds). At the end of the plateau time, the storing element will be at collector potential, either through the initial displacement current, or by electronic negative charging from twice the collector potential. If positive registry is desired, the current is not keyed-off and the element is charged positively during the decay and remains locked at collector potential. If negative registry is desired, the electron current to the selected element is keyed-off during the decay of the writing pulse and the displacement current brings the element to cathode potential (see Figure 13). This writing procedure is longer .than the previous by one charging time (practically 2.5 microseconds). Its chief advantage is to allow simultaneous writing into two, four or eight elements. This can be accomplished as follows: When all the bars of one of the *V'*, *V*, *H* or *H'* families are left at zero potential while only one group of bars in each of the three other families is selected to remain at zero, several windows remain open: two for the family *V*, four for the family *V* or *H* and eight for the family *H'*. The several windows in the family not participating to selection may be keyed separately by the corresponding bar groups. For example, in the octet V'1V2H4, the eight selected windows may be keyed separately by the controls *H'1* to *H'8*. By keying or not keying these individual controls during the decay of the writing pulse, negative or positive registry will be obtained in the corresponding storing elements. For writing-in purposes, the tube can, therefore, be considered as having one input channel with 256 storing elements, or two channels with 128 each, or 4 with 64 each, or finally as having 8 channels with 32 elements each.

Several other writing systems can be imagined in which negative and positive writing pulses are used to control the polarity of registration. Such systems are not as fast because negative charging depends on the relatively smaller current below first crossover, rather than the large current available above collector due to the transposition of negative charging into the higher-than-collector potential region (see Figures 8 and 9).

In all writing systems, immediately after the end of the writing . pulse, the selection pulses on the bars end and current is re-established to all storing elements. During the selection time all storing elements, except the selected one, do not receive the benefit of the holding currents and retain their charges in the measure of the perfection of the mica supports and vacuum in the tube. The leakage current from the storing element is in part to the collector and in part to the writing plate. These parts flow in opposite directions for negative or zero biases of the writing plate. The resulting compensation is never perfect because the maximum permissible negative bias of -60 volts . (which does not reduce the reading current passing through the element) is insufficient to make up for the difference in leakage through the front and back micas arising from their difference in temperature. At zero bias, which is the convenient recommended value, the natural storage time was always found to exceed 20 milliseconds. As this is very long compared to the few microseconds selection time intended in most applications, the unselected elements, after a violent potential excursion due to their coupling to the writing plate, will regain almost exactly their original potentials. The exact equilibrium potentials will .be reached almost immediately thereafter by virtue of the stabilizing currents.

The input access time, or time between successive registrations to any two elements of arbitrarily selected addresses, is spent between switching, actual charging of the storing element and holding information in all elements. This is illustrated in Figure 12. The switching time extends from the origin of the selecting pulse to the beginning of the actual charging and from the end of charging to the end of the selection time. It is of the nature of "red-tape" and depends on the design and power of the driving circuits. A practical limit to switching time was found to be less than 2 microseconds. The actual charging time is inherent to the storage tube, has a theoretical limit of .8 micro-second and a practical value of 2.5 microseconds, as mentioned above. The holding of information need not be done for the long interval of natural storage of at least 20 milliseconds, but is inherent in the routine of most switching circuits which include a passage through the holding state between successive selections.

Sufficient holding action is obtained when this passage is as short as feasible with any practical circuit, i.e., a fraction of a microsecond. The minimum operating input access time is, therefore, about 5 microseconds, half being spent in actual charging and half in switching and holding. Of course appreciable economy in the driving circuits can be realized with somewhat longer access times.

READING

The reading signal is derived from the electron current passing through the central hole in the storing elements. Part of the electrons aimed at the element are directed at that tiny hole (.020-inch diameter). When the element is positive, near collector potential, these electrons pass through the hole by virtue of their inertia, but when the element is negative, near cathode potential, it exercises "grid action" and the electrons are repelled and do not pass through the storage element. The presence or absence of the current through the element is, therefore, an indication of the state of the element.

Approximate electron paths resulting from the different conditions are shown in Figure 7. Figure 14 show's the reading current passing through the element as a function of the element's potential as determined from a test element to which a connection was made especially. The complete cutoff of the reading current at the lower equilibrium potential, which is a fraction of a volt negative with respect to cathode, is due principally to the depth (.020 inch) of the central hole and the length of the element's tail. The thermal electrons with initial energies sufficient to overcome the retarding potential of the element are stopped either by having too oblique a direction, or by the potential barrier developed by the space charges of returning electrons within the relatively large region in the element where the potential and fields are very low. For more positive potentials of the storing element the current through the hole increases slowly and at collector potential of 175 volts it is equal to about 35 microamperes, or one-tenth of the current directed to the head of the element. There is, of course, some variation in the reading currents from element to element, usually in the range of 20 to 40 microamperes. The reading current increases with collector voltage somewhat faster than the primary current because of improved current concentration at higher voltages.

Fig. 14 -- Reading current versus element potential (grid action).

In the quiescent state of the tube, with current present on all elements, the current which passes through the holes of all positive elements may be considerable, possibly as much as 256 times the reading current of a single element. This large irrelevant current is prevented from reaching and overloading the output circuits by the reading plate which is biased at a negative potential, about -125 volts. When reading is desired, the interrogated element is selected by applying a negative potential to all selecting bars except the four defining it, as explained above. Immediately thereafter a positive pulse is applied to the reading plate which allows the current through the selected element—if any—to proceed to the output electrodes. The current penetrates the Faraday cage through the front plate, strikes the willemite coated on the glass plate backing the rear plate, where it produces an incidental light signal and causes the emission of secondary electrons. This secondary current is collected by the nine wires located within the Faraday cage, and constitutes the reading output signal. The selecting and reading plate pulses, as well as the resulting output pulse, if any, are shown in Figure 15.

The electrostatic shielding of the output electrode is almost perfect because there is negligible field leakage to the reading wires through the holes of the front plate of the Faraday cage, and the connecting lead is completely shielded, even through the stem of the tube. For convenience of wiring, the part of the shield sealed through the glass is insulated from the cage and may be at any desired direct-current potential, such as ground. Consequently, there are no capacitive pickups in the output circuits which may have resulted from the steep and large selecting and reading plate pulses, and the output signal is exclusively due to the 35 microamperes of reading current. The output voltage i depends only on the desired speed of response. Since the capacity of the output electrode is about 20 micromicrofarads on each side of the tube, several tenths to one volt can be obtained for a time constant of about one microsecond, while 5 or 10 or more volts are available for time constants in the tens of microseconds. The reading access time, or time between successive interrogations of elements of arbitrary address, is spent between switching, reading and holding. Considerations concerning switching and holding times made previously for writing apply to this case. These times depend only on the circuit capabilities, and amount to 2.5 microseconds for reasonable assumptions. The reading time determines the obtainable output voltage and may be very short if adequate amplification is provided. The practical minimum reading access time is, therefore, about 3 microseconds. When it is made 5 microseconds, or equal to the writing access time, 2.5 microseconds are available for reading and an output of about half a volt is obtainable.

Fig. 15 -- Pulses in reading

It is obvious that the interrogation of any element can be repeated indefinitely since it is derived from a current controlled by the potential of the storing element but playing no role in maintaining that potential. It is clear also that writings and readings to any element can be interlaced in any arbitrary manner. Moreover, since holding occurs automatically in the waste time following switching-between elements, no holding routine need be provided. In fact the tube possesses truly random access since input or output access to any arbitrarily selected element is independent of any previous history.

The control characteristic of the reading plate of Figure 16 shows the percentage of output reading current as a function of the reading plate potential. This current reaches saturation when all the current passing through the storing element, passes also through the reading plate and none is reflected. It is apparent that the potentials of the writing plate and Faraday cage have no influence on this saturation value but determine the reading plate cut-off voltage. In order to avoid a reading signal due to the pulsing of the writing plate—from its zero bias to about 400 volts—the reading plate must have a sufficient negative bias of -125 to -150 volts, depending on the Faraday cage potential. In that case a reading plate pulse of 100 volts is required to obtain the full reading current. If the reading output due to the writing plate pulse is gated out by an external circuit, a reading plate voltage of only 30 volts is required with -50 volts bias. The reading plate draws no current, even when it is positive, because the reading., currents are perfectly focused through its holes. It presents, therefore, a purely capacitive load to the driving circuit, which is 52 micromicrofarads on each side of the tube or 104 micromicrofarads total.

Fig. 16 -- Reading plate control characteristic.

The current which is repelled by the reading plate when it is negative, is focused through the holes of the writing plate towards the back of the storing elements. While some of this current returns to the cathode or is reflected in the cathode region to strike the front of the elements, most of it strikes in the back of the elements, where secondary emission is suppressed for lack of collecting field. Consequently, the equilibrium potential shifts slightly to a negative value at which additional secondary emission from the front compensates the back bombarding current. This effect is negligible in practice because the reading current is only a tenth of the writing current.

The current voltage characteristic of the reading wires is shown in Figure 17, and resembles the desirable characteristic of a pentode since the current is independent of voltage for all values higher than about 150 volts with respect to the Faraday cage potential. The current to the reading wires is supplied by the secondary emission of the current entering the Faraday cage. This current comes mostly from the phosphor, but also, due to imperfect focusing, from the hole's sides of the front and the face of the back plates. The secondary emission from the phosphor is necessarily equal to the primary current striking it, since the net current to the insulated surface is zero at equilibrium, and, in general, it will be collected in part by the Faraday cage and in part by the reading wires. As the potential of the reading wires is gradually increased with respect to that of the cage, the equilibrium potential of the phosphor (or equilibrium distribution on the bombarded area) rises and a greater proportion of the secondary electrons is collected by the wires. The relatively high potential difference of 150 volts is necessary to saturate this division process. It is interesting to note that the phosphor, like the storing element, may assume the cathode equilibrium potential, particularly when low voltages are used on the Faraday cage. Usually only the center of the phosphor areas is dark, i.e., at cathode potential, while the outer ring is at a higher potential and gives light. In any case, the reflected primaries are almost totally collected by the reading wires, and this condition results in no detrimental effect other than spoiling the aesthetic value of the monitoring light signal.

Fig. 17 -- Reading wires current-voltage characteristic

When the reading plate is set above its cutoff voltage, the current passing through all positive elements is allowed to strike the fluorescent screen and a pattern of the stored information is obtained. This display, convenient for checking the operation of the tube itself, is most useful for monitoring the computing or other information-handling-machine in which the tube is the central information store. The intensity of the light depends on the potential of the Faraday cage, and is limited only by possible burning of the phosphor. Satisfactory indications in normal room illuminations are obtained at 350 volts and . voltages up to 800 volts are allowable. The potential of the reading (and writing) plate determines the focusing of the indicating spots, and may be adjusted at will when the tube is being viewed.

CHARACTERISTICS, CIRCUITS AND APPLICATIONS

The operating characteristic values of voltages and currents of the tube are listed in Table I. These values were found to be reasonable averages. Table II is a list of electrostatic capacities of pulsed electrodes with respect to all other electrodes of the tube.

When the tube is operated with a single access channel to its 256 storing elements, the writing and reading plates and the reading wires on the two sides A and B of the tube are connected in pairs, and all 18 selecting leads are used separately.

Simultaneous writing and reading access to two storing elements can be obtained as a natural result of the symmetry of the tube which may be considered as two tubes with 128 storing elements each. By connecting the selecting leads *H'* in pairs, 1' and 5', 2' and 6', 3' and 7', and 4' and 8', it is apparent that two elements are selected simultaneously in similar locations on opposite sides A and B of the tube (see Figure 5). The two input signals to be registered modulate separately the shapes of the pulses on the writing plates A and B. The reading plates A and B are pulsed together and the output signals are detected separately on the reading wires A and B.

As was mentioned previously, simultaneous writing into more than two elements is possible with modulation by bar keying. However, simultaneous reading is possible on at most two channels since there are only two reading wire outputs. This restriction is not significant in applications requiring parallel writing in many channels and serial reading from one or two channels.

In most applications of the tube, binary numbers will be used to specify the address of the information to be stored or detected. Therefore, a conversion is required between the binary signals and the inputs on the selecting leads. This can be accomplished by matrix circuits which are particularly simple in this case since the families of selecting leads are powers of two: two leads in *V*, four leads in *V* and *H* and eight leads in *H'*. These circuits must keep the leads at their zero bias for the holding state of the tube, and upon a command to select, must impress negative pulses on all leads except the ones selected by the binary inputs. Resistance, crystal or multigrid matrix circuits of various kinds can be designed for this gating operation (see Figure 18).

A circuit for one of the 2 X 4 matrices illustrates partially one solution (see Figure 19). The address of the information is assumed to be in a register. Two flip-flops of the register control four double control-grid tubes (e.g., 6AS6), so that one and only one conducts for any combination of flips or flops. The plate resistance of each double-grid tube is also connected to the plate of a paralleling triode (e.g., ½ 6J6). The grids of all four triodes are connected together and biased to cathode potential. Consequently, the four plates are at their relatively lower potential. This causes the bar-driving tubes (e.g., 6L6) to be non-conducting and leaves all the selecting bars at their bias potential, as required for the quiescent state of the storage tube. To select, a commanding pulse is applied to the paralleling triode grids and renders them non-conducting. This leaves no current on the three unselected plates of the double-grid tubes which will take their positive C+B) potential and produce thereby selecting pulses on the corresponding bars. The fourth plate, on the other hand, will have current from the selected double-grid tube and, therefore, no pulse will be produced on the corresponding selected bar. Circuits, more ingenious than this illustrative example, can be designed with smaller tubes and reduced power.

In the memory devices required for most computing machines, it is desirable to store under a given address, a group of bivalued signals— or "words" representing in coded form, numbers, letters, or command symbols—rather than merely a single signal. This can be accomplished by paralleling as many tubes as there are signals in the word (or half that number when two channels are obtained from each tube). The selecting leads of same identity of all tubes are connected together. A common matrix controls the selecting buses through suitably powered driving amplifiers (see Figure 20). Access is simultaneous to the identical address in all tubes and information is stored or detected in parallel to or from all tubes (or tube channels) through separate writing and reading circuits. Each individual writing circuit provides, on the writing plate, a triangular or square pulse depending on the polarity of the signal to be registered. The reading circuits amplify the output signals from the individual tubes. The size of these circuits depends greatly on the desired speed of response. For 5-microsecond access time, reasonable designs require 4 tubes for the writing and 2 for reading.*

Fig. 18 -- Internal connections and external matrices.

* From circuit developments by I. E. Grosdoff in connection with memory unit including a score of these storage tubes.

Table I -- Operating Characteristics

Heater Voltage	50	Volts
Heater Current	.7	Ampere
Cathode Current:		
all gates open, collector 175 volts	100 ± 10	Milliamperes
one gate open, collector 175 volts	350	Microamperes
all gates closed	0	Microamperes
Bias selecting, V and H Bars	0	Volts
Cutoff voltage: for single H bar -- to 1 per-cent of open gate value --	Collector voltage	
Cutoff voltage: for single V bar -- to 1 per cent of open gate value --	¼ Collector voltage	
Current to V and H bars	0	Microamperes
Collector voltage: averaging operating	175	Volts
Collector current: all gates open	Cathode current	
all gates closed	0	Milliamperes
Writing plate: Bias	0	Volts
Current	0	Microamperes
Writing Pulse (twice collector)	350	Volts
Reading plate: Bias, operating	-125	Volts
Bias, monitoring, spot focusing	-30 to+30	Volts
Current	0	Microamperes
Pulse	+100	Volts
Faraday Cage: Voltage	300 to 900	Volts
Current (with reading wires at specified voltage)	0	Milliamperes
Reading Wires: Voltage above Faraday cage	150	Volts
Current, per positive element	15	Microamperes min.
Current monitoring condition	10	Milliamperes max.

Table II — Electrostatic Capacities

All capacities are averages, in micromicrofarads, to all other electrodes:

Vertical Selecting Bars	
V'1, V'2 and V1	28.5
V2, V3, and V4	14.5
Horizontal Selecting Bars	
H1, H2, H3, H4	28.5
H'1, H'3, H'5, H'7	22.5
H'2, H'4, H'6, H'8	16.5
Writing Plates -- Each Side	112
Reading Plate -- Each Side	55
Reading Wires -- Each Side	20
Storing Element to Collector	.8
Storing Element to Writing Plate	.8
Total Storing Element	1.0

PERFORMANCE TESTS

About 50 tubes were built in the laboratory according to the design described above, with minor modifications from tube to tube. The tubes were first tested with direct-current or simple-pulse techniques. Uniform characteristics of selection and monitoring display were observed in all tubes, as these depend on built-in geometrical properties. The uniformity of cathode emission and of the secondary emission from the storing elements was gradually improved with experience. In the latest tubes there is approximately 20 per cent variation of primary current available at the elements. The variation of secondary emission which is more difficult to measure is certainly somewhat greater. The phosphor screens were found to be uniform in light output.

Fig. 19 -- Typical matrix for four selecting leads.

A test unit was built in which the tubes would be in dynamic conditions as similar as possible to those of actual use in a computing machine. The test system consists of setting some arbitrary pattern of information in one tube, interrogating the elements of that tube in succession and registering the results in the corresponding elements of a second tube. The initially stored pattern will, therefore, appear in both tubes No. 1 and No. 2 as shown in Figure 21. The pattern of tubes were first tested with direct-current or simple-pulse techniques. Uniform characteristics of selection and monitoring display were observed in all tubes, as these depend on built-in geometrical properties. The uniformity of cathode emission and of secondary emission from the storing elements was gradually improved with experience. In the latest tubes there is approximately 20 per cent variation of primary current available at the elements. The variation of secondary emission which is more difficult to measure is certainly somewhat greater. The phosphor screens were found to be uniform in light output.

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therefore, appear in both tubes No. 1 and No. 2 as shown in Figure 21. The pattern of tube No. 2 is then read off element by element and is registered with reversed polarity into tube No. 1, so that a pattern in which all initially positive elements are negative and vice versa, appears in tube No. 1. The test consists of letting this back and forth transfer proceed automatically at high repetition rate and observe whether the initial pattern remains unspoiled. Runs of seventeen hours without failure have been observed. The occasional transient failures were probably due to the circuits, as their number seemed to decrease with circuit improvements.

The life of the tube depends principally on cathode emission and secondary emission of the storing elements. The required emissivity of the cathode is considerably lower than in radio receiving tube practice. Therefore, it is very likely that adequate emission will be available for a very long time. The secondary emission of the nickel-plated steel elements is influenced by the barium oxide evaporated from the cathodes as well as the intense electron bombardment which has an oxide reducing action. These two mutually compensating effects are likely to produce a fairly stable secondary emitter.

Some empirical data, accumulated to this date, supports these expectations. A pair of tubes after 1500 hours of operation had still their initial cathode emissions. The secondary emission, after a drop in the initial 30 hours, leveled off to a steady value. Similar observations were found in shorter runs of several hundred hours on a dozen tubes.

CONCLUSIONS

After several years of research following the original conception of the novel principles of selection and storage, the tube has been developed in the laboratory to practical usefulness. The first steps towards manufacturing have been taken, and a series of development tubes referred to as C7761 have already been built. The Laboratories have undertaken to build a complete memory unit including 20 selective storage tubes, type C7761, with associated circuits and power supplies. The halves of the tube are used separately to provide 40 parallel information access channels. The device is to operate with an access time of five microseconds.*

** Circuit developments by I. E. Grosdoff.*

There is no doubt that a tube with superior performance will result eventually from manufacturing experience. Engineering of a full-size memory unit has already resulted in improved circuits. Early completion of the unit will also reveal valuable operational experience and further data on the life of the tubes.

The considerations on the future possibilities for better tubes based on the same principles will become more realistic in the light of these experiences, but some aspects may be speculated upon at the present time. The versatility and usefulness of computing and information handling machines is primarily determined by the capacity and speed of its random access memory. To make up a capacity sufficient merely to justify the existence of the machines, scores of tubes are already necessary. For the desired larger capacities, the relative merits, of a few large tubes or many smaller ones, must be appraised by weighing the technological difficulties of building many elements into a single tube against the increase in wiring, circuit and servicing complications resulting from the use of many tubes. The optimum capacity with the present techniques is most likely above the present 256 elements, probably 512 and possibly even 1024. Numbers of elements other than powers of two are possible, of course, and it may be practical for decimal machines to have some simple multiple of a power of ten.

The selective electrostatic storage tube described in this paper is the only truly random access storage device operating with bivalued inputs and outputs. To the author's knowledge, it is also the fastest memory for computers available at the present time. Some increase of speed is still possible by improving the electron optics, the secondary emissivity of the storing elements or the controls of the tube.

The tube can be used as an information storage tank in any machine handling digital information. Designed for the high speed inner memory of computing machines, it can be used also in other parts of these machines, particularly for the auxiliary memories associated with the arithmetical or control units.

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