Prototype double sided target magnetic deflection Graphechon tube, early 1940's. The Graphechon tube was developed to make long time storage of television quality pictures possible. Its original use was to store RADAR PPI patterns and generate television pictures from this. There are two electron guns, one at each end of the tube and a target in the center, one gun would "write" the picture on to the target while the other would "read" the pictures and develop the television signal .

THE GRAPHECHON — A PICTURE STORAGE TUBE*

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Summary—Long time storage of television quality pictures is possible with a new type of storage tube consisting of two independent cathode ray guns and a target plate coated with a thin film of insulating material. A new type of bombardment-induced conduction effect provides high sensitivity and stability. The two guns can operate simultaneously, the one to "write" down any arbitrary pattern to be stored and the other to scan repeatedly over it to both generate signals and erase the pattern at a controlled rate. The tube makes possible television pictures of oscillograms or radar patterns that can be viewed for several minutes.

Introduction

THE problem which gave rise to this tube was that of providing a means for electrically storing complete radar plan position indicator (PPI) type patterns and generating from them signals which could provide television pictures of the radar patterns. This problem arose in the Teleran System[1] for airborne navigation. Here it was highly desirable to be able to broadcast a composite television picture of a radar pattern, its associated ground map and other information. The tube that was developed to meet this need proved to have several other interesting applications. However, it seemed preferable to describe it below in terms of its major initial application.

The problem is one of obtaining a means of converting radar signals to television signals without loss of the pattern geometry. This implies storage of the radar signals for at least several seconds because it can take this long to complete one PPI pattern. Also, because television pictures are generated at the rate of thirty per second, it may be necessary to generate several hundred television copies of a radar pattern before it fades out. Such conversion of signals has been obtained by using an image orthicon camera tube with a reflection type optical system to pick up the relatively weak afterglow of a radar cathode ray tube with a P7 or similar fluorescent screen. Much better

* Decimal Classification: R583.15.

[1] D. H. Ewing and R. W. K. Smith, "Teleran," *RCA Review*, Vol. VII, No. 4, pp. 601-622, December, 1946.

results have been obtained with a special, high capacity orthicon[2] picking up the initial flash of a cathode ray tube without any afterglow, the picture being retained in the capacity of the orthicon photocathode. Both these schemes require a high-brightness cathode-ray tube and an optical system, which are unnecessary in principle because the light is used only as a link between two electrical signals. In order to obtain an all-electronic converting scheme, a new type of tube, called a graphechon, was built. This name is derived from the Greek words "Graphe" (to write) and "echo" (to keep or to hold). The tube can be regarded as a kinescope and iconoscope in one bulb, with the mosaic and kinescope screen replaced by a charge-sensitive, high-capacity, storage target. The kinescope gun will be referred to as the "writing" gun which takes the radar signal and "writes" it on the target. The other gun will be called a "reading" gun. Its function is to generate the television signal and gradually remove the stored signals.

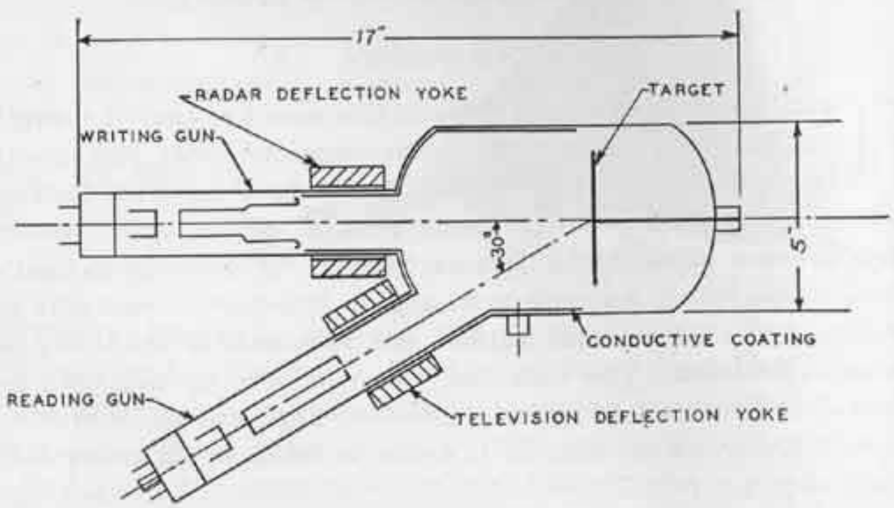

Fig. 1—Single sided target, magnetic deflection Graphechon.

Construction of the Tube

The design of the bulb is not critical and is largely determined by the requirements of the cathode ray guns. Figure 1 shows a sketch of one type of tube using magnetic deflection. In order to simplify the circuit requirements, the writing gun is mounted perpendicular to the target, which avoids the necessity for keystone correction for a radial deflection pattern. This correction has been solved very simply for the iconoscope, and so the reading gun is mounted off the axis at the same angle as is used for the standard iconoscope. The dimensions of

[2] Stanley Forgue, "The Storage Orthicon," *RCA Review*, Vol. 8, No. 4, p. 633, December, 1947.

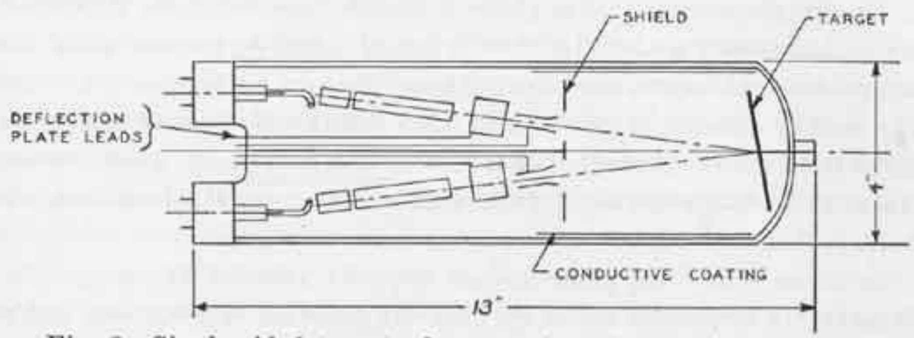

Fig. 2—Single sided target, electrostatic deflection Graphechon.

the bulb are determined by the space requirements of the deflection yokes, by the deflection angles required for obtaining adequate resolution, and by the desired target dimensions.

When preferable, a tube can be built with all-electrostatic focus and deflection. It is more suitable for oscillograph operation or, where weight and size are critical, it permits eliminating the deflection yokes. Figure 2 is a sketch of such a tube which can be made smaller and more compact than the magnetic deflection type, but is necessarily subject to the lower resolution limits imposed by the electrostatic deflection system.

Figure 3 is a sketch of the most recent form of the tube. This modification was built to make possible mounting the guns on a common axis and thereby avoid the need for keystone correction. The target construction was modified to permit the "writing" beam to penetrate through the target as will be described below.

For the magnetic deflection writing gun it is possible to use a standard kinescope gun with either magnetic focus (type 12DP7) or electrostatic focus (type 12AP4). Both types have been used for radar purposes and have adequate resolution at the rated voltages of 6,000 to 10,000 volts, which is also the range of voltage which is used in the Graphechon. The reading gun can be a standard iconoscope gun and runs at standard iconoscope voltages, which is 800 to 1,000 volts.

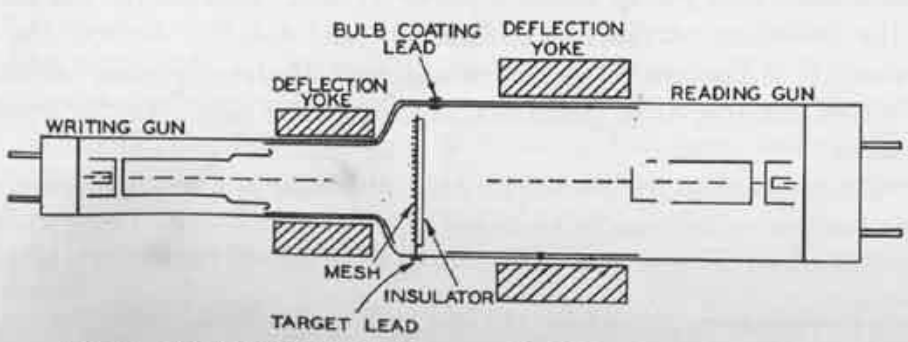

Fig. 3—Double sided target, magnetic deflection Graphechon.

The target consists of a plate of metal upon which is deposited a film of insulating material of the order of 6,000 Angstrom units thick (approximately half a micron). Where the two guns are on the same side, any of a number of metals, thick enough to be self supporting, can be used for the target. The insulator film can be any good insulator like silica or magnesium fluoride, applied by any suitable means, such as evaporation.

In tubes where the guns are on opposite sides of the target, it is necessary to make the metal backing transparent to electrons and yet strong enough to support the insulating layer. This can be done by using very fine mesh with a high transmission factor to provide the mechanical support. Then an organic film is spread over the mesh to act as a base upon which to evaporate a thin layer of aluminum. The insulating layer is then evaporated onto the aluminum and the target is complete. The high voltage "writing" gun is located on the mesh side of the target. The mesh is made fine enough so that it does not limit the resolving power of the tube. Sample targets have employed approximately 500-per-inch mesh.

PRINCIPLES OF OPERATION

The reading beam, operating at 1,000 volts, has a secondary emission ratio greater than unity. It scans uniformly over the insulator surface and therefore brings it approximately to the potential of the collector, which is the conductive wall coating. This is true regardless of the potential of the underlying metal. It is therefore possible to adjust the potential drop across the thickness of the insulating film to approximately the difference in potential between the target metal and the wall coating.

It is possible to regard the insulator as the dielectric in a condenser, one of whose plates is the target metal and the other is the surface scanned by the electron beam. As a starting equilibrium condition, the condenser is charged up uniformly over its area. Because the one plate is the insulating surface of the dielectric and does not conduct transversely, it is possible to discharge any part of the condenser without affecting the rest of it. Such discharging can occur in any arbitrary pattern.

The mechanism for discharging the dielectric is a newly discovered phenomenon[3] which can be observed in films thin enough to be wholly penetrated by an electron beam. It can be shown that currents can

[3] L. Pensak, "Conductivity Induced by Electron Bombardment in Thin Insulating Film," *Phys. Rev.*, February 1, 1949.

flow through the film which are many times larger than the bombarding beam, that the currents flow in the direction of the gradient, and that the insulation recovers on removal of the beam. Since the penetration of an electron beam increases with the square of the voltage, a film may be chosen of such thickness that, though fully penetrated by a 10,000 volt beam, it is scarcely penetrated at all by a 1,000 volt beam. If the latter, low-velocity, beam is employed to charge up the dielectric, the 10,000 volt beam may be used to discharge it. The second, high-velocity, beam is the "writing" beam which can be deflected and modulated in any arbitrary manner such as for a PPI pattern or an oscillograph trace.

The mechanism for signal generation is a simple form of that in the iconoscope.[4] The target surface is brought to equilibrium potential with the target metal at approximately 50 volts negative. Where the writing beam has struck and driven the surface negative, the second-

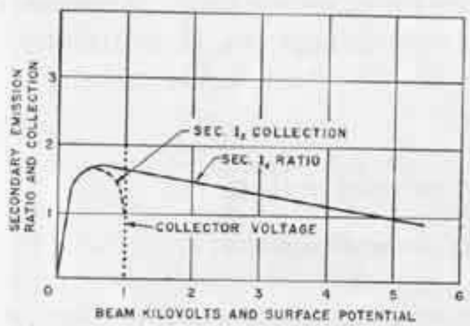

Fig. 4—Typical curve for secondary emission from silica.

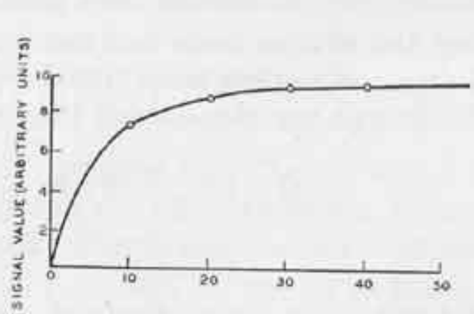

Fig. 5—Surface potential in volts below collector potential.

ary emission collection is greater than unity and some charge is removed every time the reading beam scans those areas. This removal of charge produces the signal which is amplified to operate the viewing kinescope. As is true for all condensers, removal of charge from one electrode causes an equal charge to flow onto the other, which, in this case is the signal plate. This current produces an IR drop across the load resistor R (see Figure 7) and thereby produces the signal.

The magnitude of the signal depends on the deviation from the equilibrium described above. When the surface is at collector potential, the secondary emission collection is equal to the beam current and no signal results. The dotted line in Figure 4 shows how the secondary emission collection approaches the true secondary emission curve when the surface potential falls below the collector potential. Figure 5

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

shows this in terms of signal value for a typical electrode configuration. The curve levels off at the higher voltages because the secondary emission collection tends to saturate at relatively weak fields, and the signal current therefore remains almost constant at the higher fields.

The saturation of secondary emission provides a means of obtaining many television pictures of the writing pattern. The saturated secondary emission is proportional to the beam current so that it is only necessary to reduce the beam current to reduce the amount of charge removed on each scan. However, this also reduces the signal output and the lower limit in this direction is the noise inherent in the video amplifier.

A quantitative approach to the duration of a writing signal can be based on regarding the target as a group of elemental condensers, each the size of the focussed spot of the reading beam (one picture element by television standards). The signal plate is common to all of them and the electron beam provides the other electrode. Assuming that the writing beam has completely discharged the elemental condenser, the reading beam will charge it up again to collector voltage. The charge per element will then be

$$Q = Vc \qquad \text{where } V = \text{collector voltage}$$
$$c = \text{element capacity.}$$

Assuming that the average charging current is a constant, which is reasonably correct for the condition of constant beam current and saturated collection of secondaries

$$Vc = I_c T \qquad \text{Where } I_c = \text{average charging current}$$
$$T = \text{charging time.}$$

The charging current is the difference between the secondary emission current and the average current $\bar{I}$ reaching the element or

$$I_c = r\bar{I} - \bar{I} = (r-1)\bar{I} \qquad r = \text{secondary emission ratio}$$
$$\bar{I} = \text{average beam current per element.}$$

Therefore

$$Vc = (r-1)\bar{I}T$$

However, since the beam scans over the target, the average current to each element is $1/n$ of the total beam current I, where n is the number of elements in the target.

Therefore $Vc = (r-1)\frac{I}{n}T$ or $T = \frac{Vcn}{(r-1)\,I}$.

But nc is the total capacity of "C" of the whole scanned area so that

$$T = \frac{VC}{(r-1)\,I}.$$

The formula for the capacity of a parallel plate condenser is

$$C = .0885 \times 10^{-12}\frac{kA}{d} \text{ farads}$$

k = dielectric constant
A = area of condenser
d = thickness of dielectric.

Substituting this in the equation above

$$T = .0885 \times 10^{-12}\frac{kAV}{d\,(r-1)\,I} \text{ seconds.}$$

An experimental value for T of 5 minutes was obtained with $V =$ 100 Volts, $d = 5 \times 10^{-5}$ centimeters and $r = 1.3$. One to two minutes of continuous viewing is more usual. Several thousand scans at television standards are therefore quite feasible. T can be called the viewing or charging time, or the period during which the element will produce a detectable signal in the reading amplifier. The storage time is much greater and is determined only by the leakage resistance of the insulator. A value of ten days was obtained in one test.

It should be noted that the expression for T does not involve the number of elements in the picture, nor does it require scanning, but is exactly that which would be obtained by calculating the charging time, if it is assumed that the current I is spread out uniformly over the whole area of the target of capacity C.

A second thing to be noted is the fact that the charging time is proportional to the total area of the target. A reduction in tube size will hence result in a proportional reduction in the maximum viewing time. However, in applications where it is not necessary to keep the reading beam scanning constantly, the combination of storage time and viewing time can make the picture available for periods of time greater than T as given by the equations.

The factor of insulator thickness, however, does not necessarily vary the maximum charging time even though it varies target capacity.

If it is assumed that the dielectric strength of the insulator is constant, then varying the thickness also permits varying the voltage across it in proportion. As the capacity per element goes down, the voltage can go up, and the charge per element remains constant. Therefore, the charging time remains constant and the maximum viewing time is independent of the insulator thickness. Normally, voltage and thickness are determined by other considerations. In actual practice, the tube is built to have a maximum viewing time in excess of that required and the reading beam current is adjusted to provide the desired value.

The film thickness is subject to a basic limitation arising from the requirements of the conduction effect which depends on the penetration of the film by the writing beam. The efficiency of the effect, i.e., the number of conduction electrons per primary, depends on the absorption of the energy of the beam. There is, therefore, an optimum writing beam voltage for each film thickness such that the maximum amount of beam energy is absorbed in the insulator. This voltage is somewhat greater than that required for complete penetration alone. Fortunately, this value is not very critical. Another factor affecting the efficiency is the gradient through the film which should be as high as possible if it is desired to obtain the greatest sensitivity to the writing beam.

Varying the film thickness also varies the degree of half-tone reproduction. Half-tones are obtained in the voltage range where the output signal varies with the surface potential (the sloping part of the curve in Figure 5). Beyond this slope, the signal is independent of surface potential and so produces a "black and white" picture, i.e., the signal is either at its maximum value or is not present. If the film is thin or the total film voltage is less than ten volts for any other reason, the reproduction will be all half-tone and the viewed picture will decay continuously. On the other hand, a thick layer can take a large voltage and the signal will be black and white for most of the charging time. The picture will stay at constant level for a while and then decay. The choice of film thickness will, therefore, be determined by the desired ratio of half-tone to black and white viewing times and by the penetration limitations. A typical curve of signal output versus time is shown in Figure 6. The actual duration of the signal can be made to vary by varying the reading beam, but the ratio of the times in the two modes of operation stays constant for any given voltage change on the film. Reducing this voltage from the maximum possible reduces the viewing time as well as the ratio of black and white to half-tone time.

Practice of Operation

One of the applications of the tube is as a direct current or single trace oscillograph which can provide a bright picture of the complete trace for adjustable periods of time. The circuits for such a function are relatively complex, compared to an oscillograph with an afterglow type phosphor; but there are several advantages that may justify the extra equipment. The problem of large screen oscillography, for viewing by large numbers of people, can be met by using a commercial television projection set and operating the Graphechon as an oscillograph-iconoscope combination. The problem of photography of very short duration transients can be met by recording the trace in the Graphechon and photographing the picture on a standard kinescope. If the interval between transients is long, the reading beam and kinescope need only be turned on when desired for photographing. In either case, the tube can be made very sensitive to the writing beam and thereby reduce the need for a very high voltage type oscilloscope which ordinarily might be required for high writing speeds.

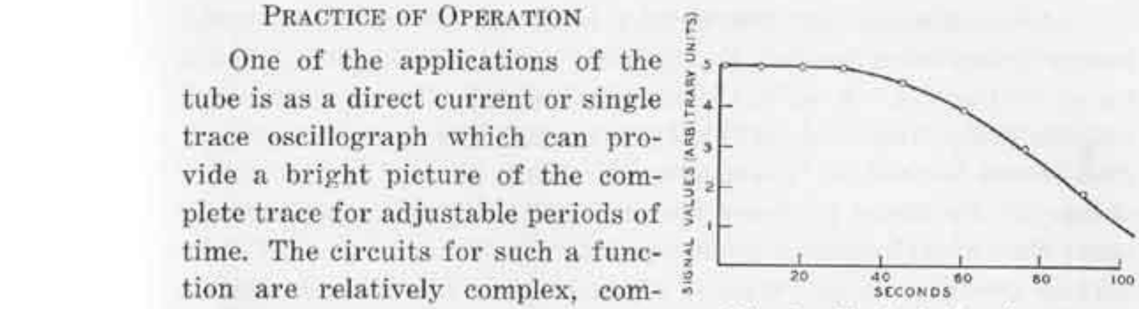

Fig. 6—Typical signal output against viewing time.

For such applications, where the writing beam is not modulated in intensity, the circuit requirements are shown in block form in Figure 7. The components are all of a type that can be found described in television and oscillography literature.

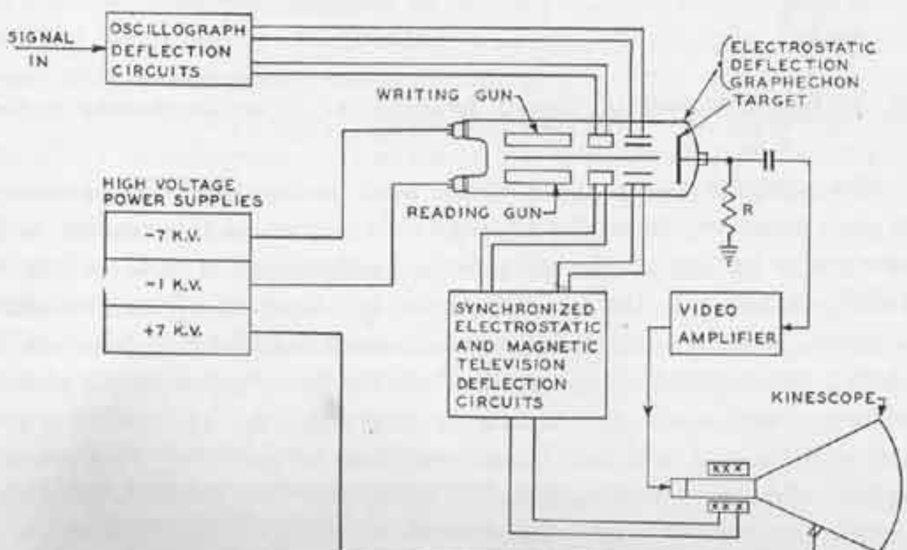

Fig. 7—Block diagram of circuits for using Graphechon as oscillograph.

The requirement that the writing beam not be modulated in intensity arises from the fact that it will produce a video signal in the target of the same form as the modulation and of an intensity that could be many times that of the signal produced by the reading beam. This occurs because, as was shown above, any removal or addition of charge to the target produces a signal and the writing beam, being above the second crossover point, tends to put down charge which will vary in amount with the intensity of the beam. As long as the writing beam intensity is constant, it produces only a direct current type of signal which is blocked by the input condenser of the video amplifier.

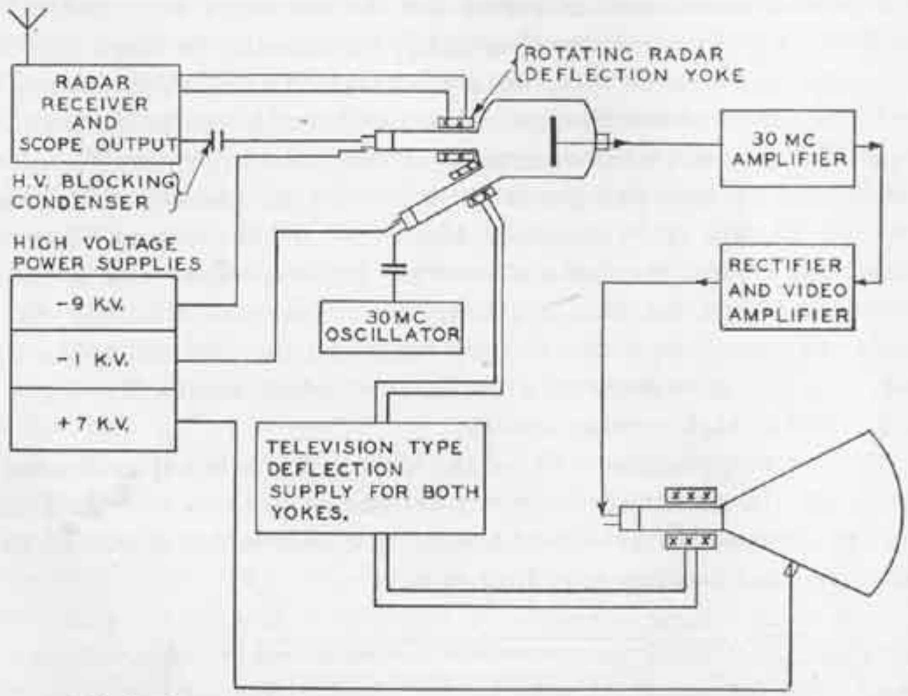

Fig. 8—Block diagram of circuits required for using Graphechon to view PPI type radar presentation.

However, for many applications, such as for radar conversion, it becomes necessary to modulate the writing beam at frequencies in the same range as that of the video output signal and it is therefore not possible to separate the two signals on the basis of signal frequency. However, it is possible to create a frequency difference between the reading and writing signals by modulating the reading beam at some frequency well above the maximum contained in the writing signal. The output signal will now be an amplitude modulated high frequency carrier, which can be amplified by conventional means and rectified to provide the desired video signal free of the writing modulation. A typical circuit is shown in block diagram form in Figure 8, giving the components required to operate the tube as a radar converter. The operation of the tube in this manner is quite satisfactory provided suitable precautions are maintained.

The original objective and main application of this tube is to provide means of viewing radar PPI patterns. A number of advantages can be attained over conventional practice with systems using tubes made with the P7 type phosphor. A few of these will be mentioned without description:

The decay curve of the brightness of a signal is very much improved over the exponential decay of phosphors (see Figure 6).

The brightness level is limited only by what the best cathode ray tubes can do, so that ambient light level is not important.

The size of the picture can be made as large as desired by television projection techniques.

The viewing time is continuously adjustable over the range of a few seconds to several minutes.

A means is provided for obtaining television type signals and this means can be used to reduce the bandwidth requirements for relaying purposes.

Improvements in signal-to-noise ratio are possible by the integration effects of superposing successive radar patterns.

A block diagram of a system is shown in Figure 8. In the tests performed, the radar system was adjusted to a rotation period of approximately 6 seconds and the sweep times were operated at both 800 microseconds (80 mile range) and 100 microseconds (10 mile range) with adequate performance at both ranges. This showed that the writing speed was adequate to record the short range radar which required much higher sweep speeds and peak currents in the writing beam than the long range radar.

The high writing speed makes possible operation of the writing gun with television type scan in which the modulating signal is applied for a thirtieth of a second (one frame time) during which time the whole target can be covered. The writing beam can then be turned off for one or more seconds before another picture is flashed on, but the reading beam, operating continuously, produces a signal for a steady picture on the kinescope. This type of operation provides a means of viewing continuously a television type picture that is generated at a rate too slow for normal viewing due to excessive flicker. Such a problem is encountered in the Teleran system, in the receiver unit on board the airplane. Because the different pictures for each altitude level are sent out as successive frames, each receiver obtains the pictures for its altitude level at a rate of between one and four pictures per second. The flicker thus produced is very objectionable, but can be reduced if viewed on a kinescope with special phosphor having a suitable afterglow. However, the picture brightness is down by the ratio of time "off" to time "on" of the signal, which can be compensated for by the use of a storage tube in the manner described above. Such operation has been tested and found satisfactory both in terms of storage time and resolution.

The resolution of the stored picture is best discussed in terms of television practice. Because the picture is formed by the action of a moving cathode ray beam, the smallest discrete picture element possible is the size of the focused spot. Therefore, the maximum picture content possible is the number of elements or adjacent spot areas that can cover the total area of the target. This is true regardless of the type of scanning used. A television type scan is the most efficient because it arranges the elements as close together as possible without producing any overlapping. The PPI type scan has considerable overlapping near the center of the picture, but this does not appreciably affect the resolution. Its only effect is to increase the bandwidth of the signal required to send its pictures over that required for the same picture rate with television type scan.

It can be shown too, that the number of picture elements possible does not vary with the target size. A larger target must be moved farther away from the electron lens of the gun if it is to be covered by the same deflecting angle of the beam. The increased gun-to-target distance causes the spot area to increase in direct proportion to the increase in target area, and so the number of elements stays constant. This property, inherent in the electron optics of cathode ray tubes, applies when all other factors stay constant.

In view of the above, it is customary to refer to the number of elements contained in a picture by the number of parallel lines in which they can be arranged, which is the number of scanning lines used to build up the picture. A standard television picture has approximately 500 lines and, if it were of square aspect, (as high as it is wide) it would have 250,000 elements. For aesthetic reasons, it has an aspect ratio of 4:3 or its height is three-fourths of its width, and it therefore contains over 300,000 elements. This is the order of magnitude of the picture content available in the graphechon with present standard guns and techniques.

Writing speed is customarily measured, in oscillographic practice, in feet or meters per second. So measured, the writing speed of the graphechon is considerably better than 4,000 feet per second. Expressed in more meaningful terms, this is equivalent to better than

Fig. 9—Single sided target, magnetic deflection Graphechon.

nine million elements per second. This speed has been demonstrated by the test of television operation in which a picture containing 300,000 elements was written onto the target in one thirtieth of a second. Still higher writing speeds can be obtained, though only at the expense of resolution, because they require higher beam currents and this causes the spot size to increase, everything else held constant.

Figures 9, 10, and 11 are photographs of actual tubes built and operated.

Fig. 10—Single sided target, electrostatic deflection Graphechon.

GENERAL COMMENTS

When the voltage across the film becomes excessive, breakdown occurs, and in an interesting manner. When the signal plate is given an increment in its negative voltage the picture on the kinescope goes white all over, indicating increasing secondary emission as a transient condition until the surface comes to collector potential. But before this equilibrium can occur, there is a sudden appearance of a large, round patch of white over part of the target. The center of this area is the point at which the film broke down with the emergence

Fig. 11—Double sided target, magnetic deflection Graphechon.

into space of a stream of electrons which sprayed over the adjacent portions of the target and charged them negative. The discharge removes the gradient from the film and gives it a chance to heal. The reading beam then proceeds to remove this surface charge and tries again to bring the surface to collector potential, but breakdown may again prevent this. No permanent damage seems to result to mar operation at normal voltages if breakdown is not permitted to occur repeatedly.

Another effect that will be noticed under some conditions, is called the co-planar grid effect. A strong writing signal produces an area of negative potential on the target which suppresses the secondary emission around it for some distance, depending on the value of the potential and the size of the area. In the viewed picture this can be shown by adjusting the appearance of the blank target to an intermediate shade of gray. A strong signal will show up as a white patch, outlined by a black border which shades off to the normal gray. The extent of this border will decrease linearly with viewing time, even though the signal from the area holds constant, because it is a function of the surface potential which decreases steadily even during the time when the secondary emission is saturated. While this effect serves to distort the picture, it may be regarded as a useful type of distortion in that it tends to emphasize the information.

Another factor that varies with viewing time is the resolution in the picture as affected by the redistribution of secondary electrons. Immediately after the writing beam produces its record, the picture has its full resolution, which is the best that the beam can do, but as the reading beam scans over the target in repeated frames, the resolution of the pattern will change in a manner depending on its configuration. An isolated spot will tend to decrease in size whereas two spots close together will tend to merge into one large spot. These effects are only apparent in the fine detail which requires better than 200 line definition to be resolved. It occurs because the strong gradients at the edges of the negative area causes complete removal of all secondary electrons emitted and so that area tends to reduce in size. These secondaries are collected by the adjacent positive areas, from which they are removed faster than they can accumulate, unless the negative areas are close together. In this case, the region between them slowly goes negative and the spots appear to merge.

Some qualitative observations were made on the two kinds of noise that relate to the operation of this tube. The first is the noise generated by the tube and its associated circuits. This occurs when the reading beam current is reduced to a very low value in an attempt to obtain the maximum viewing time. The output signal approaches the noise level of the amplifier, which causes a grainy appearance in the viewed picture that is characteristic of this type of noise. However, for most radar applications there is enough reserve viewing time so that this type of noise is not serious.

The most important type of noise is that generated by the radar receiver when its signal-to-noise ratio is low. By proper adjustment of several factors, it is possible to obtain an improvement in signal-to-noise ratio due to the superposition of successive radar scans. The true signals will occur in the same part of the target repeatedly and their effects will be added, whereas the noise is a random pattern and will not add to the same extent over any given period of time. Signals that can only be detected by such integrating arrangements can therefore be observed in the final picture.

Another important gain in this type of operation arises from the fact that the target is not completely discharged by small writing beam currents, such as occur with the noise pulses. The viewing time for these pulses will be shorter than for the stronger signal pulses which can be made to discharge the target completely. Therefore, after a short interval, the signal is still visible but the noise is largely gone except for the few noise pulses that happen to be as large as the signal.

The tubes and results described in this paper have all been produced in a research laboratory. However, because some of the processing techniques are critical, much additional development work remains to be done before consistently reproducible tubes can be produced on a commercial basis.

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