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RCA REVIEW

FOREWORD

This issue comprises Part II of the September 1951 issue of *RCA Review*. It consists of 11 papers which originally appeared in the *Proceedings of the Institute of Radio Engineers*.

Considerable effort is being expended by the industry on the study of color television systems. Because of the importance of the tri-color kinescope in a color system, it is felt that the information contained in these papers should be given the widest possible dissemination, and that republication for the benefit of *RCA Review* readers is warranted.

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The Manager, RCA Review

METHODS SUITABLE FOR TELEVISION COLOR KINESCOPES*†

By

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Princeton, N. J.

Summary—This paper is the first of a series which covers Radio Corporation of America work on color television cathode-ray picture reproducers (color kinescopes) for the home. Minimum reproducer requirements are here considered to be high-light brightness and resolution equal to or exceeding that achieved in the present United States black-and-white television system, and large-area three-color fidelity which encompasses the major part of the horseshoe-like area of the chromaticity diagram of the International Commission of Illumination (I.C.I.). Color phosphors with electron-beam excitation meet the requirements.

One color-kinescope method, which requires the beam to be accurately positioned at all times during scanning on a screen of adjacent subelemental color-phosphor areas, has practical disadvantages. In a second method, using a similar type of kinescope, the beam position controls the color signal; although accurate scanning is not required, some of the disadvantages are the same. A third method, which uses adjacent complete picture images, optically combined, has little to offer over the use of three separate color tubes. A phosphor screen, whose color can be changed by a difference in electron-beam velocity or current density, has attractive features but is not available in practical form. Methods of considerable interest are those whereby either the electron beam is electrically controlled at the phosphor screen for changing color or whereby shadowing techniques are employed to produce a direction-sensitive color screen. All these methods were investigated; subsequent papers of the series will describe some of the tubes which were built and will give information as to their design and operation.

Introduction

INVENTORS and scientists have been concerned with television reproduction in color ever since the late 1920's when a number of color television demonstrations were given using scanning-disc techniques.[1,2] Although the patent literature and occasional publications indicate that thought was being given to all-electronic means for

* Decimal Classification: R583.1.

† Reprinted from *Proc. I.R.E.*, October, 1951.

[1] J. L. Baird, July, 1928. See R. F. Tiltman, "Television in Natural Colors Demonstrated", *Radio News*, Vol. 10, p. 320, October, 1928.

[2] H. E. Ives, "Television in Color", *Bell Laboratories Record,* Vol. 7, pp. 439-444, July, 1929.

color reproduction, the most successful work of the 1930's continued to use mechanical methods. This work reached its ultimate about 1940 when the field-sequential color television system using a rotating color disc was extensively demonstrated and publicized.[3] Although the color-disc method, by adding the cathode-ray tube, eliminated some of the more complex moving parts of the mechanical scanning system, there were inherent limitations in reproduction, namely, the inability to provide color sequences at a sufficiently rapid rate for other than frame- or field-sequential methods and the inherently small-size picture which resulted from any practical direct-view receiver.

Recognition of these limitations stimulated efforts toward electronic solutions. Work in this direction by the Radio Corporation of America led, early in 1940, to a demonstration to the Federal Communications Commission of color reproduction using three optically-superimposed images from three cathode-ray tubes, thereby eliminating all moving parts.[4] By 1942, J. L. Baird, in England, also demonstrated all-electronic color pictures, but by means of a single cathode-ray tube producing two adjacent images, optically combined to give a two-color effect.[5] His British patent application of 1942 and 1943[6] showed that he had more ingenious tubes in mind. One of these, using a two-sided phosphor screen for a two-color picture, was actually demonstrated in principle by Baird in 1944. At the same time he described a more complex tube suitable for three colors.[7] RCA engineers also continued to study the single-tube color reproducer during this period, but it was not until after World War II that such factors as improved high-voltage and deflecting systems, metal kinescopes, aluminized phosphors, etc., provided the key to some of the problems. As a result of this progress, it finally became possible, early in 1950, to demonstrate a

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[3] P. C. Goldmark, *et al*, "Color Television", Part I., *Proc. I.R.E.*, Vol. 30, pp. 162-182, April, 1942; and Part II, *Proc. I.R.E.*, Vol. 31, pp. 465-478, September, 1943.

[4] "See Television in Color—Members of F.C.C. Visit Plants of RCA and Philco", *The New York Times*, p. 18, February 6, 1940; also "Television in Color Demonstrated by RCA", *The Philadelphia Inquirer*, p. 18, February 6, 1940.

[5] "J. L. Baird's Improved Colour Television", *Electronic Engineering*, Vol. 15, p. 137, January, 1943. See also *Wireless World*, Vol. 49, p. 41, February, 1943.

[6] J. L. Baird, British Patent 562,168 (provisional specification left July 25, 1942, complete specification left July 23, 1943).

[7] "J. L. Baird's Telechrome", *Jour. Tel. Soc.*, Vol. 4, pp. 58-59, September, 1944. See also *Electronic Engineering*, Vol. 17, pp. 140-141, September, 1944; *Electronics*, Vol. 17, p. 190, October, 1944; and *Wireless World*, Vol. 50, pp. 316-317, October, 1944.

satisfactory and practicable single-tube three-color reproducer for the home.[8,9]

The purpose of this paper is to present some of the problems of a three-color reproducer and to show how they may be solved in all-electronic form using cathode-ray beams and luminescent screens. This paper is the first of a series of articles; subsequent papers will present technical information on some of the color kinescopes which have been developed by RCA and the techniques necessary for their utilization.

Requirements of a Color Reproducer

Some of the requirements of a color reproducer are apparent from black-and-white television experience. The picture should have a large area, preferably equal to or larger than that of a 16-inch kinescope (14⅝-inch diagonal). For color, the picture brightness should be not less than, and perhaps exceeding, that of black-and-white home television reproduction. It is important, of course, that good contrast range be achieved; it must be noted that the effect of ambient white-light illumination, which reduces contrast in black-and-white pictures, has the additional effect of reducing chromaticity in color reproduction.

An additive color system, such as one produced by electron-beam excitation of phosphors, with or without color filters, requires only three primary colors, red, green, and blue, for good color reproduction of large-area detail.[10] More recently, it has been established[11] that the normal human eye is much less sensitive to color in small detail, the color defection resembling that known as tritanopic vision (blue blindness). Thus, a color reproducer must have good three-color primaries for the larger areas, but needs only a limited two-color, or even monochrome reproduction for fine detail. Although this characteristic of the eye is utilized in television systems employing "mixed-highs"[12] the application of the principle in a color-reproducer system is not yet

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[8] T. R. Kennedy, Jr., "RCA Shows All-Electronic Tube as Key to Color Television", *The New York Times*, p. 1, March 29, 1950; "New Color Television Tube Seen Bringing Color Programs to the Home", *Radio Age*, Vol. 9, pp. 3-5, April, 1950.

[9] RCA Laboratories Division "General Description of Receivers Which Employ Direct-View, Tri-Color Kinescopes", *RCA Review*, Vol. XI, pp. 228-232, June, 1950.

[10] Ralph M. Evans, AN INTRODUCTION TO COLOR, John Wiley and Sons, Inc., New York, N. Y., 1948.

[11] See W. E. K. Middleton and M. C. Holmes, "The Apparent Colors of Surface of Small Subtense", *Jour. Opt. Soc. Amer.*, Vol. 39, pp. 582-592, July, 1949 and other references given therein.

[12] A. V. Bedford, "Mixed Highs in Color Television", *Proc. I.R.E.*, Vol. 38, pp. 1003-1009, September, 1950.

a matter of public knowledge. (The color kinescopes to be considered later will be capable of equal resolution in each of the primary colors and, hence, will provide more color fidelity than the eye can use.)

Colorimetry makes use of the International Commission of Illumination (I.C.I.) chromaticity diagram shown in Figure 1.[10] The entire range of colors observable by the normal eye is found within the horseshoe-shaped figure, whose periphery bears numbers to indicate pure spectral wave lengths in millimicrons. Any color has x and y coordinates which specify the fraction of red and green components of a fictitious and physically unrealizable set of primary colors. A three-color television reproducer must use realizable primary colors which, in an optimum case, would lie so that lines joining their I.C.I. coordinates encompass the most important part of the area of the horseshoe of Figure 1. Suitable primary color points, as suggested by Hardy and Wurzburg,[13] are shown by the circled points in Figure 1.

The resolution, or fineness of detail, which a color reproducer must achieve, depends on the capabilities of the system with which it is to be used. Present 525-line black-and-white television, with 60 interlaced fields through a 4.25-megacycle channel, is capable, under ideal conditions, of about 340-line resolution in each direction. If it is assumed that there is no deterioration of standards, and that no use is made of the above-discussed dichromatic vision for small detail, the color reproducer should also have at least 340-line resolution in each direction and should have the appropriate number of picture-element groups, each one of which must be capable of light emission in any one of the three primary colors.

A color reproducer need not operate with all of the possible color television systems, although most all-electronic reproducer methods can be made to operate on any known color system, with more or less difficulty. Although color systems have been classified as field-sequential, line-sequential, dot-sequential, and simultaneous,[14] the distinction is not straightforward. The system, sometimes called "dot-sequential," which was successfully field tested by RCA in 1949-1950,[15] is also a simultaneous system with brightness information which amplitude modulates the main carrier, color-hue information which phase modu-

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[10] Ralph M. Evans, *loc. cit.*, Chapter 13.

[13] A. C. Hardy and F. L. Wurzburg, Jr., "The Theory of Three-Color Reproduction", *Jour. Opt. Soc. Amer.*, Vol. 27, pp. 227-240, July, 1937.

[14] "The Present Status of Color Television", Report of the Senate Advisory Committee on Color Television, *Proc. I.R.E.*, Vol. 38, pp. 980-1002, September, 1950.

[15] RCA Laboratories Division, "A Six-Megacycle Compatible High-Definition Color Television System", *RCA Review*, Vol. X, pp. 504-524, December, 1949.

lates a subcarrier (the so-called "sampling frequency"), and color-saturation information which amplitude modulates this same subcarrier.[16] The nature of the color system, simultaneous or sequential, is an important consideration in the color reproducer. A truly sequential system is one in which the colors appear one at a time in sequence and are reproduced by the reproducer only one at a time; in a cathode-ray reproducer, the electron beam or beams share the time of use between the colors. For this reason, in a color-kinescope reproducer, no matter whether one or three electron beams are used, the brightness of the sequential picture is inherently limited to ⅓ of that

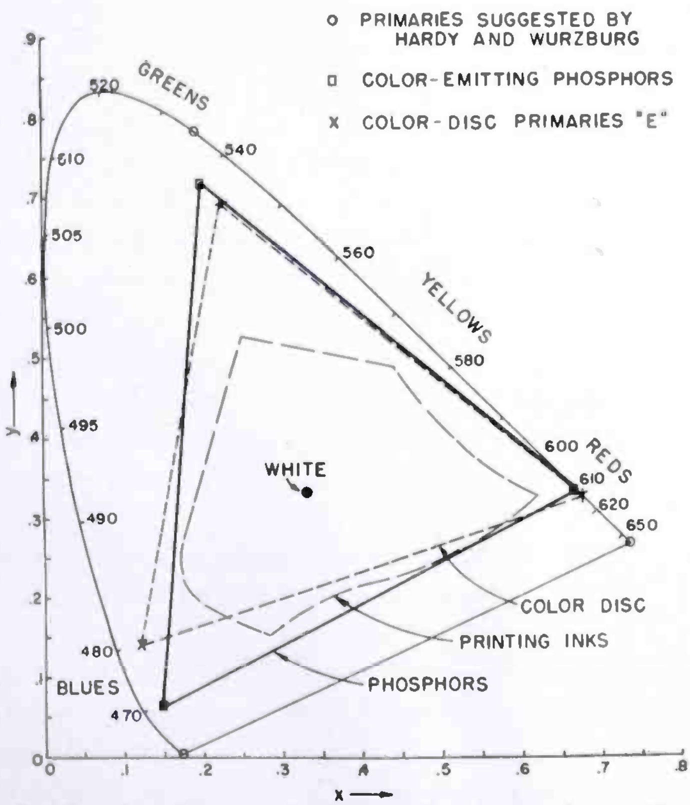

Fig. 1—The I.C.I. color diagram includes all visual colors. The three color primaries achieved by unfiltered phosphors are compared with the color disc and with the idealized primaries of Hardy and Wurzburg. The area possible with modern color printing (according to MacAdam) is shown by the dashed-line figure.

of simultaneous reproduction with three beams. A television system which permits *either* sequential or simultaneous presentation, such as the aforementioned RCA color system, is advantageous because the choice of reproducer tube and reproduction method can be made on purely economic grounds.

[16] When a black-and-white picture is transmitted by this compatible system, the amplitude of the subcarrier is zero and the transmission is identical with that of a black-and-white system.

Regarding the requirements imposed by the color system on the reproducer, it is clear that a purely sequential system requires time-switching of colors and there is, therefore, an advantage in a reproducer in which switching can be done by the application of sine waves, especially if it is necessary to change color at a rapid rate. With cathode-ray reproduction, when three electron beams are used (one for each color), simultaneous reproduction has no such problem of color switching. A reproducer with one electron beam, used for simultaneous presentation, must have some means of changing colors, but the problems are quite different from those with sequential presentation. For the inventor of new color kinescopes, a color system which allows either simultaneous or sequential presentation again has the advantage of permitting greater flexibility of design.

Color Phosphors

The requirements for a color reproducer can be well fulfilled by a cathode-ray device, provided that suitable color-emitting phosphors or color filters are used. Most luminescent materials have characteristic colors other than white, and the "white" phosphors of the black-and-white kinescope are actually mixtures of phosphors of two complementary colors, or three-color mixtures which give white. In view of this, it is clear that use of such a "white," with a color filter, as is done in the color-disc method of reproduction, makes inefficient use of the electron beam since the beam energy must divide itself among two or three color phosphors, with only one portion of the light going through the filter at a time. The best use of cathodoluminescence, then, is to eliminate filters as much as possible by choice of phosphors with high light output and I.C.I. points close to the ideal ones of Figure 1.

The art of preparing cathodoluminescent materials is an extensive one,[17] in which many varieties are available. For the color tubes demonstrated by RCA in March, 1950, willemite (Zn_2SiO_4:Mn) was used for the green and another silicate [$CaMg(SiO_3)_2$:Ti] for the blue. The third phosphor was a readily-available cadmium borate ($2CdO.B_2O_3$:Mn), which has a red-orange color which many observers judged to be not close enough to the optimum red. At the suggestion of G. C. Sziklai of RCA Laboratories, a didymium-glass filter was used which has a sharp rejection band at the yellow sodium lines; at other wave lengths it is very much like a neutral filter with 40 to 50 per

[17] H. W. Leverenz, AN INTRODUCTION TO LUMINESCENCE OF SOLIDS, John Wiley and Sons, Inc., New York, N. Y., 1950.

cent absorption. This filter made the color reproduction satisfactory,[18] and, although a substantial loss of light resulted, there was a slight compensating advantage in the improved contrast due to the neutral-filter action. However, the borate red left much to be desired in efficiency and the output of the more efficient green and blue phosphors had to be reduced to achieve a color balance.

As a result of much careful work, an improved red-emitting phosphor has been synthesized.[19] When the same green willemite phosphor, a sulphide blue ($ZnS:Ag$) of improved efficiency,[20] and the new red material [$Zn_3(PO_4)_2:Mn$] are used, I.C.I. points which form the solid-line triangle in Figure 1 are achieved, together with improved visual efficiency. A comparison is made in Figure 1 with the primaries achieved by the color-disc television reproducer, on which considerable effort has been expended over a number of years. The comparison is made with the result of this work, the so-called primaries, "E."[21] A second comparison is made with the range achieved by modern printing inks shown by MacAdam.[22] It is evident that the phosphor primaries are superior to the others and sufficiently close to the optima for excellent color reproduction. Further improvement in efficiency of the red component is, of course, still desirable.

To obtain a very desirable increase in brightness, the color phosphors can be operated at high voltages. This is readily possible provided aluminizing is used, a technique which has other advantages as well.[23]

It is now appropriate to examine the different ways in which such phosphors can be used for a color kinescope.

Accurate Beam-Scanning Method

The earliest proposals for a color kinescope were extensions of the black-and-white technique, specifying that the white phosphor screen should be covered by a "checkerboard" of color filters,[24] or

[18] Exhibit 392, "Color Characteristics of the RCA Tri-Color Kinescopes", Radio Corporation of America, F.C.C. Dockets 8736, 8975, 9175, and 8976; 1949-1950 hearings.

[19] A. L. Smith, "Luminescence of Three Forms of Zinc Orthophosphate: Manganese", *Jour. Electro. Chem. Soc.*, Vol. 98, pp. 363-368, September, 1951.

[20] Developed by H. W. Leverenz and the Chemico-Physics group at RCA Laboratories, Princeton, N. J.

[21] Exhibit 210, Columbia Broadcasting System, F.C.C. Dockets 8736, 8975, and 9175; 1949-1950 hearings.

[22] D. L. MacAdam, "On the Geometry of Color Space", *Jour. Frank. Inst.*, Vol. 238, pp. 195-210, September, 1944. Also see *Life*, Vol. 17, July 3, 1944.

[23] D. W. Epstein and L. Pensak, "Improved Cathode-Ray Tubes with Metal-Backed Luminescent Screens", *RCA Review*, Vol. 7, pp. 5-10, March, 1946.

[24] V. K. Zworykin, U. S. Pat. 1,691,324 (applied for July 13, 1925).

should be replaced by one of ruled phosphor lines of the three colors in succession.[25,26] Although, with the line screen, scanning by the single electron beam could be either parallel or transverse to the phosphor lines, scanning accuracy was easier to achieve with the former. Figure 2 illustrates this method. Obviously, extreme scanning accuracy in one direction is required if color dilution or error is to be avoided and a high-definition system seems very difficult to achieve. The checkerboard color screen, or dot screen, requires accuracy of scan in both directions; it was once considered difficult to make[25] and would certainly be difficult to operate; nevertheless, it has been revived in a very recent patent.[27] The colors may be sequentially presented when only one electron gun and beam are used and, of course, are controllable by slight shift in beam position. If the beam is controlled to excite

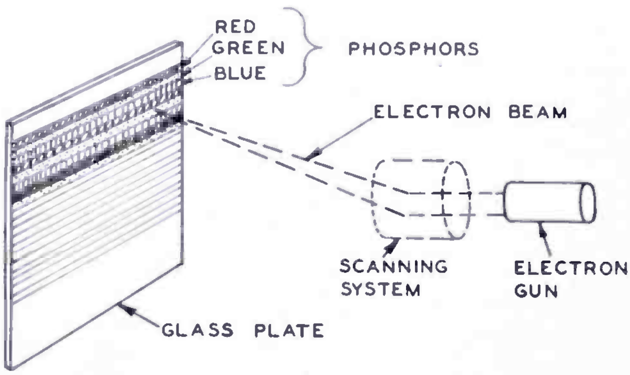

Fig. 2—Example of line-screen color kinescope using one electron beam. To assure correct colors, beam scanning must be highly accurate. No automatic registry means are shown.

more than one color strip or spot at a time, simultaneous presentation with a single beam is possible. A beam may also be split into three or more parts, separately controlled, but through a common deflecting system, to achieve simultaneous presentation.[28,29]

Line or dot screens with this method require phosphor lines or dots which are of a size less than one-third of the distance between scanning lines (when scanned parallel) or less than one-third of a picture-element size (when scanned transversely). The making of the screen is only one of the difficulties, since the scanning beam must also have a correspondingly reduced minimum spot size.

The achievement of high scanning accuracy is aided by automatic

[25] R. Rüdenberg, U. S. Pat. 1,934,821 (convention date May 5, 1931).
[26] M. vonArdenne, Brit. Pat. 388,623 (convention date June 19, 1931).
[27] H. Kasperowicz, U. S. Pat. 2,508,267 (applied for October 26, 1945).
[28] Fernseh Akt. Ges., Brit. Pat. 434,868 (convention date March 6, 1933).
[29] B. T. Hewson and A. Locan, Brit. Pat. 533,993 (Complete specification, left June 17, 1940).

control and registry by feedback methods, of which a large variety have been devised during the past decade. Some of the proposals have been published as patents[30–32] but many are still being worked on in the laboratory. Although the achievement of automatic registry by control signals or feedback may lead to complex circuitry, it seems clear that a single-beam, line-screen, color kinescope can be made with relatively little complexity since it would require few more parts than the black-and-white conventional kinescope. Among the line-screen tube disadvantages are the color error when the beam is misregistered, or incorrectly focused.

Over a number of years, experiments with line screens were made by D. W. Epstein at RCA Laboratories by a three-step phosphor-settling process through a movable mask. Subsequently, suitable screens were made by a development of the RCA Victor Division at Harrison, N. J. in which the three-color phosphor line-groups were printed, using the silk-screen process.[33] A demonstration of the principle of a line-screen tube was shown by RCA to the Federal Communications Commission on October 10, 1949. At RCA Laboratories, color pictures were achieved both with accurate scanning linearity alone and with associated feed-back circuits to lock the beam in its correct position at all times.[34]

Signal Control by Beam-Scanning Position

The method of the previous section requires extreme scanning accuracy because the scanning and the color signals are essentially independent phenomena. If, however, the color signals can be made dependent on the scanning, the latter need be no more accurate than in black-and-white practice, since the scanning now controls the colors. This may be done by use of a color-sensitive photo device, or other special signal-generating means built into the screen, by which the kinescope control grid is automatically switched to the correct primary color signal, depending on the instantaneous beam position. The method has been suggested for transverse scanning of line screens[34,35,35a]

[30] V. K. Zworykin, U. S. Pat. 2,415,059 (applied for October 13, 1944).

[31] W. H. Stevens, Brit. Pat. 803,080 (complete specification left July 4, 1945).

[32] C. E. Huffman, U. S. Pat. 2,490,812 (applied for January 3, 1946).

[33] N. S. Freedman and K. M. McLaughlin, "Phosphor-Screen Application in Color Kinescopes", *Proc. I.R.E.*, Vol. 39, pp. 1230-1236, October, 1951.

[34] D. S. Bond, F. H. Nicoll and D. G. Moore, "Development and Operation of a Line-Screen Color Kinescope", *Proc. I.R.E.*, Vol. 39, pp. 1218-1230, October, 1951.

[35] P. K. Weimer, U. S. Pat. 2,545,325 (applied for January 30, 1948).

[35a] Alfred N. Goldsmith, U. S. Pat. 2,431,115 (applied for August 5, 1944).

but, because of the need for an extremely small focussed spot, it is subject to some of the same disadvantages as the accurately controlled scanning method of the previous section.

ADJACENT-IMAGE METHOD

Not far behind the accurate beam-scanning method in point of time were proposals for a color kinescope involving two or more complete television images, in different colors, which were optically combined by mirrors or by projection. The method can be used with three beams[36,37] allowing simultaneous presentation or with one beam[38] which, in this case, is restricted to sequential presentation. Figure 3 illustrates the method in one form. Although either field-sequential or line-sequential systems are well suited for the one-beam tube, the latter system has

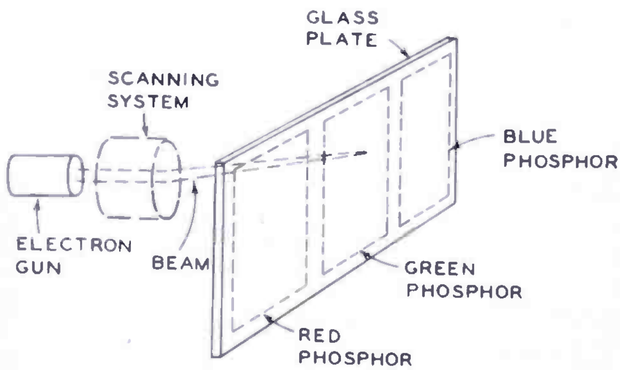

Fig. 3—Kinescope with adjacent color images. Optical combining means for direct view or projection are required.

received particular attention[38,39] because a single line scan can be made to traverse all three areas. Because of the optical registration, which is very similar to that needed for three separate color kinescopes, the combination of the three images in one tube is not a sufficient advantage to make the method attractive. For a direct-view kinescope, furthermore, the front face area is very inefficiently used. Although good performance is difficult to achieve,[40] such an all-electronic picture reproducer device has been frequently demonstrated,[5,41,42] probably because the tube is so easily constructed.

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[5] J. L. Baird, *loc. cit.*

[36] K. Schlesinger, U. S. Pat. 2,083,203 (convention date October 1, 1932).

[37] J. C. Wilson, U. S. Pat. 2,294,820 (applied for April 29, 1941).

[38] Fernseh Akt. Ges., Brit. Pat. 432,989 (convention date March 6, 1933).

[39] R. Lorenzen, U. S. Pat. 2,200,285 (applied for June 22, 1937).

[40] C. S. Szegho, "Color Cathode-Ray Tube with Three Phosphor Bands", *Jour. S.M.P.T.E.*, Vol. 55, pp. 367-376, October, 1950.

[41] Color Television, Inc., Exhibits 237, 259, 260, Federal Communications Commission, Dockets 8736, 8975, and 9175; 1949-1950 hearings.

[42] Exhibit 210, Item 8 and Item 9b, Columbia Broadcasting System, Federal Communications Commission, Dockets 8736, 8975, and 9175; 1949-1950 hearings.

The J. L. Baird two-color tube[6,7] using one color phosphor on one side of a mica sheet and the second phosphor on the opposite side, with two electron guns at opposite sides and at an angle to permit viewing, is to be classified as in the adjacent-image group but requires no optical registry. However, a two-color system is severely handicapped in comparison with a three-color one.

Multiple-Color Phosphor Screen

A superficially attractive possibility for a color kinescope uses a single phosphor or a combination of phosphors in which color is responsive to either electron velocity or current density. Considering

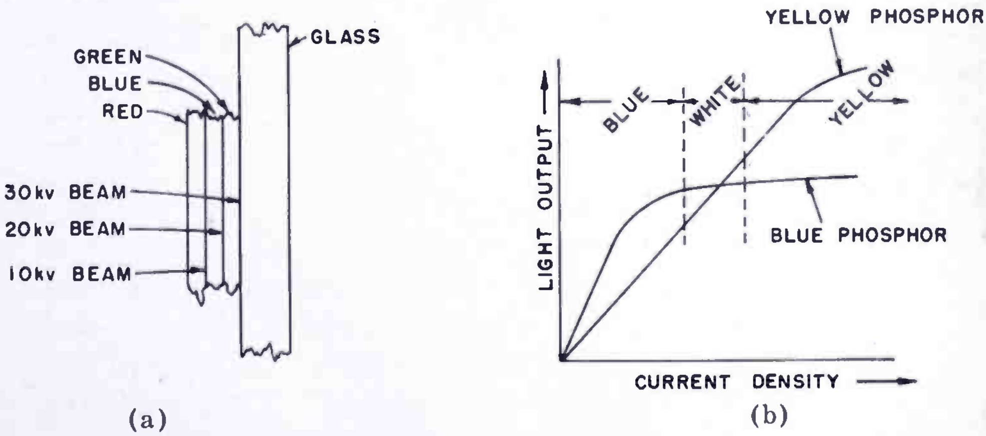

Fig. 4—Multicolor phosphor screen, (a) shows a multiple-layer screen with color depending on beam velocity. (b) shows how saturation in a two-component screen makes color dependent on current density.

the former, it is possible to build up a three-layer screen so that electrons of one velocity penetrate only the first layer, producing one color, whereas faster electrons will penetrate to the second layer and the fastest electrons reach the third layer, so producing three colors, as shown in Figure 4a.[43] A variation of the method uses barriers of different thickness on the beam side of the color phosphors.[44] Either a single gun, in which the cathode potential is varied to change the electron velocity, or three guns of differing cathode potentials can be used for color rendition. Unfortunately, it appears unlikely that such screens can be made to operate with electron-velocity differences of less than around ten kilovolts, so that sequential switching is very difficult at best. There may be inherent color dilution, as well, so as

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[6,7] J. L. Baird, *loc. cit.*
[43] C. S. Szegho, U. S. Pat. 2,455,710 (applied for December 21, 1943).
[44] G. C. Sziklai and A. C. Schroeder, U. S. Pat. 2,543,477 (applied for July 29, 1948).

to affect color fidelity. Use of three electron sources at such large velocity differences has other difficult problems, such as scanning amplitude differences.

A change of color with current density has often been observed[45] when saturation of one or more of the phosphor components sets in (See Figure 4b). This effect has been proposed for a color kinescope by using variable-frequency pulses for brightness modulation and changes in current density for color.[46] The color change in the usual two- or three-component phosphors due to saturation is slight and high-chroma colors are difficult to achieve. However, a color effect has been observed in certain *single* phosphors which have high-chroma emission of two widely separated colors, depending on current density.[47] If such a phosphor can be made with light efficiencies comparable to those now widely used, a new technique for color reproduction will become practical.

Beam Control at Phosphor Screen for Changing Color

A general method, which offers an extremely fertile field for particular and interesting variations in a color kinescope, is one in which the electron beam is deflected, or otherwise controlled, in the vicinity of the phosphor screen. In simplest form, only one electron beam is used, but modifications using multiple beams can also be employed.

Historically, the switching-at-screen approach was first used to eliminate the need for accurate scanning with the color line screens of Figure 2. The method involved insulating the color phosphor strips from each other and applying a high positive potential to the strips whose colors are to be excited, with a low or even a negative potential to the strips containing the other colors.[48-52]

An illustration is shown in Figure 5a, in which the phosphors are deposited on the surface of metal strips, the electron beam coming in at an angle to permit viewing. In view of the closeness of the color

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45 A. Bril and F. A. Kroger, "Saturation of Fluorescence in Television Tubes", *Philips Technical Review*, Vol. 12, pp. 120-128, October, 1950.

46 C. S. Szegho, U. S. Pat. 2,431,088 (applied for December 3, 1943).

47 Unpublished work of O. Schade, RCA Victor Div., Harrison, N. J., and F. H. Nicoll, S. M. Thomsen, and others, RCA Laboratories Div., Princeton, N. J.; and R. C. Bitting and L. M. Seeburger, RCA Victor Div., Camden, N. J.

48 L. C. Jesty, Brit. Pat. 443,896 (complete specification left November 5, 1935).

49 A. V. Bedford, U. S. Pat. 2,307,188 (applied for November 30, 1944).

50 H. E. Kallmann, U. S. Pat. 2,416,056 (applied for February 21, 1944).

51 L. E. Swedlund, U. S. Pat. 2,446,440 (applied for January 28, 1947).

52 L. W. Parker, U. S. Pat. 2,498,705 (applied for July 2, 1947).

strips, as required for high definition, the electric field needed for deflection to the correct color is confined to a region very close to the screen and high voltage differences are required. The color-changing circuits must, therefore, operate with voltages of many kilovolts, and are difficult to make in practical form. With a sequential presentation, the difficulties increase rapidly as the switching rate is increased, which makes switching least difficult for field or frame color sequencing. There are even greater practical disadvantages when a magnetic field is used for switching color.[53]

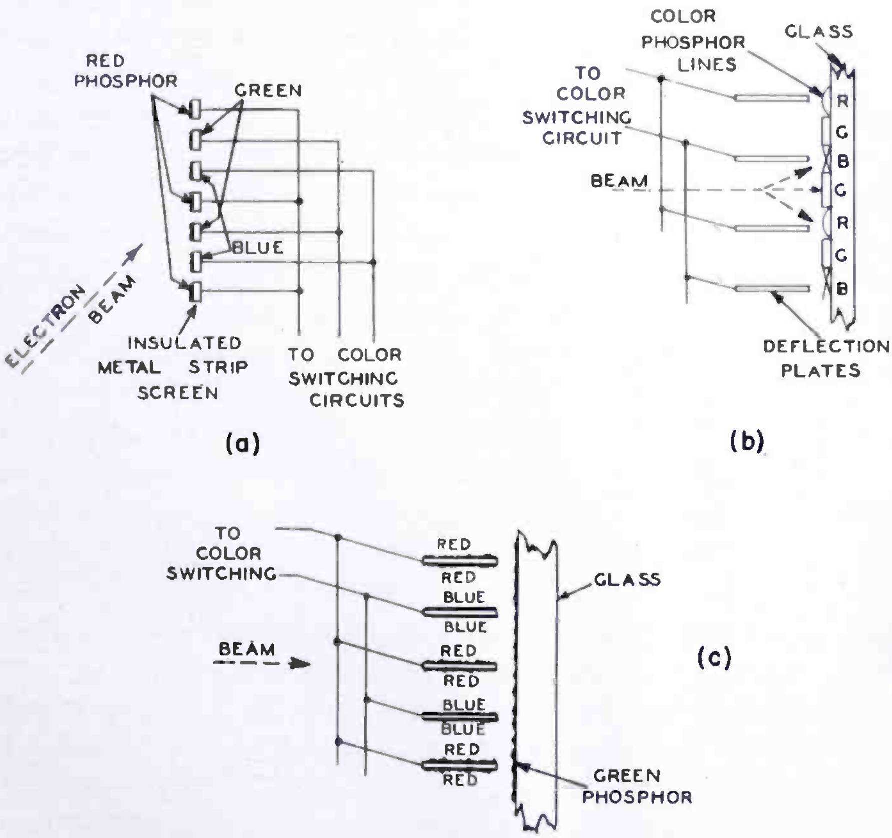

Fig. 5—Beam control at phosphor screen for changing color. (a) Simple line-screen color switching. (b) Deflection switching of colors with line screen. (c) Deflection switching without requiring registry.

One modification of the high-voltage switching method[54,55] eliminates the line nature of the screen by using three closely-spaced, phosphor-coated grids. This makes the phosphor screen easier to fabricate, but the high voltage color-changing and insulation problems

[53] T. W. Chew, U. S. Pat. 2,529,485 (filed October 9, 1945).
[54] A. B. Bronwell, U. S. Pat. 2,461,515 (applied for July 16, 1945).
[55] A. B. Bronwell, "A New Viewing Tube for Color Television", *Tele-Tech.*, Vol. 7, pp. 40-41 and 60-65, March, 1948. Also in *Electronic Engineering*, (London) Vol. 20, pp. 190-191, June, 1948.

remain. In addition, there is now parallax because the three color phosphors are no longer in the same plane; this can be overcome by projection rather than direct viewing, provided depth of focus is sufficient in the projection optics.

The impracticality of such high color-changing voltages suggests actual deflection electrodes at the phosphor screen, so that a single beam can be deflected to the correct color with much lower voltage differences than needed with Figure 5a. One such device is shown in Figure 5b which shows deflection plates aligned with the rows of color-phosphor lines.[48,56] It is seen that, when there is no potential difference between deflection plates, the beam strikes the green-emitting phosphor. Since alternate deflection plates are connected, a potential difference causes the beam to be bent toward either the red- or blue-emitting lines, depending on which group of plates is more positive. A simple calculation shows that, with deflection plates of 1 centimeter or more in width, spaced by about one picture element, only some tens of volts are required to change colors, in contrast to Figure 5a which requires from 100 to 500 times more voltage. The capacitance of the two groups of plates, since there are of the order of 150 to 300 of them in each group, is sufficiently high to pose serious difficulty when rapid color changes are needed. For sequential presentation, correct gating signals applied to the electron gun permit a sine wave to be applied to the color deflection plates, and this permits tuned circuits to be used, thus reducing the power as compared with square-corner switching wave forms.

The registry of such a large number of deflection plates with the phosphor lines is a mechanical difficulty of the Figure 5b method, which has been overcome by depositing two of the color phosphors directly on the deflection plates, as proposed by R. L. Snyder and constructed and improved by H. B. Law, both at RCA Laboratories, Princeton, N. J. An illustration is shown in Figure 5c. This simplifies tube construction but prevents use of aluminizing over the phosphors, since the red and blue light must pass through the green phosphor, which acts as a diffusing screen to reduce undesired directivity of the red and blue colors. When aluminizing is not used, care must be taken to prevent differences in charging up of the phosphors, which cause nonuniform deflection. Special techniques, of course, are also required for use of anode potentials on the kinescope above the "sticking potential" of the phosphors. Improved phosphor conductivity and transparent conducting coating under the green phosphor are methods which

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[48] L. C. Jesty, *loc. cit.*

[56] A. C. Schroeder, U. S. Pat. 2,446,791 (applied for June 11, 1946).

may be used but, in general, much more care must be taken in such a tube than in black-and-white tubes because three different and unmixed phosphors are involved. There is also limited red and blue definition, due to a finite number of deflection plates in the one direction and the diffusion of the red and blue light through the green-emitting phosphor in the other direction. On the other hand, the tube requires comparatively little mechanical registration (chiefly a tilting of the plates to keep them parallel to the deflected electron beam).

The use of fine-meshed control grids at the phosphor screen assembly for overcoming high color-changing voltages was developed by S. V. Forgue.[57] In such tubes, the light-emitting area is composed of a set of parallel, closely spaced, phosphor screens, which are separated by color control grids operated near cathode potential. When one of the color control grids is slightly positive in potential, the electron beam can pass through a subsequent phosphor screen. When the grid is negative in potential, the beam is turned back to strike a preceding phosphor screen. In a two-color tube, one control grid separates two phosphor screens. In a three-color tube, two control grids interleave with three phosphor screens. When such kinescopes are used for a sequential color picture presentation, sine-wave switching can be used for high sequence rates and the capacitance is considerably less than the deflection-plate methods of Figure 5b and 5c. There is, however, parallax between the color images which either limits the viewing angle or suggests projection optics as with the other tube using grids.[54,55]

A switching-at-screen color kinescope, which uses a single electron beam at an average angle of 45 degrees with the viewing screen,[58] was developed by P. K. Weimer. All three color-emitting phosphors are now placed on the front surface of a perforated metal sheet in adjacent line-like areas. By varying the voltage on a nearby and parallel transparent conducting coating, the electron beam is reflected back in a path which can be slightly altered to strike one, or another, color. The phosphor areas and the openings in the sheet are so located that the same color is emitted no matter at what point on the raster the beam is deflected, assuming a fixed reflecting-electrode potential. To obtain a rectangular raster, keystone correction is applied to the deflection circuits. This device has a mechanical requirement, namely, accurate

[54,55] A. B. Bronwell, *loc. cit.*

[57] S. V. Forgue, "A Grid-Controlled Color Kinescope", *Proc. I.R.E.*, Vol. 39, pp. 1212-1218, October, 1951.

[58] P. K. Weimer and N. Rynn, "A 45-Degree Reflection-Type Color Kinescope", *Proc. I.R.E.*, Vol. 39, pp. 1201-1211, October, 1951.

parallelism of the perforated sheet and the transparent reflecting electrode, but in other respects it has many advantages, among which is an effectively perfect superposition of the three color images. A sine wave can be used for sequential color switching, when necessary at a rapid rate, using circuits developed by N. Rynn.

Each of the color kinescopes in this section has been described with a single electron beam; for sequential color presentation only one beam is needed. For a simultaneous presentation, brighter pictures are often obtained by use of three separate electron beams. With the kinescopes using a color control mechanism at the screen, one may use three separate electron guns by operating them at different cathode potentials. The three guns are located as closely together as possible (if a single deflecting system is to be employed). In the methods of Figure 5a, or the Bronwell gridded tube,[54,55] the differences in cathode potentials are so large that a single deflecting system would be impracticable. However, for the Forgue grid-controlled color tube, or the Weimer 45-degree reflection tube, only a small cathode potential difference is required for the three electron guns to cause the fixed-potential color control system at the screen to act differently on each beam. With the type of operation using a transverse control field, as in Figures 5b and 5c, the analogous procedure (i.e., three guns at slightly different cathode potentials) would not be applicable and one is led to a separation of the electron guns in space, with no control field. This becomes a direction-sensitive color screen (treated in the next section), which depends on shadowing.

Direction-Sensitive Color Screens using Electron Shadowing

Because electrons in a field-free region move in substantially straight lines, one can make use of shadow techniques to produce a color-emitting phosphor screen in which color depends on the direction of arrival of the impinging electron beam. An early proposal using color phosphor lines shadowed by an aligned grid is shown in Figure 6.[59] It is seen in Figure 6(b) that a single beam may be deflected and reconverged so as to appear to come from three positions in time sequence. Alternatively, three separate and spaced electron guns may be used as in Figure 6(a). The mechanical difficulties in such a structure are great and the use of the line screen requires a nonsymmetrical deflecting voltage for normal color sequencing in a

[54,55] A. B. Bronwell, *loc. cit.*

[59] W. Flechsig, German Pat. 736,575 (applied for July 12, 1938); see also corresponding French Pat. 866,065.

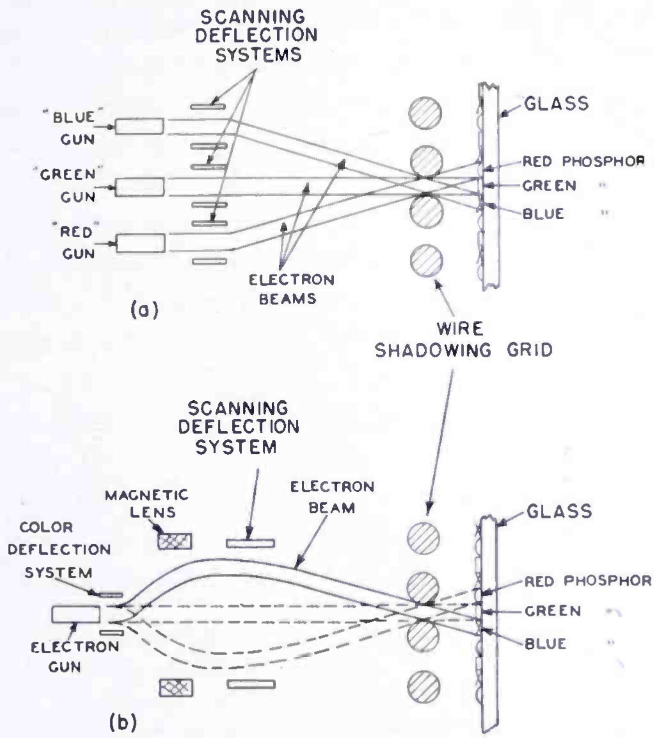

Fig. 6—Proposal by Flechsig using color phosphor lines shadowed by wire grid, (a) with three beams, (b) with one beam deflected at the gun.

one-beam tube; for this reason, a color screen with dots instead of lines has particular advantages.

The first direction-sensitive method to receive considerable publicity made use of a nonplanar surface, and was proposed by Baird for a three-color kinescope.[6,7] Shown in Figure 7, it used a ridged transparent plate with the color phosphors deposited as strips along the ridges. The third color was produced on the opposite side. Modi-

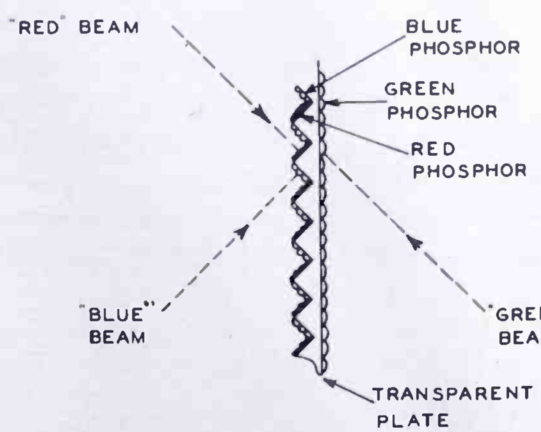

Fig. 7—Baird three-color nonplanar color screen, in principle.

[6,7] J. L. Baird, *loc. cit.*

fied nonplanar color screens using all three beams on the same side were devised by Geer[60] and others,[61,62] for which a typical illustration is shown in Figure 8. The major problems of such a tube, aside from fabrication, lie in obtaining good color directivity and in the complex deflection problems. It is necessary to produce a rectangular raster with three off-axis, keystone-corrected guns, in which not only the edges but each scanning line should be registered with those of the other two guns. Although these problems have not yet been overcome practically, they are now receiving serious consideration in at least one laboratory. A few years ago, R. R. Law and D. A. Jenny, at RCA Laboratories, Princeton, N. J. studied means for reducing the angle of separation of the three beams by using very steep pyramids on the nonplanar surface, and also by constructing alternative nonplanar surfaces, two varieties of which are shown in Figures 9a and 9b. Unfortunately, the deposition of phosphors so nearly parallel to the

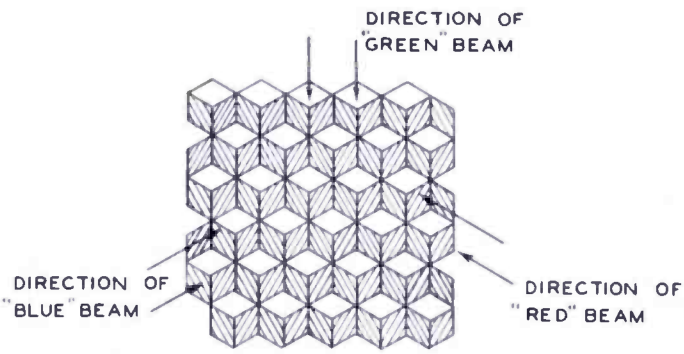

Fig. 8—Cubical-pyramid nonplanar color screen. Sides of cubes facing in different directions are coated with different color phosphors.

direction of viewing leads to so large a light loss that widely spaced guns, with their attendant deflection problems, may be essential.

There is, of course, a very substantial advantage in a direction-sensitive color screen with such a narrow angle between electron beams that a single deflection yoke can be used. Although it is possible to do this with the line-screen shadow device of Figure 6,[63] it appears to be much easier to adopt proposals of Alfred N. Goldsmith, Consulting Engineer to the Radio Corporation of America, and A. C. Schroeder, of RCA Laboratories. Special techniques developed by H. B. Law, of

[60] C. W. Geer, U. S. Pat. 2,480,848 (applied for July 11, 1944).

[61] A. N. Goldsmith, U. S. Pat. 2,481,839 (applied for August 5, 1944).

[62] "Experimental Cathode-Ray Tubes for Television" (developments of A. B. Dumont Labs.) *Electronics*, Vol. 20, pp. 113-115, March, 1947. See also U. S. Pat. 2,544,690 (applied for December 26, 1946).

[63] C. S. Szegho, "Experimental Tri-Color Cathode-Ray Tube", *Tele-Tech.*, Vol. 9, pp. 34-35, July 1950.

RCA Laboratories, showed the practicality of the arrangement and permitted successful tubes to be made using three beams, one for each color.[64] This screen uses color phosphors arranged in groups of three dots in an equilateral triangle; close to the phosphor screen and between it and the electron guns is an aperture mask which produces the shadowing. For each group of three phosphor dots, there is a hole in the shadow mask of about the same size as one dot. An electron beam approaching the scanning mask at a slight angle (of the order of 1 degree) from the line to the center of deflection, will land only

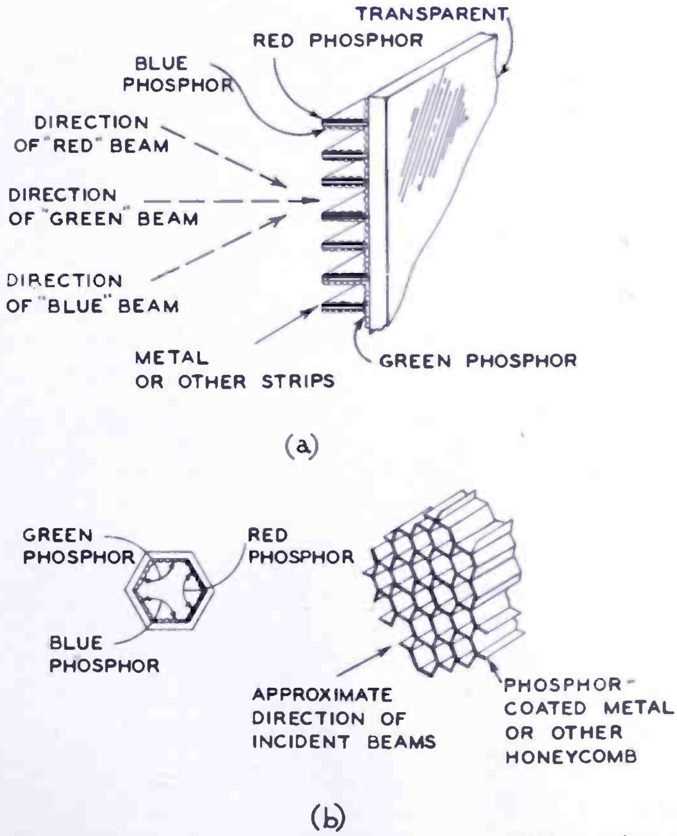

Fig. 9—Two forms of nonplanar direction-sensitive color screen.

on a single color in any one of three rotational positions, 120 degrees apart. Thus, by placing the three guns at an appropriate distance from the axis of the tube and at the correct azimuthal orientation, the three beams may be converged to a point on the screen, and each beam is able to excite only a single color. Use of a very large number of dot groups prevents discernment by the viewer of the picture structure, just as in color printing.

The technique for making the mask and dot screen and their registry is described in another paper.[64] Deposition of the hundreds

[64] H. B. Law, "A Three-Gun Shadow-Mask Color Kinescope", *Proc. I.R.E.*, Vol. 39, pp. 1186-1194, October, 1951.

of thousands of accurately located phosphor dots presented a major problem which was overcome by the use of printing techniques developed by N. S. Freedman and K. M. McLaughlin.[33] Other details of the three-gun shadow-mask color kinescope are discussed in accompanying papers.[65-67] The three beams are converged to a single point on the screen, even through wide angles of deflection, by using an anastigmatic deflection yoke and convergence system.[68]

A modification of the shadow-mask color kinescope is attainable by use of an ingenious development of R. R. Law of RCA Laboratories.[69] In this development only a single electron beam is used; prior to the normal scanning deflection, a small additional deflection at the gun and subsequent convergence moves the beam to different azimuth positions so as to cause any desired color to be emitted. When this is done in time sequence, so as to display each primary color in turn, a sequential color presentation is achieved, and it appears possible to use simple circuit components even at very high sequence rates. Alternatively, by correct control of the beam deflection at the gun, space-sharing of the color phosphors by the beam allows a simultaneous presentation.[69]

Both the one-beam and the three-beam shadow-mask kinescopes were publicly demonstrated[8] in March, 1950 in Washington, D. C. using the RCA color television system.

ACKNOWLEDGMENT

The development of all-electronic color television reproducers at RCA encompassed the entire range of methods surveyed in this paper, as well as methods not described. The accompanying papers describe a limited part of the work and reflect appropriate credit on the authors; in other instances, contributions are mentioned in footnote and text references. There are additional individuals and groups who made major contributions to engineering aspects of the color-tube work.

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[8] *The New York Times* and *Radio Age*, *loc. cit.*

[33] N. S. Freedman and K. M. McLaughlin, *loc. cit.*

[65] H. C. Moodey and D. D. Van Ormer, "Three-Beam Guns for Color Kinescopes", *Proc. I.R.E.*, Vol. 39, pp. 1236-1240, October, 1951.

[66] D. D. Van Ormer and D. C. Ballard, "Effects of Screen Tolerances on Operating Characteristics of Aperture-Mask Tri-Color Kinescopes", *Proc. I.R.E.*, Vol. 39, pp. 1245-1249, October, 1951.

[67] B. E. Barnes and R. D. Faulkner, "Mechanical Design of Aperture-Mask Tri-Color Kinescopes", *Proc. I.R.E.*, Vol. 39, pp. 1241-1245, October, 1951.

[68] A. W. Friend, "Deflection and Convergence in Color Kinescopes", *Proc. I.R.E.*, Vol. 39, pp. 1249-1263, October, 1951.

[69] R. R. Law, "A One-Gun Shadow-Mask Color Kinescope", *Proc. I.R.E.*, Vol. 39, pp. 1194-1201, October, 1951.

These include, at RCA Laboratories, Princeton, A. Rose, F. H. Nicoll, D. W. Epstein, H. Rosenthal, P. Messineo, J. Rajchman, and L. Pensak; the tube-making group under S. W. Dodge and the model shop personnel under F. H. Creager; also the engineers in R. D. Kell's group with their expert knowledge of color television and systems; and L. E. Flory, W. Pike, J. Dilley, V. Landon, and J. Eckert who designed circuits and receivers for testing the color kinescopes. In the RCA Victor Division, G. S. Briggs, H. R. Seelen, L. B. Headrick, and others, the men in the Lancaster tube shop under C. P. Smith, and those in the Harrison tube shop under K. M. McLaughlin, all must be mentioned. The Buckbee, Mears Company of St. Paul, Minnesota supplied many photoengraved parts during the later stages of the work and the active and enthusiastic cooperation of their staff is gratefully acknowledged.

Acknowledgment is due to F. J. Darke, of the Patent Department of RCA Laboratories, whose researches into early patents uncovered many of the references. The classification of color tube methods is also due to Mr. Darke.

A final acknowledgment is made here on behalf of all the authors of this series to Brigadier General David Sarnoff, Drs. C. B. Jolliffe, E. W. Engstrom, and V. K. Zworykin and the others in the management of the Radio Corporation of America whose encouragement and resoluteness were essential to the final successful results.

A THREE-GUN SHADOW-MASK COLOR KINESCOPE*†

By

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Summary—*A three-gun shadow-mask color kinescope and construction techniques thereof are described. The beams from three guns mounted together in a 2-inch diameter neck, are deflected by a single deflection yoke. The guns are pointed so that the electron beams converge to a spot on a thin, perforated metal sheet that acts as a mask and is located a short distance away from a viewing screen composed of many phosphor dots. Associated with each hole in the mask is a trio of phosphor dots capable of emitting the three primary colors, red, blue, and green. The dots are so placed that each electron beam, as it scans, can "see" only one dot of the trio. Each of the three beams is thus capable of exciting one color only, and when all three beams are modulated with the appropriate primary color information a picture in full color can be reproduced.*

An apparatus called the "lighthouse" is used to record the locations of the phosphor dots on a photographic plate placed behind the mask and in the plane of the phosphor screen. A point source of light, at the position from which the deflection of one of the beams appears to take place, is used to simulate the electron beam in recording the phosphor-dot positions. The pattern for one color of phosphor is the same as for the other two colors, and the geometry of the hole system in the mask is such that the three phosphor patterns nest together perfectly. The phosphor screens may be made by using various processes such as electrostatic printing, offset printing, photoprinting processes, silk screening, and settling. The latter two methods are briefly described in the text. Experimental tubes have shown the principles of operation and construction to be sound.

I INTRODUCTION

IN THE PAST, a number of ideas for all-electronic television picture tubes have been proposed that allow both the brightness and color of individual picture elements to be displayed. Progress toward a practical reproducer has been slow, primarily because of the technical difficulties involved. In the last few years, however, many of the difficulties have been resolved by new techniques for black-and-white kinescope production, such as metal-cone construction and aluminized phosphor screens. Other developments described below make the production of a color kinescope feasible.

A résumé of color-tube proposals has been given in an accompanying paper by Herold[1]. Some of these proposals may be compared with tech-

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* Decimal classification: R583.1.

† Reprinted from *Proc. I.R.E.*, October, 1951.

[1] E. W. Herold, "Methods Suitable for Television Color Kinescopes", *Proc. I.R.E.*, Vol. 39, pp. 1177-1185. October, 1951.

niques used in color photography and color printing. For example, color photography by layer emulsion, such as Kodachrome, has a counterpart in the proposal to use three different layers of phosphor for the screen, each phosphor element being capable of emitting one of the three primary colors when selected to do so in some manner by the scanning beam. The proposal to superimpose optically three rasters in the primary colors to form a color picture is similar to color photography employing separation negatives. As for color printing, a great many of the color reproducer proposals have incorporated a structure at or near the viewing screen to produce small elements of color that may be likened to the color dots of a printed picture.

Although a change of color can be obtained with layer phosphors, no commercial tube for the production of color pictures by this method has yet appeared. The optical superposition of three pictures in the primary colors has performed satisfactorily when three separate kinescopes have been used, and this method has served well for system experimentation. A single screen, made up of enough controllable color elements to give a good picture, seems, at first thought, complex. However, should complexity be unavoidable, a color-reproducer tube may still be useful if, by confining the complexity to the fabrication of the tube itself, the tube is made simple to operate. Whether such a reproducer tube is practical then depends on the solution of manufacturing problems. The color reproducer tube to be considered here attempts to place the complex features into the tube itself so that the user finds it nearly as simple to operate as black-and-white kinescopes.

The shadow-mask color kinescope is based on the fact that electrons, moving in a field-free region, travel in straight lines. By the use of the geometry of the color phosphor screen, it is possible to cast shadows on certain portions of the screen whose color one does not wish to excite. When the direction of arrival of the impinging beam is shifted, the shadows are shifted in position and the beam is permitted to illuminate only the desired color on the screen. The form of shadow geometry employed in the present tube incorporates proposals by Alfred N. Goldsmith, Consulting Engineer to the Radio Corporation of America and A. C. Schroeder, of RCA Laboratories Division.

This paper describes a color-kinescope shadow-mask viewing screen comprising a shadow mask placed in correct alignment with a phosphor screen consisting of a multiplicity of color-emitting phosphor dots. The shadow-mask screen is discussed in connection with a kinescope using three guns, while the application of the same shadow-mask screen to a one-gun tri-color kinescope is covered in a companion paper by

R. R. Law[2]. Later work pertaining to the problems involved in producing the tube in metal cones with printed phosphor screens is presented by members of the RCA Victor Division in companion papers.[3-6] Work undertaken at RCA Laboratories Division on the development of a suitable deflection yoke also appears in this series of papers.[7]

The first public demonstration of single-gun and three-gun shadow-mask color tubes incorporating this work was made on March 23, 1950.[8] On December 5, 1950, a triple-gun tube was demonstrated which had improved phosphors and a greater number of color elements.[9]

II Principle of Operation

In the three-gun shadow-mask color kinescope, three electron beams are used, one for each primary color. The beams strike a phosphor screen composed of a regular array of red-, green-, and blue-emitting phosphor dots as shown in Figure 1. Between the electron-gun position and the phosphor screen there is placed a thin perforated metal sheet for the purpose of partially masking the electron beams. That is, the electron beam which is to contribute the red part of the picture is prevented by the mask from striking those areas of the screen containing blue- and green-emitting phosphors. Likewise, the green and blue beams can strike only the green- and blue-emitting phosphor dots respectively.

The viewing screen is made up of closely spaced phosphor dot trios on a flat glass plate (Figure 1). Each trio consists of a red-, green-, and blue-emitting phosphor dot with the centers of the dots lying at the corners of an equilateral triangle. The trios themselves lie at the corners of an equilateral triangle of larger size. Associated with each

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[2] R. R. Law, "A One-Gun Shadow-Mask Color Kinescope", *Proc. I.R.E.*, Vol. 39, pp. 1194-1201, October, 1951.

[3] H. C. Moodey and D. D. VanOrmer, "Three-Beam Guns for Color Kinescopes", *Proc. I.R.E.*, Vol. 39, pp. 1236-1240, October, 1951.

[4] D. D. VanOrmer and D. C. Ballard, "Effects of Screen Tolerances on Operating Characteristics of Aperture-Mask Tri-Color Kinescopes", *Proc. I.R.E.*, Vol. 39, pp. 1245-1249, October, 1951.

[5] B. E. Barnes and R. D. Faulkner, "Mechanical Design of Aperture-Mask Tri-Color Kinescopes", *Proc. I.R.E.*, Vol. 39, pp. 1241-1245, October, 1951.

[6] N. S. Freedman and K. M. McLaughlin, "Phosphor-Screen Application in Color Kinescopes", *Proc. I.R.E.*, Vol. 39, pp. 1230-1236, October, 1951.

[7] A. W. Friend, "Deflection and Convergence in Color Kinescopes", *Proc. I.R.E.*, Vol. 39, pp. 1249-1263, October, 1951.

[8] T. R. Kennedy, Jr., "RCA Shows All-Electronic Tube as Key to Color Television", *The New York Times*, March 29, 1950.

[9] Jack Gould, "Improved RCA Color Is Shown", *The New York Times*, December 6, 1950.

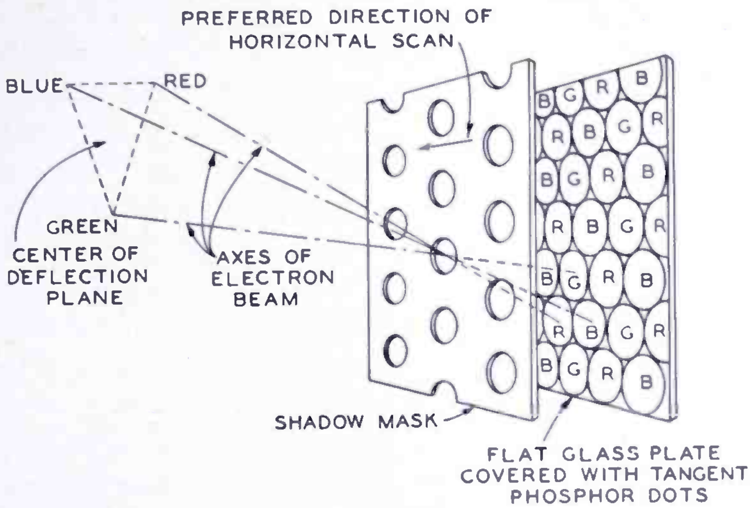

Fig. 1—An illustration of the geometrical relation between the electron beams, shadow mask, and phosphor screen in the tri-color kinescope.

of the trios is a hole in the shadow mask; these holes are also located at the corners of an equilateral triangle.

The phosphor pattern and shadow mask have a number of geometrical properties that may be more clearly seen in Figure 2. The shadow-mask hole associated with each trio is shown as a dotted circle.

The three beams, located 120 degrees apart about the tube axis, are converged to a point on the mask (Figure 3) either by pointing the guns or by a lens system.[8] If the convergence angle, or angle between each of the beams and the tube axis, is made large it is necessary to provide three separate deflecting systems capable of producing accurately registered rasters on the screen. Alternatively, if the angle of convergence is made small enough, the three beams can be included in

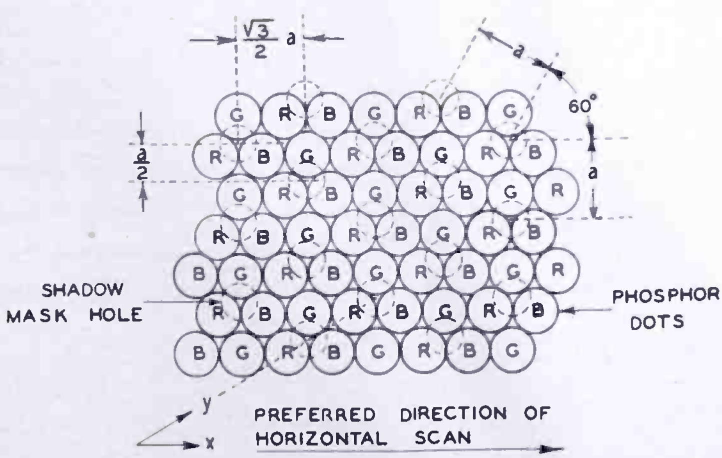

Fig. 2—Phosphor-dot array used in the tri-color kinescope. The relation between the shadow-mask holes and the phosphor dots is shown for a region near the axis of the tube.

the same neck and a single deflecting system can be used. In three-gun tubes described in this and companion papers,[3-5] it has been found possible to reduce the convergence angle to less than 2 degrees so that the three guns may be built into a two-inch diameter neck. In the one-gun tube, a single gun on the tube axis is used, but the beam is deviated from the axis, bent back again, and rotated to give virtual origins equivalent to the three guns.

The three beams go through the deflection yoke off axis, and each beam has its own center of deflection that is approximately a point. The three points for the three beams define a plane normal to the tube axis that may be called the center-of-deflection plane (see Figure 1). Each beam may be considered as originating from its center of deflection, and therefore each changes its angle of incidence at the mask as it scans. The trio of phosphor dots associated with each mask hole must

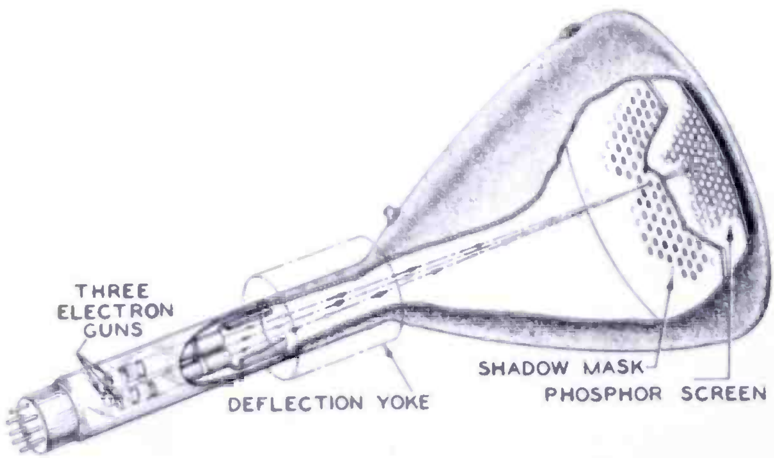

Fig. 3—Experimental shadow-mask color kinescope.

not lie directly under each mask hole, but should be displaced radially in accordance with the angle of incidence of the beam.

The geometry of the positioning of the phosphor dots is shown in Figure 4 where a plane defined by a row of mask holes and one of the deflection centers is illustrated. If an infinitely thin mask and a point source of electrons are assumed, it can be seen that the radial displacement of the phosphor dots, required for correct alignment, results in a phosphor-dot array similar to the hole array in the mask, but enlarged by the factor $\frac{L}{L-q}$, where L is the deflection-plane-to-phosphor-screen distance, and q is the mask-to-screen distance. Two other

[3] H. C. Moodey and D. D. Van Ormer, *loc. cit.*
[4] D. D. Van Ormer and D. C. Ballard, *loc. cit.*
[5] B. E. Barnes and R. D. Faulkner, *loc. cit.*

identical phosphor-dot arrays result from the remaining two deflection centers, the three arrays nesting perfectly if the correct relation exists between L and q for a given spacing between mask holes. The implication for manufacturing is that, if a stencil can be made for depositing phosphor of one color with all the dots in the right place, then the proper shift of the stencil will result in accurate positioning of the second and third colors.

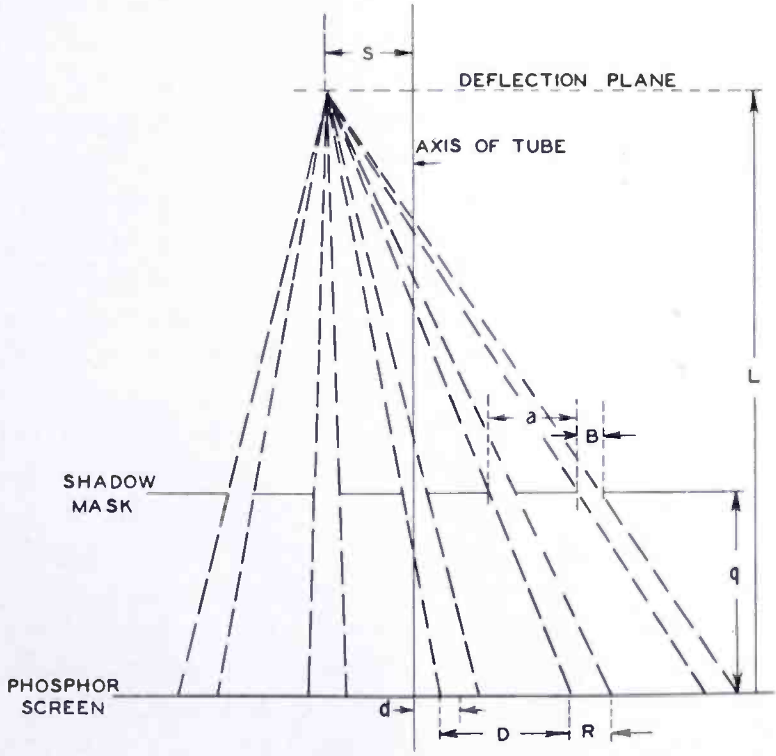

Fig. 4—A plane perpendicular to the shadow mask and passing through a row of holes in the y direction as defined in Figure 2. The geometry for a point source is shown.

Various processes may be used to place the phosphor in the desired position on the phosphor plate. These processes include electrostatic printing, offset printing, photoprinting processes, silk screening, and settling. The latter two methods will be discussed in a later section.

III Shadow-Mask Design

Regardless of the geometrical pattern of holes chosen for the shadow mask, the electron beams in scanning the mask will trace patterns on the phosphor screen that are similar to the mask pattern but slightly enlarged. In general, one gun is required for each color that is to be displayed on the phosphor screen. The design of the pattern of holes in the mask then consists of finding an arrangement of holes and a placement of beam deflection centers such that the patterns scanned by the beams on the phosphor screen will nest together without voids or overlap. One such pattern of holes in the shadow mask that would be satisfactory for any number of colors is a system of parallel slots with the deflection centers on a line normal to the slots. Another arrangement suitable for three colors is to place the holes in the mask at the corners of equilateral triangles (Figure 2). The deflection centers also occur at the corners of an equilateral triangle. The orientation of this triangle with respect to the mask must be correct or voids and overlap will result; the correct orientation is illustrated in Figure 1.

The triangular pattern was chosen for the shadow mask in experimental tubes primarily because of its mechanical properties. A thin piece of metal perforated with the pattern can be stretched taut on a frame and resist the tension about equally in all directions. Each hole in the pattern is well supported and may be expected to maintain its position better than, for example, a shadow mask made up of a grill where support is confined to the ends of the strips in the grill.

Having chosen the triangular-array dot pattern for the shadow mask, one must determine the fineness of the pattern required to realize in the reproducer the full capabilities of the transmitting system. This may be done by experimentally relating the number of holes in the mask to the maximum possible horizontal and vertical resolution due to the structure of the mask alone. An expression giving the number of holes in the mask may be found as follows: If the width divided by the height of the picture, or aspect ratio, is A, then a mask of height h has a width Ah. When the mask is oriented as in Figure 2, and the distance between holes is a, there are $2h/a$ horizontal rows of holes with $Ah/a\sqrt{3}$ holes in each row. Every hole is associated with a trio of red, green, and blue dots, so that if one wishes N such trios in the phosphor screen,

$$N = \frac{2A}{\sqrt{3}}\left(\frac{h}{a}\right)^2.$$

Now, if R_H and R_V are the horizontal and vertical limiting resolutions expressed in lines per picture height, then

$$R_H = k_H\sqrt{N}, \quad \text{and} \quad R_V = k_V\sqrt{N},$$

where k_H and k_V are the proportionality factors to be determined.

The subjective resolution of a kinescope employing a combination of a conventional scanning-line raster, together with triangular arrays of phosphor groups, has not yet been determined by a method analogous to that already employed for the scanning process alone.[10] Preliminary observations were made, however, with a high-definition-monochrome scanning raster on a shadow-mask screen assembly. Observations were also made of the resolution that can be seen when wedge patterns are placed in direct contact with a mask and viewed by transmission. The results for a number of observers were between $k_H = .67$ to $.82$ and $k_V = .72$ to $.93$. As an example of the use of these values, the shadow-mask color kinescopes which were publicly demonstrated on December 5, 1950[9] had 195,000 mask holes, corresponding to $N = 215{,}000$;[11] using the resolution factors above, a horizontal resolution between 325 and 400 lines and a vertical resolution between 350 and 450 lines is indicated.

Complete experiments, such as those in E. W. Engstrom's study of scanning line structure visibility,[12] can be performed to determine the dot structure needed for negligible visibility over a wide range of viewing distances. At normal viewing distances, the dot structure of the color kinescopes demonstrated on December 5 was unobjectionable.

For the triangular array of holes in the shadow mask a hexagonally shaped hole would allow the patterns traced out on the phosphor screen to cover 100 per cent of the area and nest perfectly. However, if the diameter of the hole is only a factor of two or three greater than the thickness of the metal, the shape of the hole obtained will depend largely on the method of fabrication. One of the best ways of making the holes, to be described later, is to etch them through the thin mask metal. Round holes of the size required are most easily made by this process and are quite satisfactory because it is possible for about 90 per cent of the area on the phosphor screen to be struck by the beam. Etched holes have the further advantage that they may be made to have sloping sides so that the masks are extremely thin from an operational standpoint; i.e., mask holes as viewed from the deflection center do not appear to close up near the edge of the mask because of the thickness of the mask.

Another factor to be considered is possible color dilution in the picture caused by secondary electrons from the mask striking the

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[9] Jack Gould, *loc. cit.*

[10] M. W. Baldwin, Jr., "The Subjective Sharpness of Simulated Television Images", *Proc. I.R.E.*, Vol. 28, p. 458, October, 1940.

[11] The actual number of holes in the mask is about 10 per cent less than those computed for a rectangular picture because of the rounded sides of the picture displayed.

[12] E. W. Engstrom, "A Study of Television Image Characteristics", *Proc. I.R.E.*, Vol. 21, p. 1631, December, 1933.

phosphor screen. Since the shadow mask is at the same potential as the aluminized screen, high-velocity secondaries (reflected electrons) from the shadow-mask apertures may strike the phosphor screen. When one of the three guns is turned on and the direct beam strikes a phosphor of a single color, slight color dilution could result if these electrons, scattered from the shadow mask, fall on phosphors of all three colors. Assuming equal efficiency for the phosphors, the effect would be a white dilution. If, as is true of currently available phosphors, the red is not as efficient as the other two, the dilution of the red would be slightly greater than that of the other colors because of the larger beam current needed in the red gun. The dilution caused by scattering is a minimum as a result of the tapered holes. As the beam strikes the sharp edge of the taper, a smaller fraction of the high-velocity secondaries can be scattered through the hole than if the hole had straight sides like a punched hole. Using tubes made in this way, colorimetry measurements by W. F. Davidson of RCA Laboratories indicated the dilution is not an important factor, since it was only 3 per cent or less.

As a further step in the design of the mask, the preferred orientation of the mask array with respect to the horizontal scan must be determined. The shadow mask contains a regular array of holes through which the three beams pass to reach the phosphor screen. Because of the regularity of the array, the holes fall into rows in certain directions. If the scanning beams travel parallel to a row of holes, then the raster will be modulated normal to the direction of scan unless the scanning line separation is an exact multiple of the separation between rows of holes. If the scan lines are not parallel to the rows of holes, the modulation will take place at some angle other than normal to the raster. Modulations of these types, if noticeable, may produce an effect called moiré.

Experimentally, it was found that noticeable moiré could be eliminated by scanning the mask in the x direction, (Figure 2) but that considerable moiré resulted from scanning at an angle approaching either plus or minus 30 degrees from the x direction. The experiments were confirmed in a theoretical study by E. G. Ramberg, of RCA Laboratories, in which the maximum deviation from the average transmission of the mask was determined as a function of the angle between the scanning lines and the optimum scanning direction. In the calculations, a bell-shaped density distribution in the electron spot was assumed. For a picture with approximately 470 *visible* scanning lines corresponding to present United States 525-line black-and-white standards, with a scanning spot small enough to resolve these lines easily, and a shadow mask of $N = 215{,}000$, the calculations showed that intensity variations from the average (moiré) were negligible, being only 1 per cent when the mask was scanned in the x direction of Figure 2. Within an angle of 2 degrees from this optimum direction, variations were still under $\pm$ 2 per cent, a tolerable value. Again checking observation, a 30-degree deviation, i.e., horizontal scanning along the y direction of Figure 2, was shown to lead to intensity variations of $\pm$ 35 per cent from the average. For shadow masks with larger numbers of holes, of course, the allowable deviation from the favored direction is increased. The effects are greatly decreased when the scanning spot size is increased to the point at which the scanning lines are just resolved.

Although of rare occurrence, another source of moiré is possible with certain types of signal. A strong intermittent signal of high video frequency can combine with the dot structure in the tube to form a "beat" pattern. When a sufficiently large number of mask holes is used, or with scanning spots which cover more than one hole, the effect is also of small magnitude.

IV Design Geometry

Thus far, in discussing the geometry of the tube, each electron beam has been considered as originating from a point source at its center of deflection, which implies that the holes in the mask may be nearly equal in size to the phosphor dots. Since the electron beam at the center of deflection is by no means a point, its diameter will require a reduced mask-hole size to obtain proper shadowing action at the phosphor screen. To study the effect, a simple approximation is to assume that electrons originate and travel in straight lines from a disc that represents the cross section of the beam at the center of deflection. Peripheral rays would then define the electron beam as it goes through the shadow mask to the phosphor screen.

Figure 5 represents a plane through the axis of the tube and one of the deflection centers; the beam cross section disc diameter is M and the distance from its center to the axis is S. The geometry will be discussed for only one of the beams and its associated phosphor dots because the other two colors have identical geometry. Figure 2 shows a view of the phosphor dots in the plane of the phosphor plate and indicates by the y axis the row of single phosphor dots considered.

The centers of adjacent phosphor dots making up a trio lie at the corners of an equilateral triangle. As shown in Figure 5, let R be the phosphor dot diameter when the three-color array consists of tangent dots, D the minimum distance between dots of the same color, and d the distance from the center of a trio to the center of one of the dots of the trio. Then

$$D = R\sqrt{3} = 3d. \tag{1}$$

In Figure 5 similar triangles may be used to get the relations

$$\frac{d}{q} = \frac{S}{(L-q)}, \text{ and } \frac{D}{L} = \frac{a}{(L-q)}, \tag{2}$$

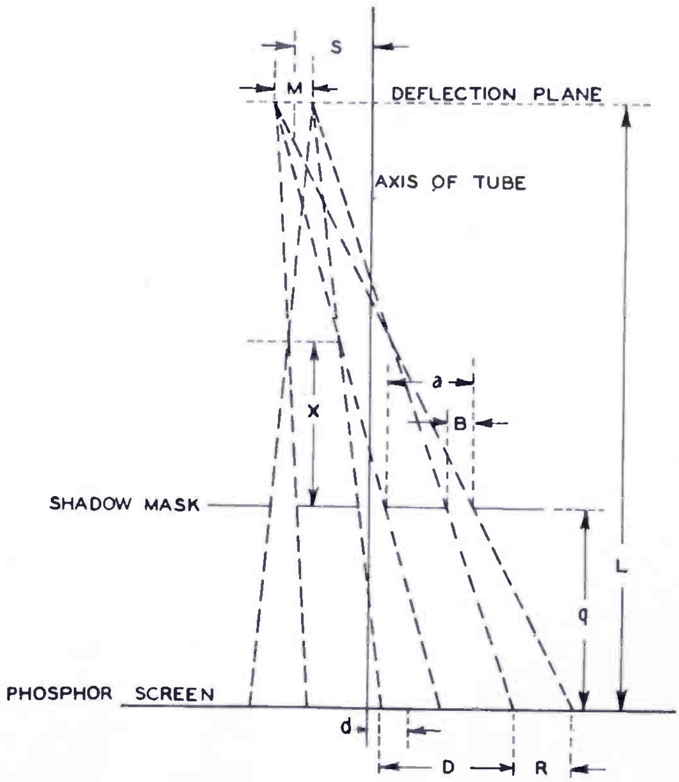

Fig. 5—A plane perpendicular to the shadow mask and passing through a row of holes in the y direction as defined in Figure 2. The geometry for a source of diameter M is shown.

where S is the separation of the axis of the electron beam from the tube axis in the deflection plane, a is the distance between holes in the mask, L is the deflection-plane-to-phosphor-screen distance, and q is the mask-to-phosphor-screen distance. By eliminating $(L-q)$ and using Equation (1), the following relations may be found:

$$q = \frac{La}{3S}; \quad \frac{1}{D} = \frac{1}{a} - \frac{1}{3S}; \quad \frac{1}{R} = \sqrt{3}\left(\frac{1}{a} - \frac{1}{3S}\right). \tag{3}$$

Again from similar triangles,

$$\frac{\frac{B}{2}}{x} = \frac{\frac{M}{2}}{L-(q+x)}, \text{ and } \frac{\frac{B}{2}}{x} = \frac{\frac{R}{2}}{q+x}, \tag{4}$$

where x is the crossover point of the peripheral rays, B is the mask-hole diameter, and M the diameter of the electron beam in the deflection plane. Eliminating x and using the above relations, the mask-hole diameter, B, is related to the hole spacing, a, by

$$B = \frac{a}{3}\left(\sqrt{3} - \frac{M}{S}\right). \tag{5}$$

The ratio of the open area of the mask to the total àrea is an important variable in determining picture brightness. From the above relations this ratio in terms of M and S is

$$\frac{\text{Hole area}}{\text{Total area}} = \frac{\pi B^2}{2a^3\sqrt{3}} = \frac{\pi}{18\sqrt{3}}\left(\sqrt{3} - \frac{M}{S}\right)^2. \tag{6}$$

The open area becomes zero when $M = \sqrt{3}\,S$ or when the cross sections of the beams are tangent discs in the deflection plane. If the beams originate from point sources in the deflection plane, i.e., when $M = 0$, then the open area would be a maximum of $\frac{\pi}{6\sqrt{3}} = 30.3$ per cent.

V Design for Maximum Efficiency of Operation

From Equation 6, the beam striking the phosphor screen will be

$$I_S = I_m \frac{\pi}{18\sqrt{3}}\left(\sqrt{3} - \frac{M}{S}\right)^2, \tag{7}$$

where I_m is the current arriving at the mask. To evaluate I_m a simple approximation is to assume that the cross section of the beam in the deflection plane is a geometrical enlargement of the cross section in the final limiting aperture of the gun. As a result of this assumption, there is effectively an aperture of diameter M in the deflection plane with a beam centered in the aperture. Now assume that in this aperture there is a current density distribution

$$\rho = \rho_0 e^{-\frac{r^2}{b^2}}, \tag{8}$$

where r is the radial distance from the center of the beam, ρ_0 is the current density on the beam axis, and b is the radius at which the current density has fallen to $\frac{\rho_0}{e}$.

The current arriving at the mask is then

$$I_m = 2\pi \rho_0 \int_0^{\frac{M}{2}} r e^{-\frac{r^2}{b^2}} dr = \pi \rho_0 b^2 [1 - e^{-\frac{M^2}{4b^2}}] \tag{9}$$

and the total current in the beam is

$$I_0 = \pi \rho_0 b^2. \tag{10}$$

The current to the phosphor screen from Equations (7), (9), and (10) is then

$$I_S = I_0 [1 - e^{-\frac{M^2}{4b^2}}] \frac{\pi}{18\sqrt{3}} \left(\sqrt{3} - \frac{M}{S}\right)^2. \tag{11}$$

An inspection of Equation (11) shows that the larger S, the more efficiently the beam is used, i.e., I_S/I_0 becomes larger. Also, from the equation it can be seen that the smaller b, the larger I_S/I_0. However, since the total beam current, I_0, increases with b (Equation (10)), the optimum value of b for maximum beam current involves gun design that is considered beyond the scope of this discussion. Accordingly, conditions for maximum beam utilization and not maximum beam current will be investigated. Further inspection of Equation (11) shows that $I_S/I_0 = 0$ for both $M = 0$ and $M = \sqrt{3}\,S$, which indicates there is an optimum M. It is the purpose of the discussion to find this value of M.

From Equation (11) the value of M for maximum efficiency of operation may be found by setting $\frac{d\,I_S/I_0}{dM} = 0$. The result is

$$\frac{S}{M} = \frac{1}{\sqrt{3}} \left[1 + \frac{4b^2}{M^2} (e^{\frac{M^2}{4b^2}} - 1) \right]. \tag{12}$$

Equation (12) enables the value of M for maximum I_S/I_0 to be calculated when any combination of S and b have been chosen. By expanding $e^{\frac{M^2}{4b^2}}$ in Equation (12) it can be shown that S/M approaches $2/\sqrt{3}$ as b approaches infinity, i.e., when there is a uniform current density across the diameter M. In this case the open area of the mask is 7.5 per cent. To find M graphically from Equation (12) for other values of b it is convenient to plot S/b against S/M. This has been done in Figure 6.

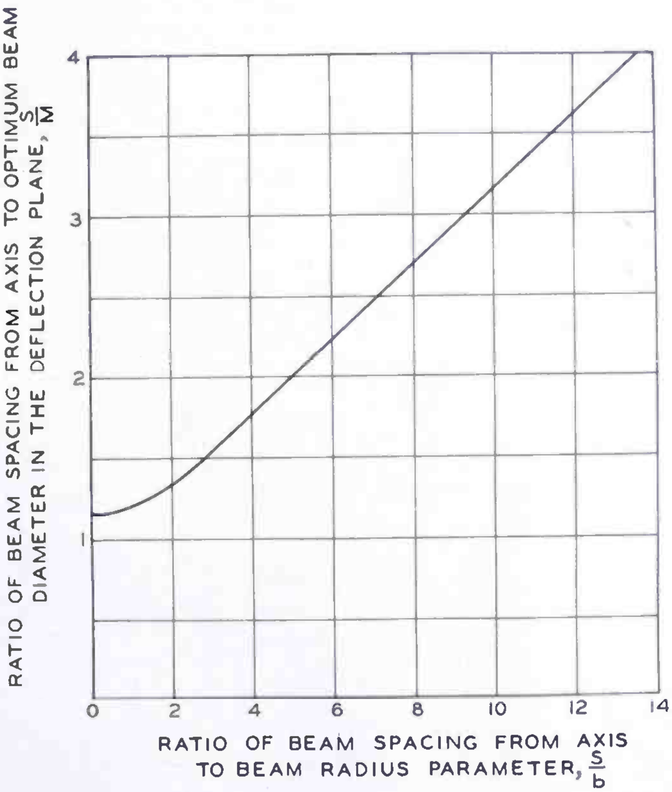

Fig. 6—Plot of the relation between b, S, and the corresponding optimum value of M. S is the distance between the axis and the center of each beam in the center-of-deflection plane, M is the diameter of the electron beam in the center-of-deflection plane, and b is the radius of the beam in that plane at which the current density in the beam has reduced to $1/e$ of its maximum value.

It is of interest to find the open area of the mask as well as how efficiently the beam is used, for the optimum values of M, when combinations of S and b have been chosen. Equation (7) for the open area of the mask, I_S/I_m, and Equation (11) for the efficiency in use of the beam, I_S/I_0, have been plotted in Figure 7. In the latter plot the optimum value of M from Equation (12) was used by eliminating b between Equations (11) and (12).

In Figure 7 it may be seen that the beam efficiency goes to zero for $S/M = 2/\sqrt{3} = 1.15$. The efficiency becomes zero because b becomes infinite when $S/M = 2/\sqrt{3}$, and infinite b means that the beam current is infinite. If at $S/M = 2/\sqrt{3}$ the current density were uniform over the area of the beam diameter M, but zero elsewhere, the efficiency in use of the beam would be simply the transmission of the mask at $S/M = 2/\sqrt{3}$ or 7.5 per cent.

As an example of the way the curves in Figure 6 and Figure 7 may be used, suppose the current density distribution in the deflection plane is as postulated, and a typical gun is used that results in 80 per cent of the cathode current passing through a disc of 0.200-inch

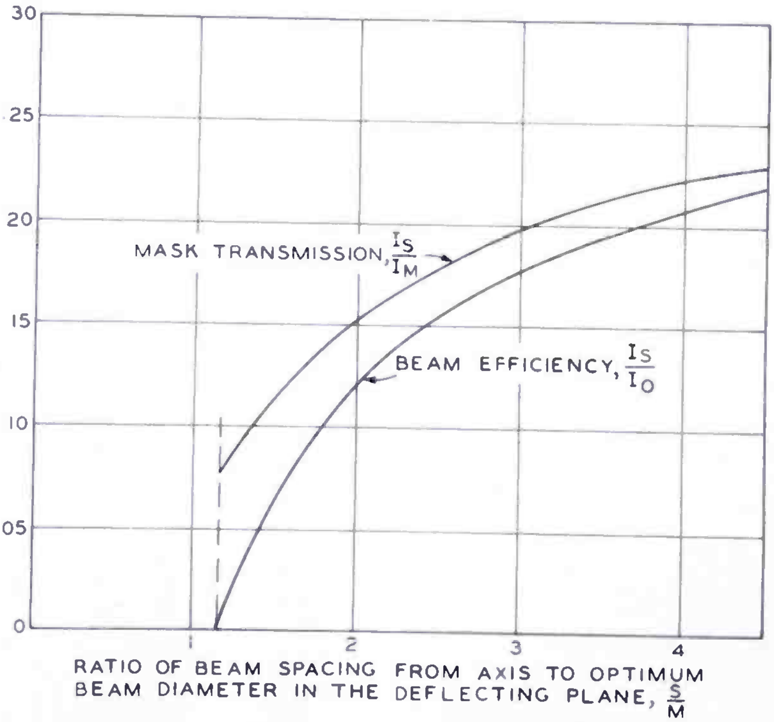

Fig. 7—The efficiency with which the cathode current is utilized and the open area of the mask as a function of S/M for the optimum values of M found in Figure 6.

diameter in the deflection plane. Then the b value may be found from Equation 9 as follows:

$$.8 = 1 - e^{-\frac{.200^2}{4b^2}} \; ; \; b = .0786 \text{ inch.}$$

Once b has been found, S may be chosen and the optimum value of M found. The .200 inch assumed for M in the example above was only for the calculation of b and is not necessarily the optimum value for the S to be chosen. Proceeding with the example, if $S = .300$ inch then $S/b = 3.82$ and $S/M = 1.72$ for optimum M as found from the curve in Figure 6. For the chosen value of S, then, $M = .174$ inch. From Figure 7 the proper transmission for the mask is 13.3 per cent and the beam is used with an efficiency of 9 per cent.

The current to the phosphor screen for a black-and-white and for a three-gun color tube may be compared, using the typical gun data mentioned above. For black and white, a single gun is used, and the assumption was made that 80 per cent of the cathode current reaches the screen. Three such guns are used for the color tube, with each gun delivering 9 per cent of its own cathode current to the screen for a total of 27 per cent. The ratio of current arriving at the black-and-white screen to that of the color-phosphor screen is then $\frac{80}{27} \approx 3$. Because of differences in anode voltage, phosphors, etc., however, it must not be concluded that the color kinescope necessarily sacrifices brightness.

VI Construction Techniques for Shadow-Mask Screen Assemblies

A vital part of the complete tube is the screen assembly which consists of a shadow mask, spacer frame, and phosphor-dot screen. Experimental shadow masks were made with the appropriate array of holes in thin copper sheet by using photoengraving techniques. The master dot pattern for photoengraving was made by contact printing a grill twice on the same photographic plate, the second time after the grill had been rotated through 60 degrees. A pattern of properly positioned diamond-shaped spots results from the shadowing effect of the opaque part of the grill. Subsequent printing steps, with shaped light sources and a spacer between the negative and the photographic plate to be exposed, make it possible to transform the diamond dots into approximately circularly shaped black dots.

Having obtained a suitable negative, the steps in producing the holes in the shadow mask are as follows: the thin copper is coated with engravers enamel, exposed through the negative with ultraviolet light, and developed. The exposed enamel is insoluble but the unexposed enamel washes away to uncover the metal underneath. Ferric-chloride etching solution is then applied to etch holes where the metal is exposed. Shadow masks with spacings between holes of from .018 inch to .030 inch were made for experimental tubes.

The shadow masks were mounted on cold-rolled steel frames designed to be of the right thickness to act also as a spacer between the shadow mask and the glass plate on which the phosphor-dot pattern was placed. Because the shadow-mask-to-phosphor-screen distance must be held uniform over the screen area, it was found necessary to stretch the shadow mask on the spacer frame. The required tension was produced by placing the mask between heated metal blocks while screws clamping it to the frame were still loose. The mask expands but the frame remains relatively cool so that when the clamps are tightened and the hot blocks removed the mask quickly draws tight.

The glass plate for the phosphor-dot screen is fastened to the other side of the spacer frame. It was necessary to fix the position of the glass plate with respect to the shadow mask at room temperature and yet allow for differential expansion of the glass and metal during tube processing. The required result was obtained by an alignment hole on one end of the spacer frame and an alignment slot in line with the hole on the other end. Two corresponding holes were drilled in the glass and close fitting pins served to locate the glass accurately.

In order to position correctly the phosphor dots on the glass plate, each beam may be considered as originating from its center of deflection with electrons traveling in straight lines from the deflection center to the mask. Using an apparatus that has been called the "lighthouse," a point light source placed at the center of deflection of the beams was used to simulate the electron beam. A photographic plate placed in the plane of the phosphor screen was used then to record the correct position of the phosphor dot of one color under every shadow-mask hole. It was not necessary to make an exposure from the remaining two deflection centers to locate the other two color-dot arrays since, as shown above, the patterns would be the same except for a shift of position. A reference for making the shift as well as locating the pattern on the spacer frame was obtained by recording the hole and slot positions on the photographic plate at the time the dot pattern was exposed.

With the photographic plate it was possible to make a settling mask of thin copper by again using photoengraving techniques. A single mask that was shifted after each color was deposited was used in settling early experimental screens, as were three masks made from plates exposed from all three beam positions. Settling was done with the masks in contact with the glass plate. The masks were then removed before pouring off the settling solution. Later, phosphor screens printed by the silk-screen process were also made.[6]

The three phosphors used were green willemite ($Zn_2SiO:_4Mn$), blue silicate [$CaMg(SiO_3)_2:Ti$], and red-orange borate ($2CdO \cdot B_2O_3:Mn$).

[6] N. S. Freedman and K. McLaughlin, *loc. cit.*

After all three colors had been laid down, the alignment was checked by assembling the phosphor plate on the spacer frame with the mask in position and by illuminating the phosphor screen from one of the centers of deflection. Diffusion of light in the phosphor dots makes it easy to observe with a microscope the individual beams as defined by the holes in the shadow mask. The phosphor screen was then disassembled and aluminized, both to increase the light output of the screen and to insure a field-free region between the shadow mask and the phosphor screen.

VII EXPERIMENTAL SHADOW-MASK COLOR TUBES

Experimental tubes were made by mounting the assemblies already described in glass kinescope bulbs having 2-inch necks to provide

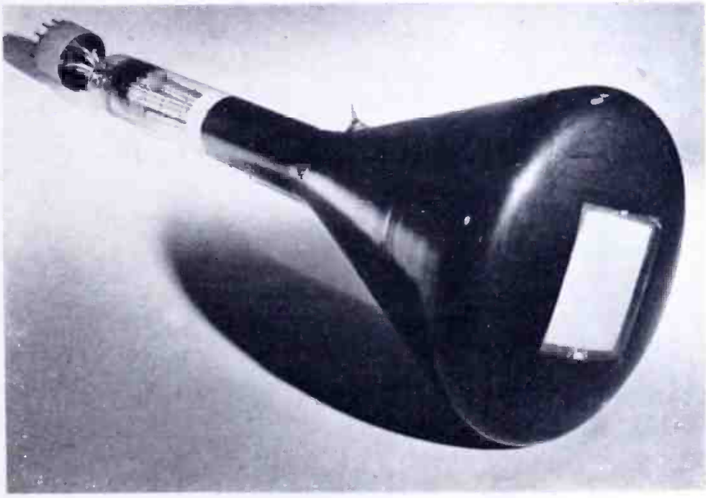

Fig. 8—Experimental shadow-mask color tube containing a test sample of dot screen.

room for the three guns. One of the first such tubes for testing a small portion of a full-size screen is shown in Figure 8. The screen assembly in this tube, 3×3 inches in size, has a mask with spacings between holes of .030 inch for a total of 11,500 holes. The three guns mounted in the neck all point to a spot on the mask with a convergence angle of about 2 degrees.

In operating the tube it was found necessary, because of slight gun misalignment, to use very small permanent magnets mounted on the outside of the neck adjacent to the individual guns in order to bring the spots accurately together. A correction was also required for the earth's field to keep the beams from being bent away from their respective color centers. If the tube was set up for good color fields, a rotation of the tube in the horizontal plane would cause dilution of the pure fields. One remedy was to place Helmholtz coils around the tube and adjust them so that the earth's field was neutralized. Since the coils required readjustment when the tube was rotated, however, a Mu-metal shield was used to eliminate the earth's field inside the tube as well as any stray fields that might be present.

Even with all magnetic fields in the tube eliminated, the beam did not accurately go through the color centers because of a misalign-

Fig. 9 — Unassembled parts for an experimental shadow-mask color kinescope.

ment of the guns with respect to the phosphor-screen assembly. It was possible, however, to place a permanent magnet in such a position that its effect was to produce pure color fields. If, at the same time, a Mu-metal shield was used, then rotation of the tube and the permanent magnet in the earth's field produced no change in the pure color fields. Color pictures shown on the tube were bright with the colors cleanly separated. Even though this early tube was crude and contained only a small portion of a full screen, experiments with it showed that the principles of operation and construction were sound.

Tubes with finer masks were built, but the screen size was limited because of glass-tube construction. Figure 9 shows the parts for a tube with a 4 × 6-inch screen having a hole spacing of .018 inch in the shadow mask, the total number of holes being 85,500. The convergence angle in this tube was reduced to a little over 1 degree. Color pictures obtained showed a marked improvement in texture.

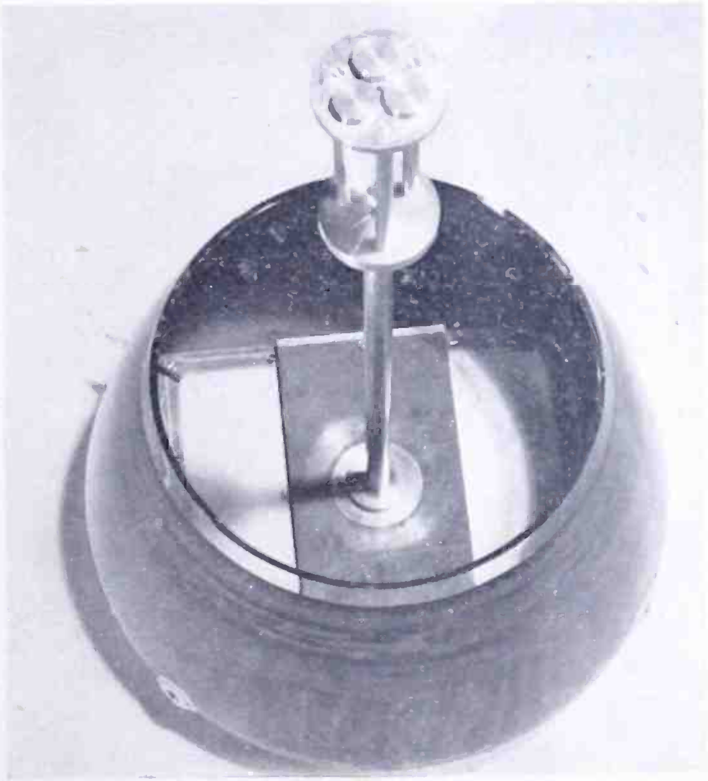

Fig. 10—Jig for locating the electron guns with respect to the phosphor-screen assembly in an experimental shadow-mask color kinescope.

Figure 10 shows the jig arrangement for locating the guns. The fixture protruding from the tube contains the information on the proper orientation and distance from the mask for the guns. By placing the glass cone and the gun press in position, the correct location of the gun press was spotted, and then the jig was removed before the glass seals were made.

Improved tubes, making use of the techniques and principles herein discussed, are described elsewhere.[5]

[5] B. E. Barnes and R. D. Faulkner, *loc. cit.*

VIII Conclusion

It has been demonstrated experimentally that a single kinescope can be made to present color pictures of good color purity when the principle of electron shadowing is used in the construction of the viewing screen. Although classed as a "structure" screen, its construction has proven to be less difficult than some. Its successful fabrication depends, in a large measure, on techniques whereby the screen and its mask are handled as a whole, as constrasted to the construction and assembly of individual elements. Of equal importance is the fact that it was found practical to reduce the angle between guns to the point where the deflection of all three beams could be accomplished with one deflection yoke instead of three. The result of this work has been the demonstration of a direct-view color kinescope with good resolution capabilities and a nondirectional viewing screen of large size with very good color separation.

IX Acknowledgment

Sincere thanks are due the many people mentioned in the first paper of this series for their valuable contributions, particularly F. H. Nicoll who designed the electron guns that were used in experimental tubes, L. E Flory and his group for their cooperation in testing sample tubes, and E. W. Herold who coordinated the work being reported in this series of papers and who has been very helpful and given much time to the reading of this manuscript.

A ONE-GUN SHADOW-MASK COLOR KINESCOPE*†

BY

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Summary—*A direct-view shadow-mask three-color kinescope employing a single electron gun is described. Color selection in this tube is accomplished by controlling the direction of approach of a single electron beam to a direction-of-approach sensitive color screen. For sequential presentation the beam is shared in time sequence between the three primary colors. For simultaneous presentation the beam is shared continuously among the three primary colors. The new problems presented by the one-gun shadow-mask color kinescope arise from the special requirements placed on the electron optical system, from the need for deflecting the beam into different color positions, and in the case of sequential presentation, from the necessity for blanking off the beam as it is switched from one color position to the next. Practical solutions to these and other problems are presented.*

INTRODUCTION

THIS one-gun shadow-mask color kinescope is an outgrowth of the RCA work on all-electronic color television. It makes use of a single electron gun and a direction-of-approach sensitive color screen which emits light of any combination of the three primary colors depending upon the direction of arrival of the impinging electrons. Because an electron beam has very little inertia and its direction of approach can readily be changed, a single beam from a single electron gun can be shared in time sequence between the primary colors to reproduce a color television picture from any color television signal capable of sequential[1] presentation; alternatively, by the use of appropriate color-signal circuits, the single beam can be shared continuously among the three primary colors to achieve simultaneous reproduction from signals which so permit. In each case the brightness signal is applied to the electron gun control grid, but the method of color selection depends upon the mode of presentation. In the case of field-sequential or line-sequential presentation, stepwise switching from color to color is desired. In the case of dot-sequential presentation, sine-wave switching by circular deflection with uniform angular

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* Decimal Classification: R583.1.
† Reprinted from *Proc. I.R.E.*, October, 1951.
1 "The Present Status of Color Television," Report of the Senate Advisory Committee on Color Television, *Proc. I.R.E.*, Vol. 38, pp. 980-1002, September, 1950.

velocity is preferred. In the case of simultaneous presentation, the color signals determining hue and saturation are applied to the color-selection deflection system to vary the direction of approach continuously.

In one successful application,[2] the direction of approach of a single electron beam is changed from picture element to picture element as it is made to scan a screen which employs a multiplicity of color dots and an apertured shadow-mask[3] registered therewith. Thus the electrons approaching from a particular direction can strike only a single color phosphor no matter which part of the raster is being scanned. In this manner it is possible to reproduce a color television signal[4] in which a line on the raster consists of dots of the three primary colors arranged from left to right in the sequence red, blue, and green.

The concept of the one-gun tube is understood as follows. Electrons may be "color-tagged" as they leave the electron gun by imparting to them a desired direction. This is possible, because in an axially symmetric electron optical system, within the limits imposed by aberrations, electrons emerging from a common source point at the gun may be reconverged to a common image point at the screen carrying intact their original direction-of-approach "color tag". Control of current to represent brightness is accomplished in the conventional manner.

The operation of the one-gun color kinescope is different from the operation of the three-gun color kinescope[3] in that the beam from the single gun may be deflected away from the axis by any amount and in any direction, so that it will return to the axis with any desired direction and angle of approach. In case a dot-sequential presentation is employed, the beam is deflected so that, in effect, it occupies in time sequence the three positions of the three guns in the three-gun kinescope. If a simultaneous presentation is employed, the direction of deflection is changed continuously to vary the angle of approach in accord with the hue and saturation information. The problems unique to the one-gun kinescope arise in part from the differences in electron optics, the need for deflecting the beam into the different color positions, and, in the case of sequential presentation, the necessity for blanking off the beam as it is switched from one color position to the next.

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[2] RCA Laboratories Division, "General Description of Receivers for the Dot-Sequential Color Television System which Employ Direct-View Tri-Color Kinescopes," *RCA Review*, Vol. XI, pp. 228-232, June, 1950.

[3] H. B. Law, "A Three-Gun Shadow-Mask Color Kinescope," *Proc. I.R.E.*, Vol. 39, pp. 1186-1194, October, 1951.

[4] RCA Laboratories Division, "A Six-Megacycle Compatible High-Definition Color Television System," *RCA Review*, Vol. X, pp. 504-524, December, 1949.

First, the electron optics of the one-gun color kinescope are analyzed in regard to both the basic optical principles and the fundamental limitations imposed by space charge. Second, the problem of "sampling," as used in a sequential presentation, is examined with particular regard to the color purity to be expected when the beam is keyed on and off in synchronism with the changes in direction of approach to provide automatic sampling. Third, these findings are compared with the performance of practical tubes working in accord with these principles.

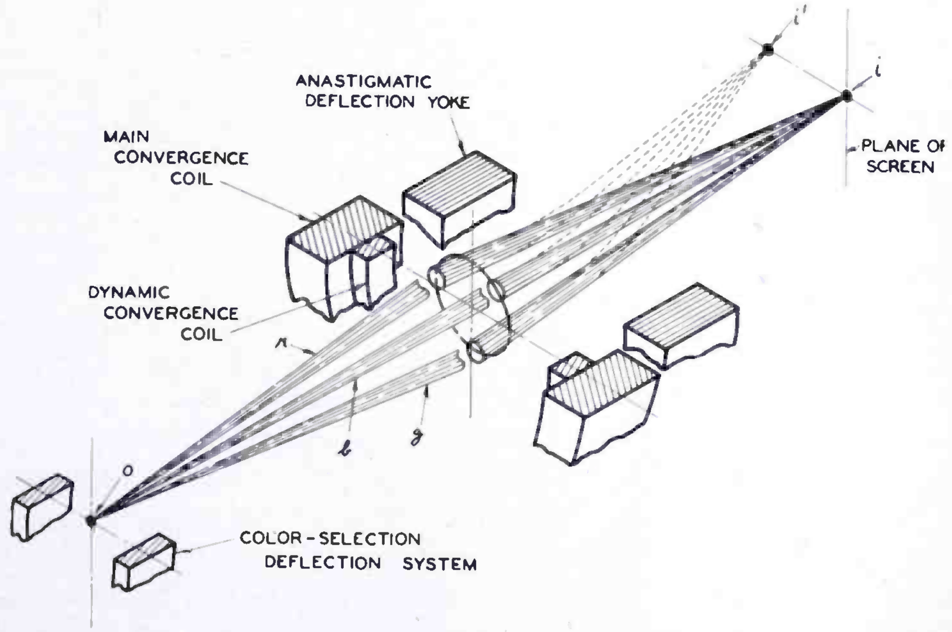

Fig. 1—Electron optics of the one-gun color kinescope.

Electron Optics of the One-Gun Color Kinescope

As is well known, in an axially symmetric electron-optical system, in the absence of space charge and within the limits imposed by aberrations, electrons emerging from a common source point may be reconverged to a common image point.[5] Thus, in the electron-optical system of Figure 1, the three separate beam pencils, r, b, and g, emerge from a common object point, o, on the axis of symmetry. They may be reconverged to a common image point, i, also on the axis of symmetry, with direction-of-approach angles so that they may excite the red, blue, or green phosphors of a direction-of-approach sensitive color screen. Furthermore, within the same basic limitations, and if the current through the dynamic-convergence coil is adjusted to compensate for the fact that less convergence is required as the beam is

[5] Bruche and Scherzer, "Geometrische Electronoptik," Julius Springer, Berlin, 1934.

deflected from the center, the three-pencil beam will still reconverge at a common image point, i, on a flat screen even after it has been caused to trace out a raster by the anastigmatic deflection yoke. When an individual beam pencil is traced through the system, it will be found that the direction of approach of the beam pencil at the image is related to the direction of emergence of the beam pencil from the object. Thus, a single beam pencil may be used to give any one of the desired primary colors by deflecting the beam pencil into any one of the positions, r, b, or g. It should be emphasized that the functions of the color-selection deflection system and the anastigmatic deflection yoke are quite independent: the color-selection deflection system serves to "color-tag" the electrons as they leave the gun; the anastigmatic deflection yoke serves to deflect the beam over the raster. As a result, the "color-tagged" beam may be focused on the screen and deflected over a raster in much the same manner as the beam in a conventional cathode-ray tube except for the greater diameter of the composite beam which necessitates a wider aperture electron-optical system.

The requirements on the elements of this electron-optical system will become less stringent as the beam pencils are crowded closer and closer together. But it will be seen from Figure 1, that as the angle of approach is reduced, the individual beam pencils must be made smaller and smaller if they are not to overlap. The question now arises whether space-charge mutual-repulsion effects will permit the individual beam pencils to be made as small as desired. This problem of space charge is of much greater concern for the one-gun tube than for the three-gun tube because of the different current requirements. When the one-gun color kinescope is used to reproduce a color television picture sequentially,[2] the single electron beam is shared in time sequence between the three primary colors and blanked off as it is switched from one color position to the next. As a result, the average beam current to any particular color phosphor can only be a small fraction of the peak current capability of the single electron gun. When allowance is made for this low duty factor and the loss of electrons on the shadow-mask, peak beam currents of several milliamperes may be required to give a picture of adequate brightness.

A rigorous analysis of space-charge effects is beyond the scope of this presentation, but a simple approximate analysis suffices to give a satisfactory indication of the point where space-charge effects may become important. In terms of the geometry of Figure 2, by making certain simplifying assumptions, Thompson and Headrick[6] have shown

[6] B. J. Thompson and L. B. Headrick, "Space Charge Limitations on the Focus of Electron Beams," *Proc. I.R.E.*. Vol. 28, pp. 318-324, July, 1940.

that for a beam of circular cross section the minimum radius is given by

$$r_m = R_0 \epsilon^{-(V_d m/4Ie) V_r^2}, \tag{1}$$

where

R_0 = Initial radius of outer beam surface, in centimeters.

r_m = Minimum radius of beam, in centimeters.

V_r = Initial inward component of velocity of outer electrons, in centimeters per second.

V_d = Axial component of velocity of the beam, in centimeters per second.

I = Electron beam current, electrostatic units.

e = Electronic charge, electrostatic units.

m = Electron mass, grams.

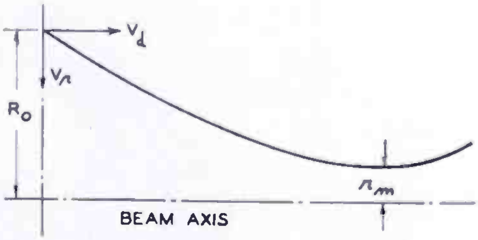

Fig. 2—Diagram of a half-longitudinal section of a beam of circular cross section beyond an electron lens.

The assumptions made in developing this relationship are: first, the radial component of the velocity of the electrons as they leave the electron lens is assumed to be proportional to their distance from the beam axis; second, the beam is assumed to be a uniform cylinder of electrons moving in a field-free space, except for the field due to the electron-charge density of the beam; and third, the axial velocity of the electrons in the beam is assumed to be constant. In practice the deviations from the assumptions will tend to increase the size of the focused spot. For the purpose of this analysis, this relation will be construed as setting a lower limit to the beam size obtainable in a high vacuum rather than being a measure of the spot size.

In a practical design of the one-gun shadow-mask color kinescope, the lens-to-screen distance is 14 inches, the angle of approach is 1.2 degrees, and the second-anode voltage is 18 kilovolts.[2] In this case, a simple computation based on the geometry of Figure 1 will show that if the beams are not to overlap, the diameter of the individual beam pencils in the plane of the converging lens cannot exceed 0.52 inch. Translated in terms of the geometry of Figure 2, R_0 cannot be greater than 0.26 inch. Furthermore, if the converging lens is adjusted so that the beam comes to a point focus in the absence of space charge corresponding to low levels of beam current, V_r cannot be greater than 0.0187 V_d. Under these specific conditions, the variation of r_m with I as computed by Equation (1) is shown in Table I.

Table I

I (milliamperes)	r_m (inches)
15	0.035
9	0.009
6	0.002

The practical tube for which the above calculations were made gives a picture approximately 9 inches high.[2] For 500-line vertical resolution the spot should not be more than 0.009 inch in radius, and if space-charge effects are to be unimportant, r_m as computed above must certainly be less than 0.009 inch. If the point where space-charge effects limit the performance is arbitrarily taken to be that point where r_m equals 0.009 inch, Table I shows that the beam current should not exceed 9 milliamperes.

By a similar calculation one may determine the limiting beam current corresponding to other beam-approach angles. The results of these calculations are shown in the following Table II. As is to be expected, the limiting beam current varies as the square of the beam-approach angle.

Table II

Maximum beam current that can be focused in spot (milliamperes)	Beam-approach angle (degrees)
9	1.2
3	0.7
1	0.4

In the preceding calculation for a tube with a lens-to-screen distance of 14 inches and an angle-of-approach of 1.2 degrees, we saw that the individual beam pencils might approach one half inch in diameter at the plane of the converging lens. By similar reasoning, it is easily shown that the composite beam may exceed one inch in diameter. It has been possible to provide an electron optical system which will handle this relatively large diameter beam. As already pointed out in connection with Figure 1, this system includes a large-aperture primary converging lens, an auxiliary dynamic-convergence lens to compensate for the fact that less convergence is required as the beam is deflected from the center, and an anastigmatic deflection system. Some of these problems have been encountered in the design of projection-tube systems. It is known that a large aberration-free aperture can be obtained with a sufficiently large magnetic lens located outside the tube envelope.[7] When such a primary magnetic converging lens is used, dynamic convergence is conveniently accomplished by an auxiliary coil inside the main lens. The solutions of dynamic conver-

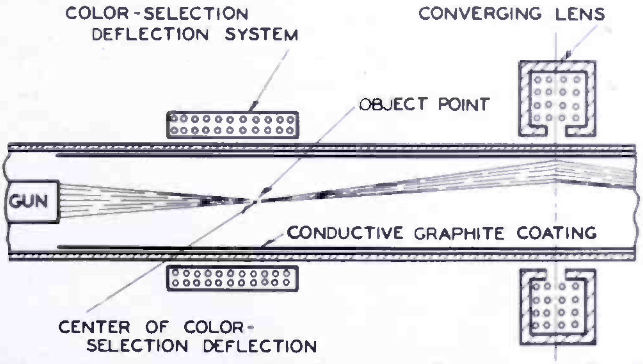

Fig. 3—Electron optics of a developmental one-gun color kinescope.

gence and anastigmatic deflection problems are similar in both the three-gun and one-gun color kinescope and are discussed in detail elsewhere.[8]

An electron source which meets the requirements schematically indicated in Figure 1 was suggested and developed by D. A. Jenny of RCA Laboratories. As indicated in Figure 3, it includes a standard 5TP4 projection-type electron gun, a color-selection deflection system which serves to deflect the beam into the successive color positions, and a converging lens which bends the beam pencils back toward the axis to form the image. The voltages applied to the electrodes of the gun are so adjusted that the beam comes to a focus at the object point. The electron optical requirements are met when the longitudinal position of the object point is so adjusted that the virtual object point coincides with the virtual center of deflection of the color-selection

[7] R. R. Law, "High Current Electron Gun for Projection Kinescopes," *Proc. I.R.E.*, Vol. 25, pp. 954-976, August, 1937.

[8] A. W. Friend, "Deflection and Convergence in Color Kinescopes," *Proc. I.R.E.*, Vol. 39, pp. 1249-1263, October, 1951.

deflection system. This relationship is shown in greater detail in Figure 4. In the field-free region beyond the deflection system the electrons are assumed to travel in straight lines. Insofar as the converging lens is concerned, the electrons appear to have originated from a virtual source at the apex of the dashed-outline cone formed by tracing the straight line trajectories back into the deflection system. Because of the finite length of the deflection system, the virtual center of deflection lies somewhat ahead of the geometric center of the color-selection deflection system. Also, because the beam is bent somewhat before it reaches the virtual center of deflection, the true object point traces out a circle around the virtual object point.

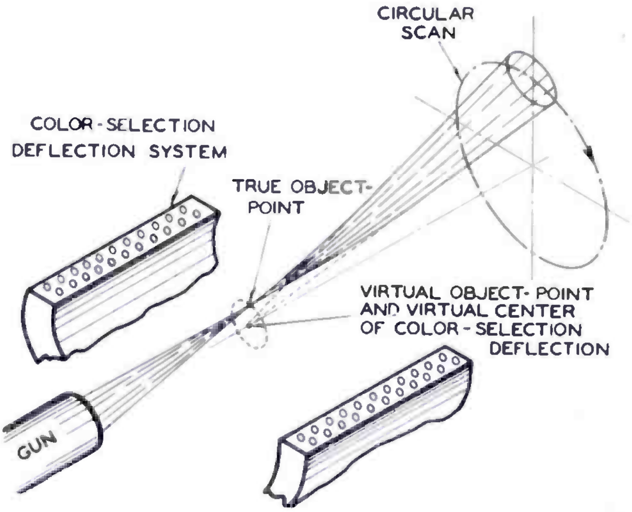

Fig. 4—Electron trajectories in the region of the color-selection deflection system.

Such a system was used with the one-gun color kinescope in the March 1950 demonstrations.[2] The standard 5TP4 projection-type electron gun was used to form the object point. This gun, itself, is unnecessarily long for this application. Also, as the first-anode voltage is lowered to move the object point in close to the gun, less than normal beam current for the gun is obtained. By placing an auxiliary magnetic-type electron lens over the electrostatic electron lens formed by the first-to-second-anode transition as shown in Figure 5, it is possible to raise the first-anode voltage and increase the beam current several fold. This arrangement was suggested by F. H. Nicoll of RCA Laboratories. To reduce the length of the tube further, the simplified shortened electron gun shown in Figure 6 was developed. The electron optics of this arrangement are of course similar to those encountered in the system of Figure 5. The details of the performance of these several practical designs are reported in a later section.

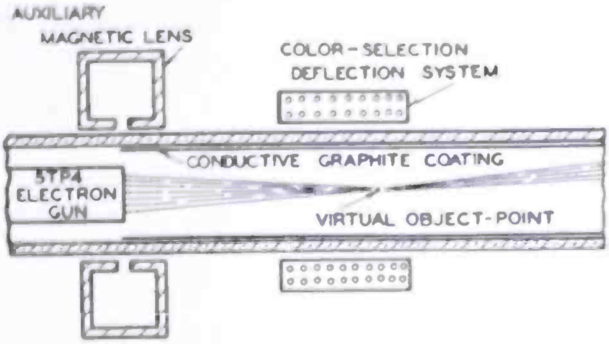

Fig. 5—Developmental electron gun with auxiliary magnetic lens.

Color Selection in the One-Gun Color Kinescope

Color selection in the one-gun color kinescope is accomplished by deflecting the beam into appropriate color positions. Because the energy stored in a magnetic field makes it difficult to suddenly change the direction of deflection, the choice of magnetic deflection or electrostatic deflection for color selection will depend upon the color system under consideration. In the case of field-sequential or line-sequential color systems, stepwise switching from color to color is desired. This problem is no more difficult than the raster scan, and it should be possible to accomplish the switch by magnetic means during the beam retrace time. If the direction of approach is to be changed from picture element to picture element to provide a dot-sequential presentation of the color signal, magnetic-deflection color selection with sine-wave switching by circular deflection with uniform angular velocity is preferred since it leads to considerable circuit simplification. In the case of simultaneous presentation of the three primary colors with the brightness signal applied to the gun-control grid and the color signals determining hue and saturation applied to the color-selection system, the ability to change continuously is desired. The rate of change of direction of approach required will be determined by the

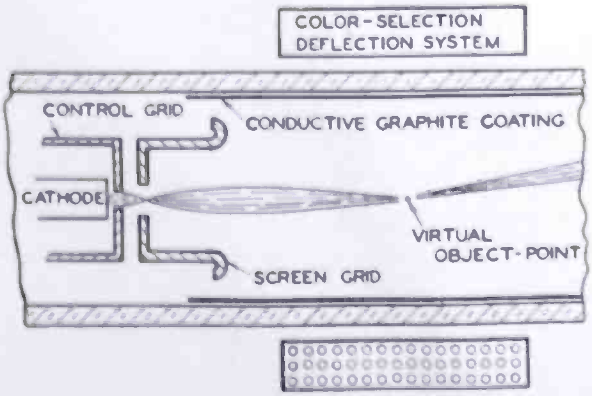

Fig. 6—Developmental simplified short electron gun.

bandwidth of the hue and saturation information. Ordinarily this bandwidth will be great enough to make electrostatic color-selection deflection desirable.

In the receiver previously described,[2] dot-sequential presentation of the color signal is employed and color selection is done magnetically. The required circular deflection is provided by a small deflection yoke having two sets of coils which are fed with quadrature currents at color-subcarrier frequency to produce a rotating field. Service adjustment of color phasing is provided by mechanical positioning of this yoke. The amplitude of the circular deflection is adjusted to produce the proper convergence angle as required by the mask and phosphor-dot screen. The duty factor of the beam is controlled by a signal having a frequency three times the color-subcarrier frequency which is injected into the kinescope cathode circuit. The amplitude and phase of this signal are determined by the alignment of a filter circuit which utilizes the third harmonic of the circular-deflection driver tube.

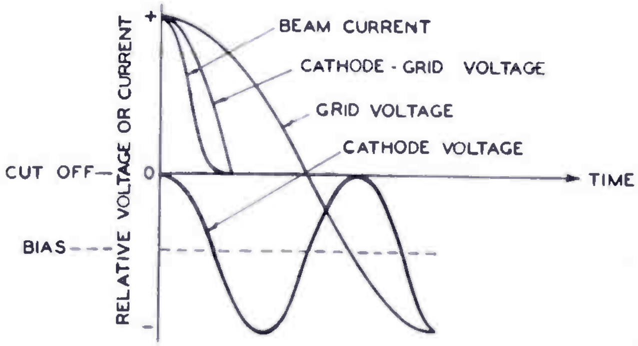

Fig. 7—Time variation of voltage and current when reproducing a single primary color of uniform brightness.

The performance of the one-gun color kinescope under the above operating conditions is well illustrated by analyzing the case of a large-area single primary color at various relative brightness levels. The essential features of such an analysis are illustrated in Figures 7, 8, 9, and 10. All amplitudes in these figures are expressed as relative values. Inasmuch as the circular scan is synchronized and locked in phase with the incoming signal, time may be expressed in either electrical degrees at the color-subcarrier angular velocity or azimuth angle of the circular scan. The phase is adjusted so that the beam is centered on the desired phosphor at the moment the desired single primary color signal is a maximum. In the present analysis, time arbitrarily starts at this instant.

Proceeding now to the detailed analysis, one sees that the voltage arriving at the grid is a sine wave of fundamental frequency whose amplitude is proportional to the brightness of the desired monochrome

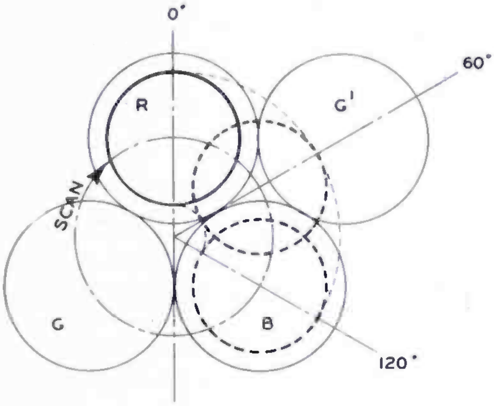

Fig. 8—Diagram of beam positions assumed during circular color scan.

area. In keeping with the requirement that the current must be zero with zero signal, this sine wave is plotted in Figure 7 about a voltage axis corresponding to the cutoff voltage. It is indicated by the curve labeled "grid voltage." As already mentioned, the duration of the beam pulse is controlled by a signal which is injected into the kinescope cathode circuit and which has a frequency three times the color-sub-carrier frequency. This signal is represented in Figure 7 by the curve labeled "cathode voltage," and is plotted about a voltage axis marked "bias voltage" equal to the peak third-harmonic voltage amplitude. The algebraic sum of these voltages is the resultant signal between the cathode and the grid. It is represented in Figure 7 by the curve labeled "cathode-grid voltage." In the particular case portrayed, the third harmonic amplitude is one half the fundamental amplitude. When the kinescope is operated in the space-charge-limited region of its characteristic, the beam current is very nearly proportional to the five halves power of the cathode-grid voltage. It is represented here by the curve labeled "beam current."

The shadow-mask screen is described elsewhere.[3] Two features are of importance in the present analysis: first, the phosphor dots of contrasting colors occupy adjacent tangent circles; second, to provide a factor of safety for errors in mechanical alignment, the openings

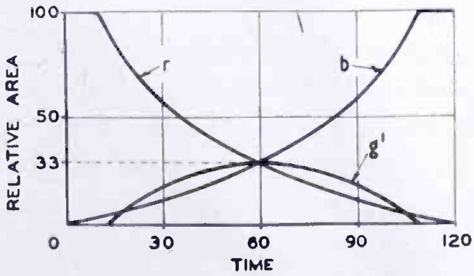

Fig. 9—Time variation of area of each color bombarded by beam with uniform, angular-velocity, circular scan.

in the shadow mask are of such size that the electron beam transmitted by each opening arrives at the phosphor plate in a spot smaller than the individual phosphor dots. Because of the circular deflection of the beam, the electron spot scans the trio of contrasting phosphor dots with a uniform circular motion as shown in Figure 8. The position of the hole in the mask, the mask to phosphor-dot-screen distance, and the convergence angle are so related that the spot traverses a circular path from the center of the desired phosphor dot through the centers of each of the undesired phosphor dots and returns to the center of the desired phosphor dot. Thus in Figure 8, at zero electrical degrees or zero angle of scan, it is centered on the desired phosphor dot, R. At 60 degrees it impinges equally on the desired phosphor dot, R, and the undesired phosphor dots, G′ and B. G′ will be recognized as one of the phosphor dots of an adjacent trio. In a similar manner, the

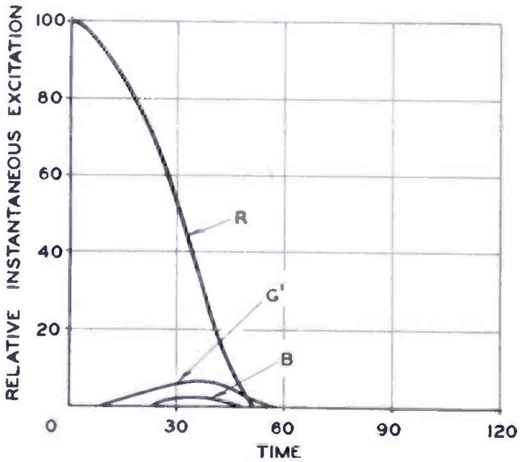

Fig. 10—Time variation of relative instantaneous excitation of each color due to single primary-color signal.

remainder of the cycle may be traced out in detail. In the following analysis, the relative area of the spot on each of the phosphor dots has been computed for the case where the diameter of the electron spot is 80 per cent of the diameter of the phosphor dots. The results of this analysis are indicated in Figure 9. The relative areas at various angles of scan are shown by the curves r, g′, and b. The analysis has been carried out for the remainder of the scanning cycle, but for reason of simplicity is not reproduced here.

The instantaneous relative excitation of the several phosphor dots is now, of course, the product of the relative instantaneous values of current and area. The variation of instantaneous excitation with scanning angle for one third cycle is shown by the curves R, G′, and B in Figure 10. And finally, the relative light output of each color is numerically equal to the relative area under each of these curves.

When the complete cycle is traced out in this manner, it can be shown that light of the two undesired colors is produced in equal small quantities. Since an equal small portion of the desired color may be combined with the undesired colors to produce white, the net contaminating effect may be expressed as a slight dilution. For the purpose of this analysis, dilution is arbitrarily defined as:

$$\text{Dilution} = \frac{\sum \text{Light output of undesired colors}}{\text{Light output of desired color}}.$$

The foregoing analysis gives the dilution and the light output for one particular operating point. During modulation corresponding to changes in the brightness level of the monochrome area, the signal

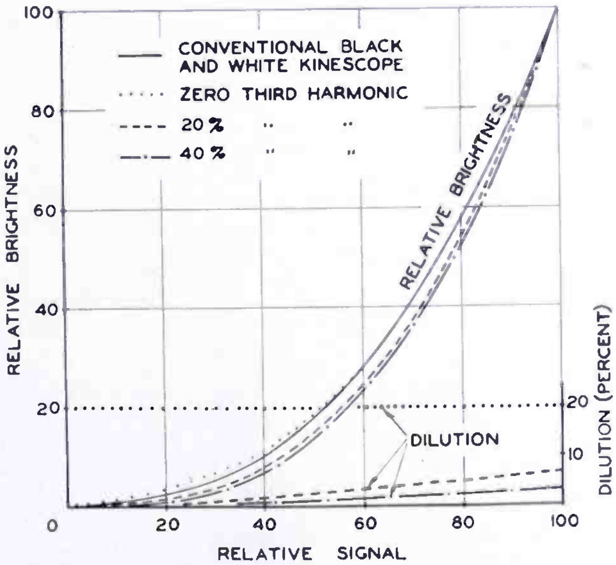

Fig. 11—Kinescope transfer characteristic and dilution for various values of third harmonic.

on the grid changes but the third-harmonic signal applied to the cathode does not. By repeating the analysis using a fixed third harmonic signal with various relative amplitudes of the fundamental, it is possible to deduce a transfer characteristic and the dilution at corresponding points. The effect of using other relative values of the third harmonic may be computed in the same manner. The results of these computations are shown in Figure 11. As is to be expected, the dilution decreases as the relative amplitude of the third harmonic is increased. Of particular interest from a practical standpoint is the fact that dilution can be substantially eliminated by the addition of a third-harmonic component. For example, the introduction of a 20 per cent relative amplitude third harmonic reduces the dilution to about 6 per cent. Also, the relative transfer characteristic is observed to change very little as the third-harmonic content is changed.

To translate relative brightness into true brightness, it is necessary to know the duty factor, i.e., the ratio of average beam current to peak beam current. Inasmuch as high-light brightness is measured in the "whites" of the picture, the duty factor of greatest interest is that for a white field. The duty factor for a white field is readily determined from Figure 7; it is simply the ratio of the area under the desired beam-current-versus-time curve to the area possible if the beam current remains at peak amplitude throughout the cycle. Figure 12 shows the results of such a graphical analysis for various third-harmonic-amplitude ratios. To better show the relation of dilution to duty factor, the dilution data of Figure 11 are replotted in Figure

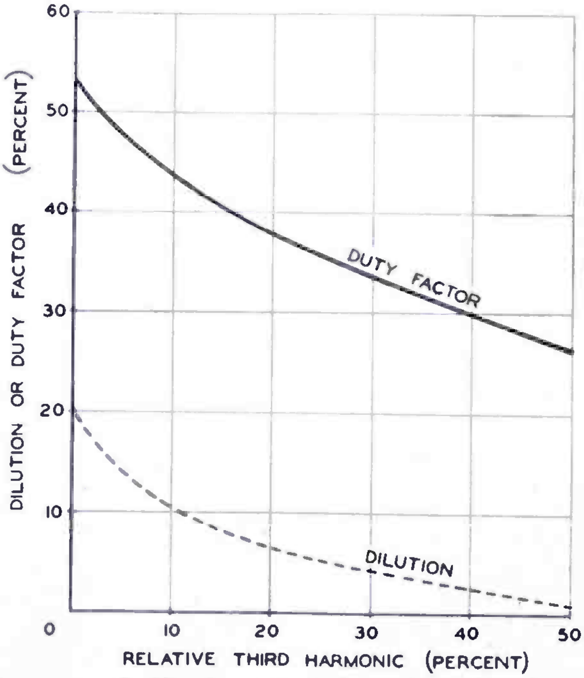

Fig. 12—Duty factor and dilution as a function of relative amplitude of third harmonic.

12 with relative third harmonic as the independent variable. It will be observed that the introduction of a 20 per cent relative third harmonic which reduces the dilution by a factor of more than three reduces the duty factor, and consequently the brightness, by less than one third.

It should be pointed out that the foregoing questions of dilution and duty factor do not arise when appropriate means of simultaneous reproduction are employed. In one method of simultaneous presentation, proposed by G. C. Sziklai of RCA Laboratories, the rest position of the beam is on the axis of the electron-optical system. In the rest position the beam strikes the three phosphor dots equally to produce white; as the current is varied, a black-and-white picture is reproduced so long as the beam remains on the axis. Color information is imparted by deflecting the beam from the axis to vary the direction of approach: the direction of deflection in azimuth serves to determine the hue of the color, and the amplitude of deflection serves to determine the saturation of the color.

This method can take advantage of the principle of mixed highs since the relative beam direction need only be changed as color changes are required. Furthermore, because of the symmetry of the three phosphor dots with respect to both the electron optical axis and the hole in the shadow mask, off-axis excursions of the beam are large only for high saturation. On this account, less accurate convergence may be tolerated. It should be emphasized, however, that stringent requirements are made upon the accuracy of the shadow-mask screen assembly in any system where hue and saturation are directly dependent on direction of approach. Thus, deviations in the shape and uniformity of the phosphor dots and in alignment of the shadow-mask holes with respect to the phosphor dots may lead to less faithful color rendition.

Performance of Practical One-Gun Shadow-Mask Color Kinescope

As already indicated, to move the object point in close to the gun, the first anode of the standard 5TP4 projection-type electron gun, used in the tube for the March, 1950 demonstrations,[2] was operated with a lower-than-normal first-anode potential. Instead of the normal six kilovolts, it was necessary to operate the first anode at about three kilovolts. Under this condition, tests indicate that the peak beam current is less than 0.5 milliampere.

Although a detailed correlation of peak beam current and observed high-light brightness involves details of colorimetry beyond the scope of this paper, an approximate analysis is of interest because it indicates the influence of the several operational factors. The details of colorimetry may be incorporated in an assumed value for the "white" visual output in lumens per watt. For the present calculation, assume that the tube is operated under the following conditions:

"White" visual output	7 lumens per watt
Shadow-mask transmission factor[3]	0.20
Relative third-harmonic sampling voltage	0.20

Duty factor (from Figure 12)	0.40
Peak beam current	0.5 milliampere
Anode voltage	18,000 volts
Picture size	9 × 12 inches

Under these conditions, a high-light brightness of 7 foot-lamberts is to be expected. When allowance is made for the 0.6 transmissivity of the "minus-yellow" filter employed for color correction of the phosphors in use at that time,[9] the high-light brightness is reduced to 4 foot-lamberts. This checks the observed value.[10]

With the improved phosphors presently available, no filter is required. Also, as already indicated, the performance of the tube is greatly improved by adding an auxiliary magnetic-type electron lens over the electrostatic lens as shown in Figure 5. By this means it is possible to increase the useful beam current several fold. Tests of this by V. D. Landon and associates of RCA Laboratories indicate that peak beam currents of 1.5 milliamperes may be used. Under these conditions, pictures with good fidelity and color rendition and with 20 foot-lamberts high-light brightness are obtained. Substantially the same result is obtained with the simplified shortened electron gun of Figure 6. This gun makes possible an improved tube, for not only is the first-anode voltage obviated, but the shorter gun makes it possible to reduce the tube length by approximately seven inches.

A further improvement is brought about by using a shadow mask with reduced angle of approach. As already indicated, when the beam pencils are crowded closer together, the requirements on the electron optical system become less stringent. Tubes of this design were built using a shadow-mask screen with 0.7 degree angle of approach. The most noticeable difference is simplification of dynamic convergence.

ACKNOWLEDGMENTS

Although space does not permit recognition of the many individuals who contributed to the development of the one-gun shadow-mask color kinescope, in addition to those already mentioned in the text of this and the companion papers, acknowledgment is made of the help of the RCA Victor Division in Lancaster, Pennsylvania and Harrison, New Jersey, who built the demonstration tubes as well as F. H. Norman, J. E. Eckert, E. O. Keizer, and G. A. Olive of RCA Laboratories, who carried out much of the experimental work.

[9] *Television Digest*, Vol. 6, No. 13, April 1, 1950.
[10] *Television Digest*, Vol. 6, No. 14, April 18, 1950.

A 45-DEGREE REFLECTION-TYPE COLOR KINESCOPE*†

BY

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Summary—The 45-degree reflection-type color kinescope is an experimental tube of the single-gun type in which the color is changed by applying a control voltage directly to the screen assembly. The screen assembly consists of a multiapertured metal plate coated on the front side with red, green, and blue phosphor strips and mounted parallel to a glass plate coated with a transparent conductive film. An electron beam scans the back of the metal plate at an angle of incidence of approximately 45 degrees. The portion of the beam passing through the slots is reflected by the electric field between the plates, causing it to fall back on one set of phosphor strips. By varying the potential of the glass "reflector" plate, the beam can be shifted from one color phosphor to another. The scanning beam is not required to follow the aperture pattern and the color purity is independent of beam focus.

A feature of this tube is the automatic registry of the three colors over all parts of the screen. The screen is not difficult to construct; the power required to switch colors at megacycle frequencies is small. Other characteristics of this tube which should be noted are: the unconventional shape of the bulb, and the need, in some forms of the tube, for a "keystoning" correction of the scanning.

Experimental one-gun tubes having screens seven inches in diameter have been built and operated with the RCA color system. Tests have shown that the 45-degree reflection-type color kinescope is capable of good quality, high definition pictures. A complete evaluation of tubes of this type, in which advantages and disadvantages are weighed against those of other color kinescopes, cannot be made at this time.

Associated circuits for operating the tube with the RCA color signal are outlined. Variations of the tube including a three-gun version are also described.

INTRODUCTION

A NUMBER of proposals for color kinescopes have been outlined in a preceding paper by E. W. Herold.[1] The 45-degree reflection-type kinescope falls into the class of tubes in which the emitted color is controlled by deflection of the beam in the immediate vicinity of the phosphor screen. A desirable feature of this class of tubes is that the color control is entirely independent of the scanning

* Decimal Classification R583.1.

† Reprinted from *Proc. I.R.E.*, October, 1951.

[1] E. W. Herold, "Methods Suitable for Television Color Kinescopes", *Proc. I.R.E.*, Vol. 39, pp. 1177-1185, October, 1951.

process and of the beam focus. A color picture inherently free from misregistry of the three colors may be obtained using a single gun with conventional scanning techniques. The three primary components of the color signal may be presented sequentially at any rate, depending upon the color system employed.

The screen arrangement for the "beam deflection" type of color kinescope usually consists of a beam-defining structure in registry with an array of red-, green-, and blue-emitting phosphor strips or dots, plus some means of bending the beam from one strip to the next. An important advantage of tubes that have a beam-defining structure near the color screen is that the color purity is insensitive to beam focus. This is to be contrasted with the "line-screen" arrangement[2] wherein the beam must be aimed and focused by the gun onto a thin strip of color; here, even a slight defocusing tends to dilute the colors.

Pairs of minute deflection plates mounted in front of each set of color strips have been proposed[3] as a means of switching the beam from one color to another. Such structures are difficult to build on a fine enough scale to give a high quality color picture. Furthermore, the switching voltages required and the capacitance to be driven are likely to be inconveniently high.

The 45-degree reflection-type kinescope employs a relatively simple method of controlling the beam in the neighborhood of the screen. This paper will describe some of the early experimental tubes with 7-inch screens having a line structure sufficiently fine to give about 180 black-and-white lines resolution (540 color lines). This size screen was chosen for convenience and was a part of a larger screen capable of 360 black-and-white lines resolution and filling a 16-inch envelope. The 7-inch experimental tubes were tested with the RCA color television signal and were found to give color pictures of pleasing quality, judged on the basis of the limited number of picture elements available.

Principle of Operation

Figure 1 shows a cross-sectional diagram of the 45-degree reflection kinescope. The screen assembly, which is shown in greater detail in Figure 2, consists of two parts: a metal aperture plate, and a transparent reflecting electrode. The beam approaches the aperture plate at an angle of incidence of approximately 45 degrees and a fraction of the beam passes through the slots. An electric field between the

[2] D. S. Bond, F. H. Nicoll and D. G. Moore, "Development and Operation of a Line-Screen Color Kinescope", *Proc. I.R.E.*, Vol. 39, pp. 1218-1230, October, 1951.

[3] L. C. Jesty—British Patent 443,896.

aperture plate and the reflector electrode causes the transmitted portion of the beam to be reflected and to return in a parabolic path to the aperture plate, where the beam strikes one of the phosphor strips deposited on the front side of the aperture plate. The color picture is viewed directly through the transparent reflector electrode. The phosphor is deposited on the plate in the form of strips so that a group of three strips emitting red, green, and blue light respectively is laid between each pair of apertures. The width of each of the phosphor strips within the group is approximately the same as that of the aperture, so that the reflected beam can be made to fall on any one of

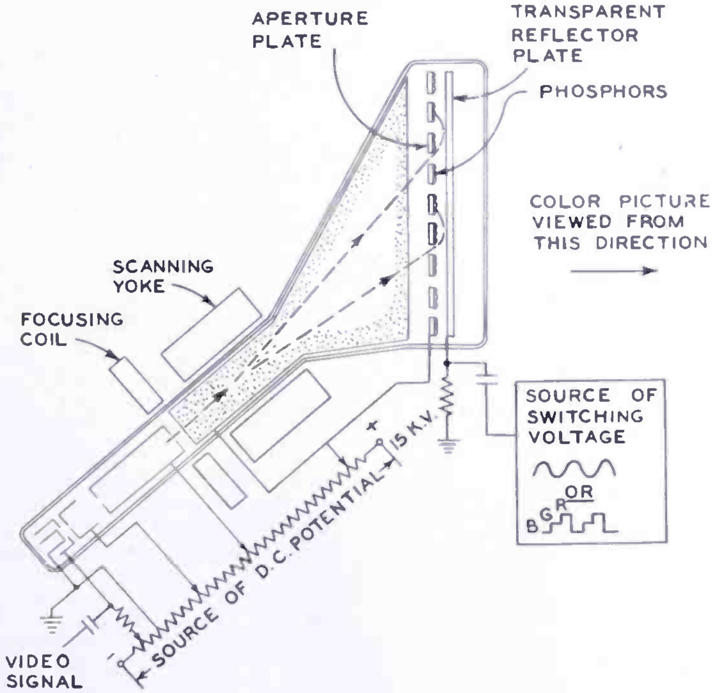

Fig. 1—Cross-sectional diagram of the 45-degree reflection-type three-color kinescope. Although the beam scans the screen at approximately a 45-degree angle, the picture is viewed in a normal manner.

the three colors selectively. When the voltage on the reflector electrode is varied, the point of impact of the reflected beam can be shifted from one color to another. The voltage change required to switch colors is inversely proportional to the distance between the aperture through which the beam passes and the corresponding bombarded spot. In some experimental tubes, the strength of the reflecting field was so chosen that the reflected beam actually jumped across about thirty slots before returning to the plate. Under these conditions less than 100 volts change in voltage of the reflector plate shifted a 12,000-volt beam from one color to another. A still finer pattern would require less power to switch colors. The capacitance to be driven by the color-control voltage need not exceed 50 to 100 micromicrofarads.

It must be noted that the color reproduction is entirely independent of the scanning raster and of the focus of the beam. The beam is not required to follow any particular pattern of slots on the aperture plate. A conventional gun and deflection yoke are entirely adequate, with no possibility of misregistry of the three colors assuming, of course, that the pattern is sufficiently fine.

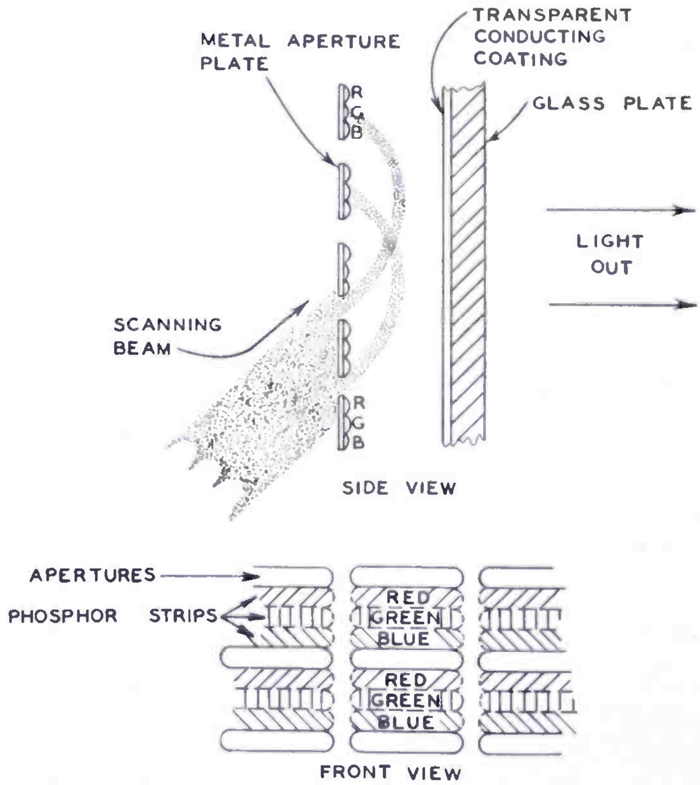

Fig. 2—Screen assembly of the 45-degree reflection kinescope shown in greater detail. By varying the potential on the transparent reflector plate, the reflected portion of the beam can be switched from one color phosphor to another.

The 45-degree angle of incidence of the beam requires a tube envelope of unconventional design. However, as a compensating feature, it permits a more compact cabinet design. In the tubes tested, a keystoning correction has to be added to the scanning to give a rectangular picture. Tests of the tube with the RCA color television signal are described below.

Electron Optics

Basic Equations—Color Switching. In the experimental 45-degree reflection-type kinescopes described herein, the aperture plate and the reflector plate are accurately flat and parallel. The electron motion in such a uniform field is similar to that of a projectile in a gravitational field and is readily calculable. It is found that the distance between the point where the beam passes through an aperture and the point where it returns to the aperture plate is given by

$$S = \frac{2V_B D}{V_B - V_R} \sin 2\theta, \tag{1}$$

where S is the range of the reflected beam (see Figure 3),

D is the distance between the reflector plate and the aperture plate,

V_R is the potential of the reflector plate in volts,

V_B is the potential of the aperture plate in volts,

θ is the angle of incidence of the beam with respect to the aperture plate.

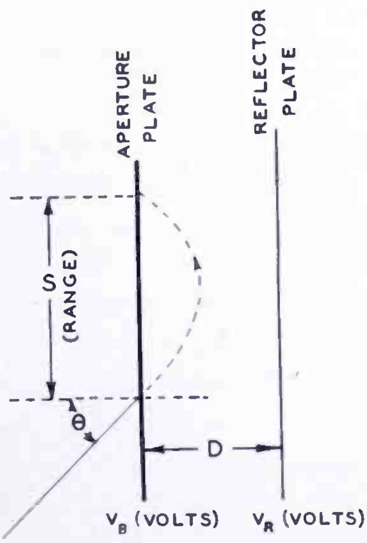

Fig. 3—Parabolic electron trajectory in the reflecting field between the aperture plate and the reflector plate.

In order to shift the beam from one color to another, the rate of change of S with respect to a change in the reflector-plate potential is of interest. From Equation (1), the differential displacement is

$$\Delta S = \frac{2V_B D \sin 2\theta \, \Delta V_R}{(V_B - V_R)^2}, \tag{2}$$

where ΔS is the displacement of the point of impact of the reflected beam produced by a change of reflector voltage of ΔV_R.

In the operation of these kinescopes, it was found convenient to keep the mean potential of the reflector plate at ground. Setting $V_R = 0$ in Equations (1) and (2),

$$S = 2D \sin 2\theta \tag{3}$$

and

$$\Delta S = \frac{2D}{V_B} \sin 2\theta \, \Delta V_R. \tag{4}$$

Experimental tubes were made with a spacing $D = 0.44$ inch approx., giving $S_{max} = 0.88$ inch. In the approximate center of the picture, where $\theta = 45$ degrees, the center-to-center spacing of the color strips was approximately 0.007 inch. Substituting these values in Equation (4), the voltage change required to deflect a 12 kilovolt beam from one color to the next is

$$\Delta V_R = \frac{V_B \Delta S_{max}}{2D} = \frac{12{,}000 \text{ volts} \times 0.007 \text{ inch}}{2 \times 0.44 \text{ inch}} = 95 \text{ volts.}$$

The 95 volts required to switch from one color to another were readily obtainable with sine-wave color switching at 3.58 megacycles, the color sequence rate in use during tests with the RCA color television system. By Equation (2), the required switching voltage could have been reduced to approximately 50 volts for the same target structure if V_R, the average potential of the reflector plate, had been run at 3,000 volts instead of at ground. Under these conditions the beam will skim much closer to the reflector plate but not strike it because its energy at the instant of closest approach will be directed parallel to the plate.

It is noted from Equation (4) that the shift of the reflected beam produced by a change in voltage of the reflector plate is proportional to the spacing D between the reflector and aperture plates. The spacing of 0.44 inch was chosen as a compromise giving adequate voltage sensitivity without sacrificing resolution. A very much larger spacing would allow the use of still less power for switching but would require a beam of exceedingly narrow angle of convergence to avoid objectionable spreading in a direction parallel to the slots. (The reflecting field provides a focusing of the beam but only in a direction perpendicular to the slots.) On the other hand, if extra power for switching is available, a further reduction in spacing would be desirable in order to make the tube still less susceptible to misalignment and to stray magnetic fields.

Color Uniformity. An electron-optical problem connected with the 45-degree kinescope is that of making the reflected beam fall on the proper color phosphor over all parts of the screen. Three possible approaches were considered.

1. Curving the aperture plate and reflector plate so that the beam

approaches the aperture plate at exactly 45 degrees over all parts (Figure 4A).

2. Using plane electrodes but providing an electron lens between the gun and the front of the aperture plate so the 45-degree angle of incidence is preserved over the whole screen (Figure 4B).
3. Using plane electrodes but arranging the position of the apertures and phosphors to compensate for the different angles of approach over the target (Figures 1 and 5).

The greater simplicity of constructing plane electrodes as compared to the curved electrodes ruled out the first approach for the initial experiments. The electron lens method mentioned in the second ap-

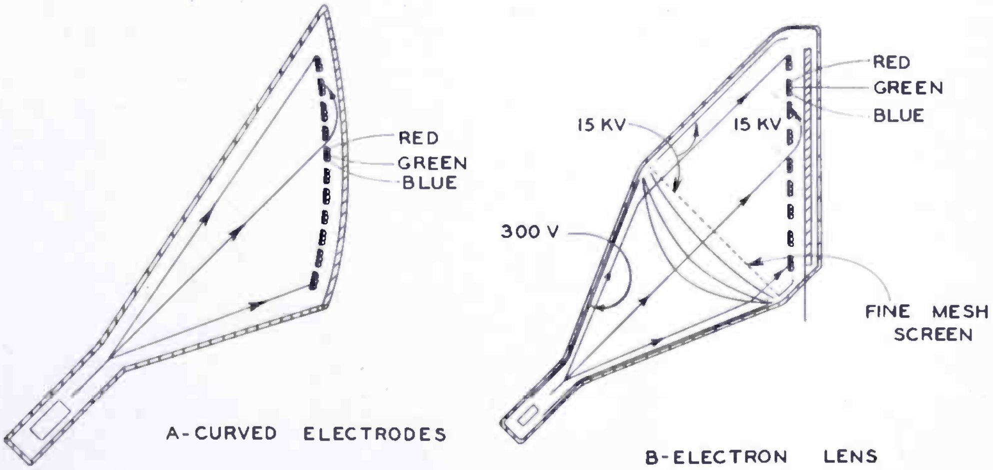

Fig. 4—Two alternative methods of achieving color uniformity by causing the beam to strike the entire screen at 45 degrees. The electrodes in (A) are nonspherical surfaces whose vertical cross section is a spiral and whose horizontal cross section is a circle. The electron lens method in (B) permits plane electrodes to be used and eliminates the need for a "keystoning" correction in the scanning.

proach is promising, but requires a longer tube with some loss in brightness due to the fine mesh screen. The third approach was used and gave very satisfactory results. Equations (1)-(4) show that the maximum values of the range S and the displacement dS occur in the center of the picture where the angle of incidence, θ, is exactly 45 degrees. At the top and bottom of the picture where θ approaches 60 degrees and 30 degrees, the range may decrease as much a 20 per cent. To compensate for this effect, a particular pattern of apertures has been devised for the aperture plate.

Figure 5 shows the particular arrangement of apertures used in the 45-degree reflection-type kinescope. The insert shows an enlarged view of the slot-like apertures. These apertures are formed on concentric arcs of circles,[4] the centers of which lie on a common point O, obtained by dropping a perpendicular from the center of deflection to the plane of the target. The phosphors are laid on arcs about the same center, with three rows of phosphor between each two rows of apertures (Figure 2). Along each arc the beam approaches the aperture plate at the same angle. Thus, for a constant voltage on the reflector plate, the beam will excite the same color phosphor all along the arc.

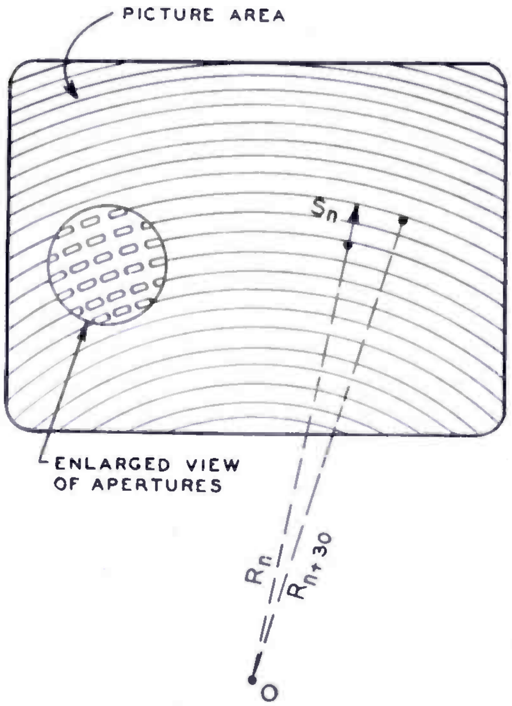

Fig. 5—Circular pattern of apertures used in experimental 45-degree reflection kinescopes. Plane electrodes are made feasible by arranging the position of the apertures and phosphor strips to compensate for the varying angle of incidence across the screen (see Figure 1). The insert shows an enlarged view of a small section of the aperture plate.

The color uniformity from top to bottom was achieved by arranging the spacing between adjacent concentric arcs to take into account the fact that the range, S, is a maximum for a 45-degree angle of incidence as indicated by Equations (1)-(4). For a 16-inch kinescope employing a picture 9 inches high, the spacing between rows may be approximately 20 per cent greater in the center of the picture than at the top and the bottom.

The radii of the arcs along which the apertures were to be formed were calculated in a stepwise manner from Equation (3). The plane of the target was set 8.5 inches from the center of deflection, and the

[4] The circular pattern of apertures was suggested by E. G. Ramberg, RCA Laboratories Division, Princeton, N. J.

angle of incidence varied between 30 degrees at the bottom of the picture to 60 degrees at the top. It was decided arbitrarily that the range should span thirty rows of apertures over all parts of the target and that the maximum range in the center of the picture (45-degree incidence) should be 0.8854 inch. The radii of successive arcs were then given by

$$R_{n+30} = R_n + 0.8854 \sin 2\theta_n \, ,$$

where

$$\theta_n = \text{arc tan} \left(\frac{R_n}{8.5} \right).$$

The radii were calculated for 393 arcs covering a vertical distance of 10.75 inches. This pattern would permit a useful picture about 9.5 inches high having approximately 1000 color-phosphor strips. The experimental tubes described herein used an aperture plate based on the central part of these calculations giving a screen diameter of 7 inches.

The Focusing Action of the Reflecting Field. The preceding discussion has assumed that the angle of incidence of the beam over all parts of the aperture screen is specified exactly by a line connecting the bombarded aperture with the center of the deflection coil. This is, of course, true only for the central core of the beam and then only in the absence of perturbing fields or possible misalignments of the screen. The dependence of the range S on the angle of incidence was given by Equation (3).

Inasmuch as a variation in the range of one part in 120 in the present screen moves the beam from one color phosphor to another, the rate of variation S with a small change in θ is of interest. Differentiating Equation (3) with respect to θ, one obtains

$$\frac{dS}{d\theta} = 2S_{\text{max}} \cos 2\theta. \tag{5}$$

It is noted that $\frac{dS}{d\theta}$ is small in the neighborhood of 45 degrees. This means that the electric field between the aperture plate and the reflector plate has a focusing action in the plane of incidence of the beam. Thus, the fraction of the beam passing through each aperture may actually diverge and still be brought together by the reflecting field to strike a single color strip without appreciable excitation of adjacent color strips. The relaxation of the requirements on alignment of the target and on the shielding of the beam from stray magnetic fields are further advantages of this focusing effect.

Equation (5) shows that if the angle of incidence is greater than 60 degrees or less than 30 degrees, $\frac{dS}{d\theta} > S$ which is equivalent to defocusing. This would appear to limit the total angle of scan to 30 degrees if the benefits of the focusing action are to be obtained. Such a limitation is not a severe restriction on tube dimensions or receiver cabinet design since a 30-degree total angle centered about a 45-degree angle of incidence would permit a shorter cabinet for the same size picture than a conventional tube with a total angle of 60 degrees.

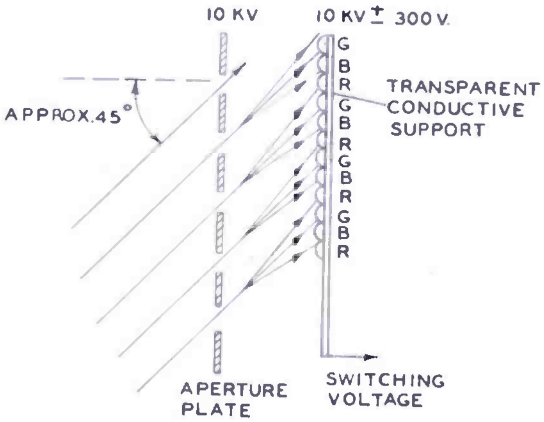

Fig. 6—An alternate form of 45-degree color kinescope. This "transmission-type" tube was considered less attractive than the reflection type on the grounds that it was more difficult to construct, required more power to switch colors and lacked the desirable focusing features of the reflecting field.

The tapering off of the focusing effect of the reflecting field at the top and the bottom of the picture makes some magnetic shielding desirable to prevent stray fields such as the earth's magnetic field from shifting the beam from the proper color. The focusing of the reflecting field in these areas does not appear to be essential for color purity since the convergence angle of a high velocity beam is a very small fraction of one degree.

It may be noted that the two alternative methods of achieving color uniformity, illustrated in Figure 4, profit by having a 45-degree angle of incidence over the entire screen.

Alternate Forms of the 45-Degree Color Kinescope

Transmission-Type Kinescope. A variation of the 45-degree reflection-type kinescope is the transmission-type tube operating by the method illustrated in Figure 6. The beam strikes the phosphor strips on the second plate at high velocity. The color is switched by applying an alternating-current voltage to the second plate.

Simple calculations show that the transmission-type tube at 45 degrees requires four to eight times as much switching voltage as the reflection-type tube for the same beam voltage and target spacing. There is no focusing action of the field, and the target is very sensitive to stray magnetic fields. Unlike the reflection-type tube, this form requires accurate mechanical registry of the two plates. A satisfactory solution to the uniformity problem would have to be worked out before a useful tube could be built. It may be noted that the circular pattern of apertures used to achieve uniformity in the reflection-type tube does not appear attractive here because of the lack of focusing.

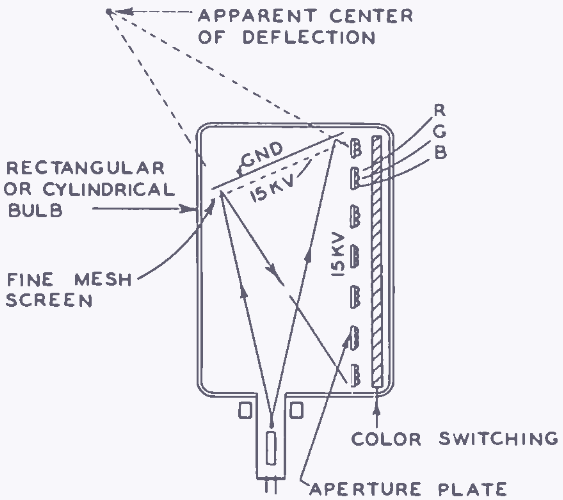

Fig. 7—The use of an electron mirror to shorten or simplify the bulb design of the 45-degree color kinescope.

Electron Mirrors for Compactness and Simplification of Bulb Design. The electric field between a flat plate and a fine mesh screen can be used as a plane mirror for electrons. Figure 7 shows how such a mirror might be used to simplify or shorten the bulb design of the 45-degree tube. The target would be aligned for the apparent center of deflection instead of the actual center of deflection. The principal disadvantage is the loss in beam strength produced by the double transit through the screen. With available high-transmission screens this loss might be reduced to about 50 per cent.

Three-Gun 45-Degree Kinescope. An alternative 45-degree kinescope arrangement which does not require a color switching signal consists of three guns mounted as close together as possible with a 45-degree reflection-type target. With a 12-kilovolt beam, color separation can be achieved by operating the cathodes of the red and blue guns approximately 95 volts above and below the potential of the green gun. For each color the electrons pass through the apertures with slightly different velocities thus falling on different colors (see Equation (4)).

The beams should be as nearly superimposed as possible for best registry of the three colors. Even so, the three rasters will be slightly different in size, owing to the different velocities of the beams when passing through the deflection coil. For this reason the screen should be designed to shift colors with as little change in beam voltage as practicable. With the screen assembly described above, and using a magnetic-type scanning yoke, the red and blue rasters differ in size from the green raster by about 0.4 per cent. The resulting displacement, which is of the order of a picture element, occurs only at the edge of the picture and will be unnoticed.

Construction of an Experimental 45-Degree Color Kinescope

Aperture plates for the experimental tubes were made from copper sheets 0.002 inch thick having openings etched by photo-engraving techniques. A photographic master of the pattern desired was first obtained by ruling on a heavy lucite block with a stylus mounted on a vertical milling machine. The radii of the arcs were set to an accuracy of a few ten-thousandths of an inch according to the calculations outlined previously. This pattern was transferred to a photographic negative by contact printing using a point light source. A second ruling of radial lines was then combined with the curved pattern to give a negative of the slot pattern complete with radial cross bars. The cross bars were made as thin as possible consistent with adequate mechanical strength of the final aperture plate.

The copper sheet was coated with a "cold top" photosensitive enamel and exposed with ultraviolet light through the slot pattern negative. The action of the light makes possible the formation of an acid-resistant coating over all parts of the copper except where the slots are to be. Immersion in an etching solution forms the holes in an accurate copy of the original pattern.

The aperture plate was then coated with the three phosphor materials emitting the primary colors. Each material was deposited in turn by settling through a mask similar, but not identical to, the aperture plate itself. Other methods of laying down the phosphors could have been used equally well. For a small target, a copy of the aperture plate itself could be used as a settling mask for all three colors without appreciable error by simply displacing the mask in turn for each color. For a large target with a wide angle of scan, each color should have its own settling mask ruled so that the center of its arcs coincide with the center of curvature of the aperture plate. In the experimental tubes with the 7-inch screens, a satisfactory compromise was made in which a settling mask was computed and ruled for the phosphor row falling midway between the slots. The error, resulting from displacing the mask ± 0.007 inch for the adjacent colors, was not objectionable for the 7-inch picture. Figure 8 shows a photomicrograph of the three phosphors deposited on the aperture plate. The thicknesses of the coatings were adjusted for color balance to give an acceptable white.

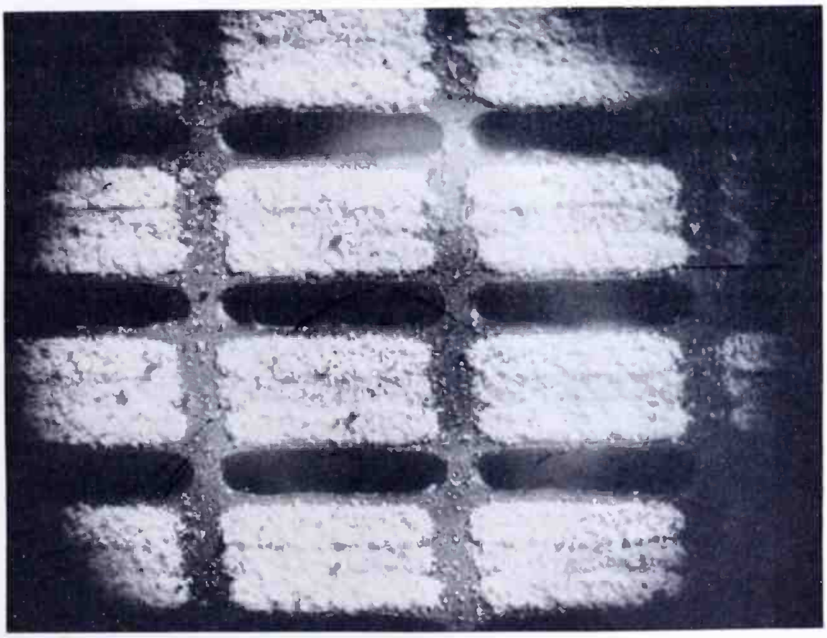

Fig. 8—Photomicrograph of the 3 sets of phosphor strips deposited by settling on the copper aperture plate.

When the tube was assembled, the copper aperture plate was mounted on a rigid frame which permitted it to be stretched tight and flat. The frame also supported the glass reflector plate spaced parallel to the mask. The tolerances on parallelism and flatness of each plate were quite close. The inner surface of the glass plate was coated with a transparent conducting coating, called "Nesa," supplied by the Pittsburgh Plate Glass Company. The Nesa coating is highly transparent and could be formed on the glass with a surface resistance of several hundred ohms per square. The resistance was sufficiently low to give no objectionable voltage drop or power loss even when switched at megacycle frequencies. Lavite spacers were used to support the glass 0.443 inch from the aperture plate.

Early tests of the screen assemblies were made by placing the structure in a demountable vacuum system shown in Figure 9. Color uniformity, color stability, brightness, contrast, resolution, and moiré could all be readily examined without requiring a complete color signal.

In parallel with the development of the screen, the associated circuits were developed for operating the tubes with an RCA color television signal. Sealed-off experimental tubes with 7-inch diameter screens were built and tested successfully with a full color picture.

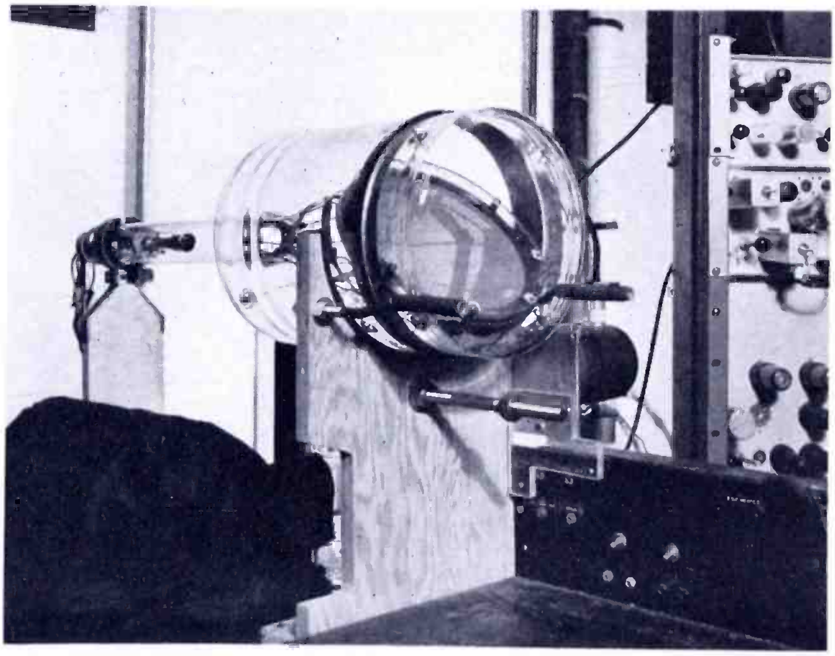

Fig. 9—Demountable vacuum system used for testing color kinescope screens. A 7-inch diameter 45-degree reflection-type screen is shown in position for test prior to being sealed in a bulb.

Operation of the 45-Degree Kinescope with the RCA Color Television Signal

The 45-degree reflection-type color kinescope belongs to that class of color tubes in which the primary color emitted is determined by a control voltage applied to the screen structure. The phosphor strips were laid down on the aperture plate in groups of three having the order red, green, blue, (Figure 2). In the absence of the color switching signal, the proper direct-current bias was applied to the reflector plate to give a uniform green color. For sequential three-color reproduction, a repetitive wave form of proper magnitude was applied to the reflector plate to cause the reflected beam to oscillate from the central green phosphor to the adjacent red and blue phosphors. At the same time, the beam current was modulated in turn with each primary signal so that the total light emitted by each tri-color element carried the proper intensity, hue, and saturation.

Figure 10 shows two forms of switching voltage which may be applied to the reflector plate for a sequential color presentation. In 10 A, a step wave is shown. This wave shape would give the maximum light output, each color being on one-third of the time. Generating this wave form at high sequence rates presents an unusual circuit

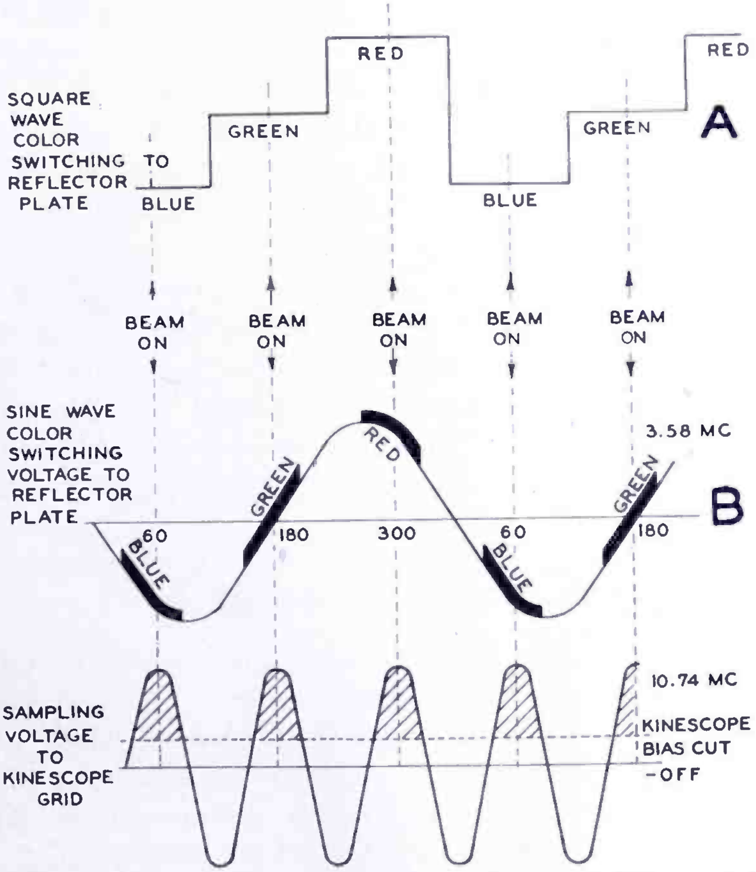

Fig. 10—Wave forms of the color-switching voltage which may be applied to the reflector plate. For low-speed switching the step wave shown in A would be preferable. For high-speed switching at megacycle frequencies the sine wave shown in B was entirely suitable. Beam blanking at three times the switching frequency was used to give the required color sequence.

problem and an attempt was made, with some encouraging results, to do it by means of a multiresonant circuit as a plate load of a class C amplifier. For the work with the RCA color television system, however, using a 3.58-megacycle color subcarrier, it was found more convenient and, for all practical purposes, just as effective, to use the sine-wave form shown in Figure 10B. Sequential color presentation with the RCA system requires color switching at the subcarrier frequency.[5]

[5] RCA Laboratories Division, "A Six-Megacycle Compatible High-Definition Color Television System", *RCA Review*, Vol. X, pp. 504-524, December, 1949.

A 3.58-megacycle sine wave of approximately 75 volts root-mean-square value was applied to the reflector plate. By switching the beam on at 120-degree intervals with proper timing (say at 60 degrees, 180 degrees, 300 degrees, 60 degrees, etc.) the BGRBGR (Blue, Green, Red, etc.) sequence of the dot-sequential presentation was preserved. If the beam was not switched on and off, whichever color was the center color (in this case green) was repeated twice for every one of the other two to give a BGRGBGR sequence. Thus, the beam blanking performed the double function of eliminating the extra green line and of effecting "sampling." Beam blanking was accomplished conveniently by modulating the video on the grid of the kinescope with a sine wave of three times the switching frequency, or 10.74 megacycles (as shown in Figure 10B) synchronized with the switching voltage. This was done by linearly adding this sampling frequency to the video and then operating the grid of the kinescope class C, much the same as in grid modulation of an amplitude-modulated radio signal.

The use of sine-wave switching has the advantage of reducing the power requirements of, and of simplifying, the circuitry. Resonant-circuit techniques were employed throughout.

Figure 11 is a block diagram showing this use of sine-wave switching and the associated video and deflection circuits.

Switching and Sampling Circuits. The circuits involved were straightforward and presented no unusual problems beyond a mechanization of Figure 11. A possible exception was keystoning, of which more will be said later. The major difficulty encountered was that of transmitting signals over long leads and/or cables first to a demountable and then to a test rack. This is reflected in the "brute-force" type of circuits which were used, rather than the compact circuitry usually encountered in receiver design.

The input signals used were received via two cables connected to the master color television signal generators set up in the television studio at RCA Laboratories. One signal consisted of the 3.58-megacycle color synchronizing signal and the other was the RCA color signal, i.e., standard black-and-white synchronization and blanking, a video signal with a 3.58-megacycle color subcarrier, and a 3.58-megacycle burst on the back porch of the horizontal sync pulse. The burst was not used because of the availability of the separate color synchronizing signal. The circuits were divided into two parts: the color switching and sampling circuits driven by the 3.58-megacycle sine wave, and the more or less standard video and deflection circuits.

The schematic diagram of the switching and sampling circuitry is shown in Figure 12. The color-sequence phase shifter adjusted the phase of the 3.58-megacycle signal so that it was in correct phase with the color synchronizing signal. This allowed a green portion of picture to appear as green, a red portion as red, and so on. The phase shifter used consisted of a phase inverter in conjunction with a variable resistance-capacitance network to produce a continuously variable phase shift of 0 degrees to 140 degrees.

The output of the phase shifter was put through an isolating stage and then into a switched delay cable. The cable consisted of two

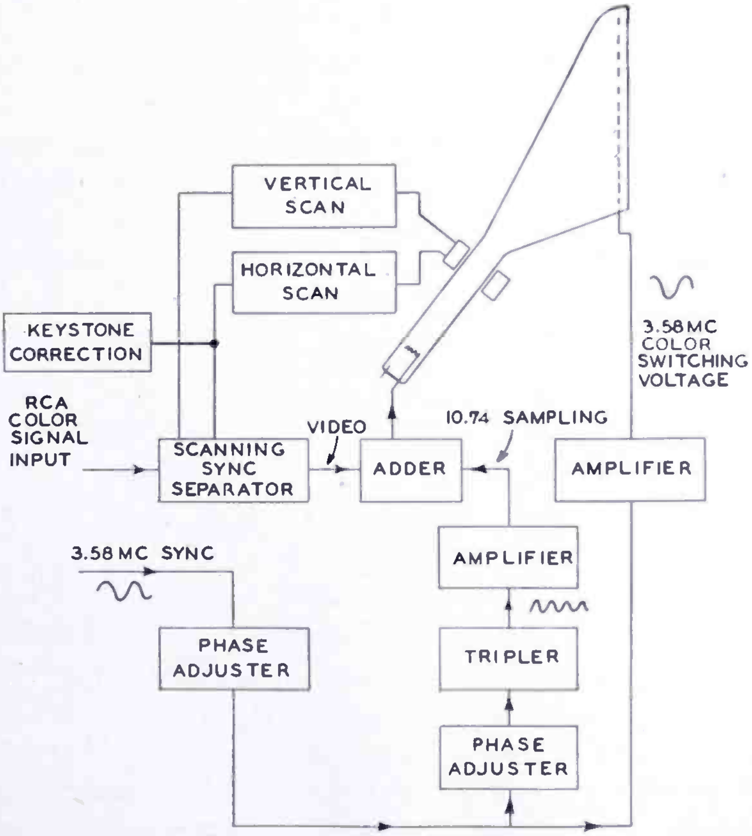

Fig. 11—Block diagram of associated circuits for operating the 45-degree reflection kinescope with the RCA color signal. A 3.58-megacycle sine wave is applied to the reflection plate and a 10.74-megacycle sine wave used for sampling the signal at the gun.

lengths of 1000-ohm coaxial transmission line cut to give a fixed delay equivalent to 120 degrees at 3.58 megacycles for each section. This arrangement, in conjunction with the continuously variable unit, gave complete control over a full 360 degrees of phase shift. The output was then amplified and applied to the reflector plate of the kinescope by resonating the capacitance formed by the reflector plate and the aperture mask with a coil.

Although the Nesa coating of the reflector plate has resistivity, no difficulty was encountered that could be attributed to it. The out-

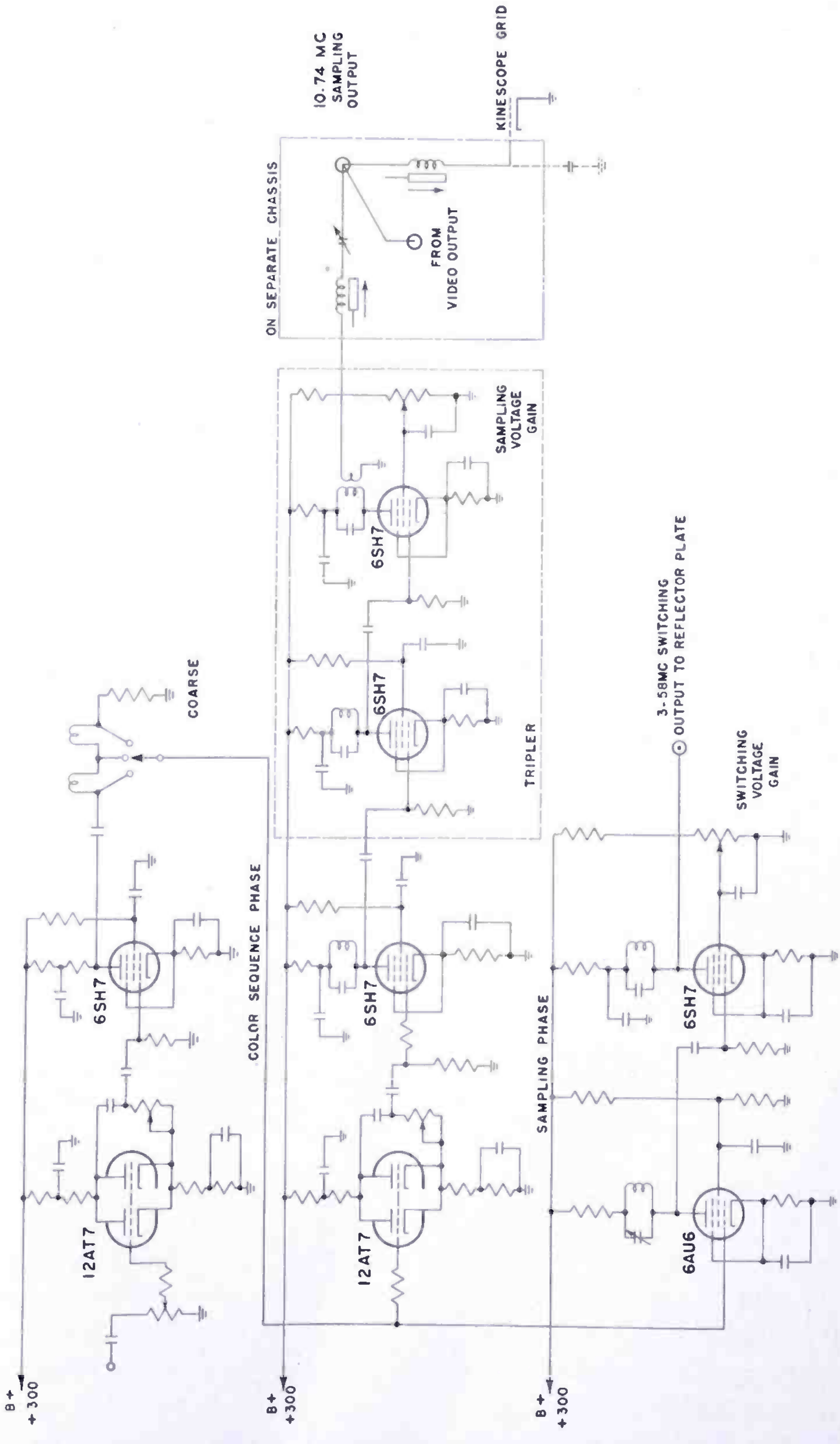

Fig. 12—Schematic diagram of the switching and sampling circuits.

put of the color-sequence phase shifter was also put through a sampling phase shifter of the continuously variable type just described. The output of this unit was amplified, tripled, amplified again, and then added to the video. The adding circuit consisted of a step-down radio-frequency transformer, the secondary being a link coupling into the resonant circuit shown. The 10.74 megacycles was then series resonated with a very small capacitor (2-5 $\mu\mu$f). The net effect was to present a low impedance to the sampling frequency and a high impedance to video. The video was injected at the point shown in Figure 12 and then put through a parallel LC arrangement which presented a low impedance to the video. The LC combination was then resonated with the kinescope grid-to-ground capacitance to form another series-resonant circuit for the sampling frequency. In this manner an adequate sampling voltage was developed on the kinescope grid without adversely affecting the video.

The video amplifier was conventional and had a 4-megacycle response. The final output stage provided a low output impedance to drive a long lead.

Keystoning Correction to the Deflection. The 45-degree angle of incidence of the beam in a tube of the type shown in Figure 1 causes one side of the screen to be much closer to the gun than the other, resulting in a distortion of the scanning raster. A similar problem has been faced in television pickup tubes such as the iconoscope, although the difficulty is now accentuated because of the wider angle of scan and the higher voltages. The resulting distortion appeared to be somewhat easier to correct when the screen was oriented so that part of it closest to the gun was either at the top or the bottom of the picture. The correction to be applied to the scanning then consisted of modulating the horizontal sweep with a sawtooth component, at vertical frequency.

Relatively small attention was given to the design of the keystoning correction circuit, but the circuit shown in Figure 13 was found to be adequate. It was necessary to decrease the size of the power feedback capacitor in the horizontal deflection system to allow the deflection unit to follow the modulation and to minimize the effect of rectification by the damper.[6]

RESULTS

Color Uniformity. An exacting requirement of a color kinescope is

[6] This rectification amounts to a detection of the vertical saw-tooth modulation and would cause a circulating current of this waveform in the yoke, thus skewing the picture.

that it give a uniform color field in each of the three primary colors. The 45-degree kinescope having a screen diameter of 7 inches gave substantially uniform colors, in some cases without the benefit of any correcting coils or magnets. In other cases, one small magnet was mounted near the deflection yoke on the target side. The purpose of such a correcting magnet was to change slightly the angle of incidence of the beam, thus correcting for target misalignment or possible effects of the earth's field. In general, the tests proved the feasibility of using plane electrodes with the aperture pattern computed to compensate for varying angles of incidence.

Color Purity. Color purity was not measured quantitatively, but in general it appeared to be good. For best color purity it is desirable

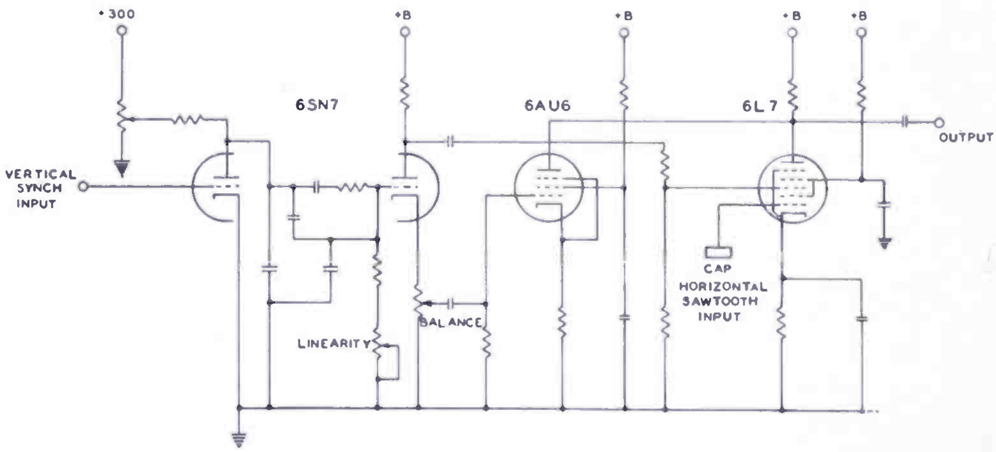

Fig. 13—"Keystoning" circuit used in test of the 45-degree color kinescope.

that the collimated fraction of the reflected beam be slightly narrower than the color strips, or that an insensitive guard band be used between strips. In most of the tubes no guard band was used but the effective slot width ordinarily gave a reflected beam which was slightly narrower than the phosphor strips.

Brightness. The 7-inch color kinescope of the 45-degree reflection-type produced pictures of brightness comparable to that of other single-gun color kinescopes. The target structure itself permits bombarding voltages of at least 15 kilovolts. However, expansion of the aperture plate owing to heat dissipated by the bombarding beam gave some trouble in experimental tubes having a two-mil-thick aperture plate. A four-mil-thick plate was found to be preferable.

An ideal color kinescope of the color-switching type should allow the full beam current, I_B, to fall in turn on each of the three color phosphors. In the 45-degree reflection tube the maximum transmission of a plane aperture plate is 25 per cent since the phosphor strips must be laid on the aperture plate itself.[7] The vertical cross bars used in the pattern shown in Figure 5 reduce the maximum transmission to about 20 per cent and the oblique angle of incidence further reduced the effective opening to about 15 per cent. This efficiency is comparable to the aperture-mask type of screen used in the developmental tri-color kinescopes described in an accompanying paper.[8]

Resolution. The automatic registry of the three colors over all parts of the screen is a very significant advantage of the 45-degree tube. This characteristic showed up in improved detail when compared with other types of color kinescopes which did not have the automatic registry feature.

In addition to the registry of the three colors, the resolution is, of course, a function of the fineness of the color strips. The 7-inch experimental tube here described had color strips approximately 0.007 inch wide in the center of the target and 0.0065 inch wide at the top and bottom of the picture. Allowing for the aperture itself which is 0.007 inch wide, the total height of a white picture element was 0.028 inch or less. This allowed a vertical resolution of about 360 black-and-white lines in a picture 10 inches high, but allowed only about 180 lines in the 7-inch diameter screens tested.

The limitation on resolution in the tests made appeared to be set by the structure itself and not by electron optical limitations. This suggests the desirability of a finer pattern. In the experimental tubes, the curved slots were also broken up by vertical supporting crossbars approximately 0.006 inch wide and 0.040 inch apart in the center of the picture. These vertical black bars were visible upon close viewing of the picture and did limit resolution of a stationary picture slightly. If the test pattern were moved to minimize the effect of the stationary bars, the observed resolution in a picture 5 inches wide was approximately 300 lines.

It should be noted that the focusing action of the reflecting field occurs only in the vertical direction. This means that to obtain maximum horizontal resolution, the beam focus should be set for sharp focus of the reflected beam on the phosphor screen. The focusing action of the reflecting field will, however, make the vertical height of the reflected beam spot the same as the height of the defocused

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[7] A 45-degree reflection kinescope for two colors would permit a maximum efficiency of 33 per cent.

[8] H. B. Law, "A Three-Gun Shadow-Mask Color Kinescope", *Proc. I.R.E.*, Vol. 39, pp. 1189-1194, October, 1951.

beam initially passing through the aperture. The vertical resolution can, of course, never be better than the distance between the slots, and moiré is minimized if the width of the beam covers at least two slots.

The difference in throw of the beam from top to bottom of the picture will also give some difference in focus unless a beam of very narrow angle of convergence is used. This effect was not objectionable in the 7-inch experimental tube but a larger tube may require a slight vertical saw-tooth fed into the focusing electrode for best resolution.

Moiré. A moiré pattern resulting from the "beating" between the straight scanning lines and the curved slots was observed. The moiré pattern was most intense when the distance between the scanning lines was about equal to the distance between the slots, and the spot size was less than this distance. Loss of vertical interlace was also noted to intensify the moiré.

In general the moiré as observed with the 7-inch tube was noticeable but not particularly objectionable. The visibility of the moiré would be expected to decrease with any of the following modifications:

1. Closer spacing between slots so that the beam always covers two or more apertures.
2. An elliptical spot with the largest dimension perpendicular to the slots to achieve condition (1) with the existing pattern. The 45-degree angle of approach of the beam does give a slight ellipticity to the defocused spot.
3. Orientation of the scanning raster so that the lines make an angle of 45 degrees to 90 degrees with curved slots. Such a change in angle of approach affects the type of keystoning correction required.
4. Forming the slots in a curved dot pattern rather than along continuous arcs.

Contrast. Qualitative observation of the color pictures obtained with the 45-degree reflection tube indicated good contrast. This result was due partly to the use of a flat screen and partly to the complete absence of optical halation caused by multiple reflections sometimes encountered when the phosphor is deposited on a glass plate. However, there is an electron-optical effect in a reflection type tube which partially reduces the contrast. A small fraction of the beam impinging on the phosphor is always reflected at high velocity. If the electric field is such as to return these electrons to the phosphor, the contrast is reduced.

In the 45-degree kinescope an intense stationary beam was observed to have a white halo around the bright spot on the phosphor. The halo was white because the scattered electrons fall uniformly on all three color strips. The radius of the halo was approximately the same as the range S of the reflected beam (see Figure 14). A still fainter disc of white light was observed around the point on the aperture plate where the incident beam passed through. This disc resulted from scattering of the primary beam on the edges of the aperture. The loss of contrast in an actual picture due to the scattering effect was barely perceptible and no effort was made to minimize it.

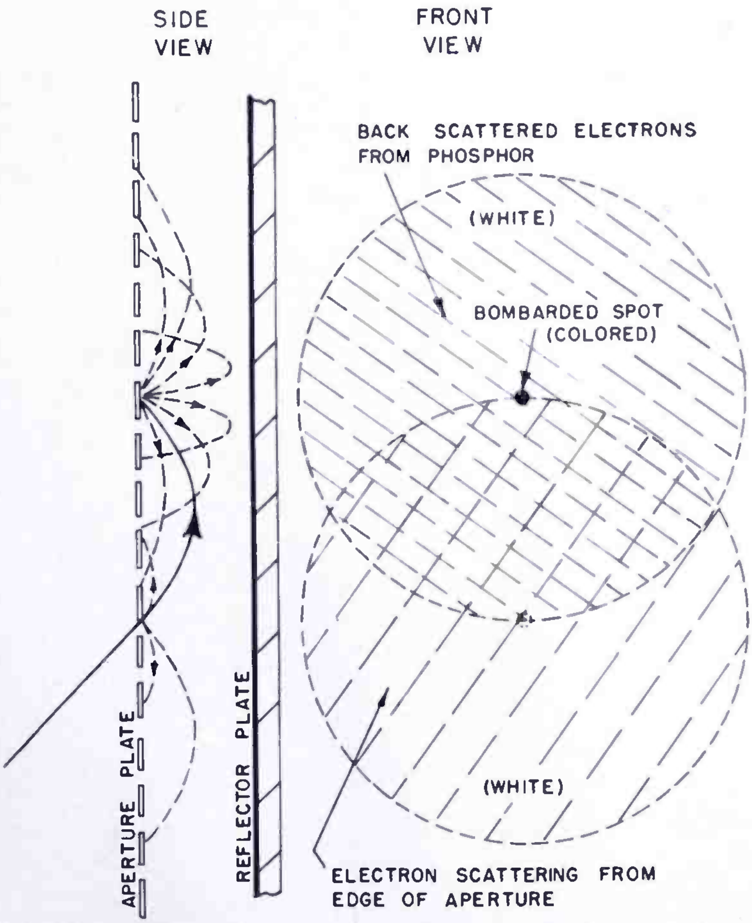

Fig. 14—Electron paths of high-velocity scattered electrons which may contribute to reduction of contrast in a reflection-type kinescope.

Color Stability. It is well known that an electron beam striking an insulator will drive the bombarded surface to some equilibrium potential whose value depends upon the secondary emission ratio of the material, the potential of surrounding electrodes, etc. Some concern was felt that the phosphor might assume a potential sufficiently different from the aperture plate to deflect the beam to the wrong color.

Experimental tests showed no evidence of charging of the phosphors. The colors remained stable for all anode voltages tested ranging up to 15 kilovolts.

Acknowledgments

The writers wish to express their appreciation for the advice and encouragement of E. W. Herold, H. B. Law, and Albert Rose. The cooperation of S. W. Dodge and L. Hart has contributed to the construction of experimental tubes.

A GRID-CONTROLLED COLOR KINESCOPE*†

By

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Summary—*A new color kinescope makes use of a series of closely spaced screens, each covered with a different primary color phosphor and separated from each other by fine mesh control grids. Small voltage changes of these grids control the depth of penetration of the scanning beam or beams into this assembly of screens. This arrangement permits individual excitation of any one or combination of the primary colors which go to make up the colored image. Experimental tubes have been built, first in two-color form to test principles, and then in three-color form. They have been operated with a color picture using the RCA color television system signal.*

I. Introduction

THE name "grid-controlled color kinescope" has been given to a single multicolor television viewing tube having a number of closely-spaced fluorescent screens, separated by control grids and scanned by one or more electron beams. The beam(s) penetrates this assembly to different depths determined by the control-grid voltages and produces a different primary color image on each of the fluorescent screens. When viewed directly, the individual color images are superimposed to form a single polychromatic image.

Proposals have been made for a different color reproducer tube having a series of fluorescent screens.[1] Colors are changed by keying the screens with a switching voltage of several kilovolts. Such a tube would be difficult to operate, particularly in a television system employing high color-switching rates. In the tube here discussed, color-control grids reduce the required switching voltage to small practical values.

An experimental grid-controlled kinescope using a 9-inch envelope is shown in Figure 1.

II. General Description and Operation

A. Two-Color Tube. As an aid in understanding the three-color tube operation, the simpler two-color version will first be described.

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*Decimal Classification: R583.1.

† Reprinted from *Proc. I.R.E.*, October, 1951.

[1] A. B. Bronwell, "A New Viewing Tube for Color Television", *Tele-Tech*, Vol. 7, pp. 40-41 and 60-65, March, 1948.

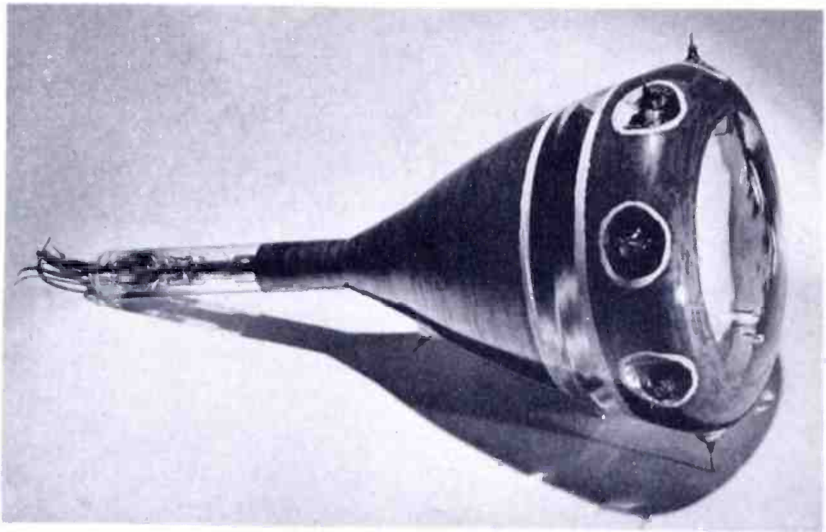

Fig. 1—Experimental grid-controlled color kinescope.

Figure 2 is a diagramatic representation of a typical two-color single-gun grid-controlled kinescope. Characteristic operating voltages are shown. Here a conventional kinescope gun scans, in normal fashion, an array of screens shown as S_1, C, S_2. Screen S_1 consists of a metallic grid structure perforated by photoengraving. On the viewed side of this screen a red phosphor is uniformly settled. A high-transmission mesh of finely woven wire is used as the color-control grid, C. Screen S_2 consists of a clear sheet of glass upon the scanned side of which is formed a transparent conducting layer. The thickness of the glass is determined by mechanical strength only. An electrical connection inside of the tube is made to the conducting layer in parallel with the screen S_1, unless it is desired to bring these elements out separately.

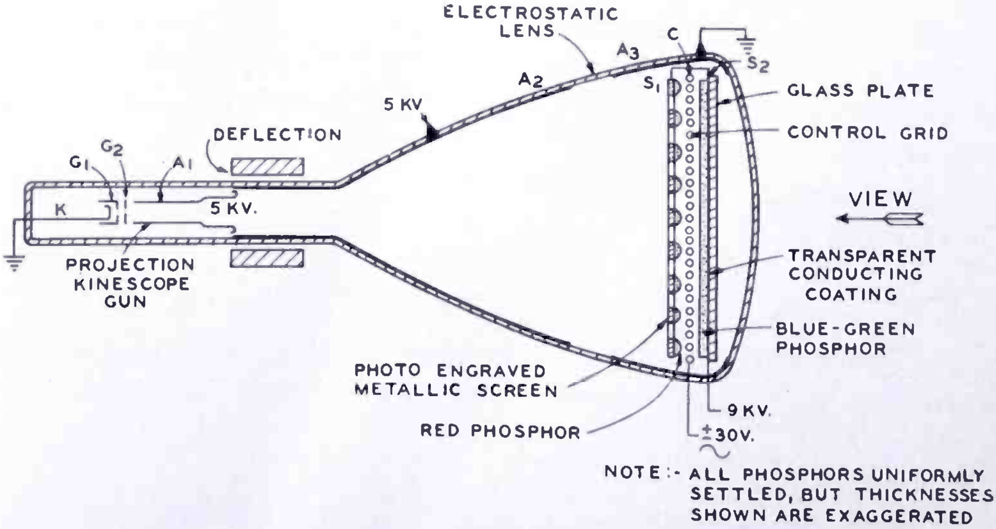

Fig. 2—Two-color single-gun grid-controlled color kinescope.

A blue-green phosphor, complementary in color to the red, is uniformly settled upon the conducting coating in a thickness which is a compromise between phosphor efficiency on the one hand and light transmission and secondary electron collection on the other.

In operation, the voltage of the control grid C determines whether or not the scanning beam will penetrate it, and thus, whether the red or blue-green screen will be activated at a given time. If C is about +30 volts, the beam passes through it and is then accelerated again up to several kilovolts to strike the blue-green phosphor. If C is negative, the beam, energetically unable to reach it, is reflected, and returns to scan the red phosphor. The graphite wall coating is divided to form an electrostatic lens which insures normal approach of the scanning beam to the screen over all parts of the raster. The three screens are

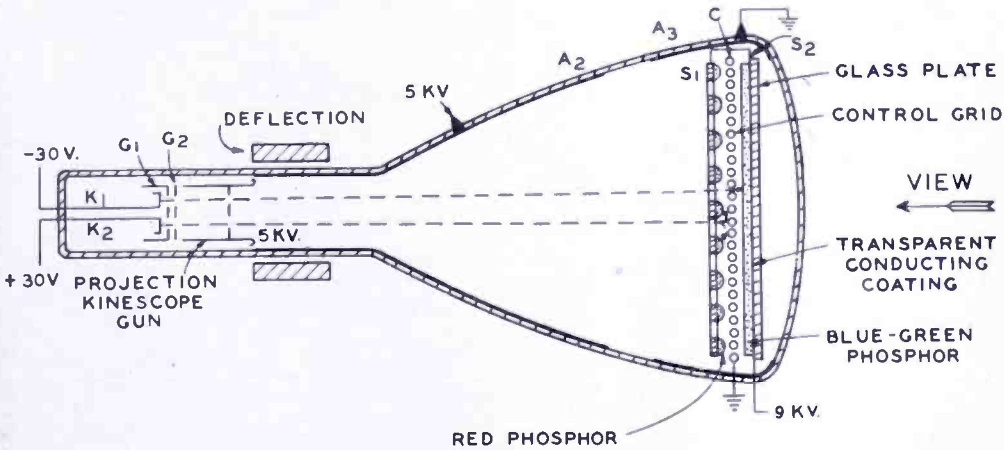

Fig. 3—Two-color two-gun grid-controlled color kinescope.

spaced as closely together as possible to avoid parallax. Voltage breakdown sets a lower limit to the spacing.

When the color changes are to be made at a rapid rate, it is necessary to consider the capacitance of the circuit. The high capacitance between the control grid C and screens S_1 and S_2, is biased through a high impedance bleeder. In this way the capacitance, which is driven by the color changing voltage, is reduced to the free-space capacitance of the combination S_1, C, and S_2; this varies about linearly with screen diameter as contrasted to the parallel plate capacitance which varies as the square of the diameter. Instead of applying the color-control voltage to this grid combination, it can alternatively be applied to the electron gun which has even lower capacitance. In this case, the voltage of C is held fixed, and the cathode, control grid, and screen grid of the electron gun are varied together. The color control voltage used is too small with respect to the accelerating voltage to affect either focus or scan size appreciably.

In the arrangement shown in Figure 3, two separate electron guns are used. The color control grid, C, is biased at a fixed voltage, shown here as ground. The gun cathodes are biased at potentials such that the beam from one gun (biased negatively) can penetrate the screen C and scan the blue-green phosphor at all times that the current from this gun is on. The other gun, biased positively with respect to the control screen, gives an electron beam which is unable to penetrate screen C, is reflected, and always scans the red phosphor. The guns differ in potential so slightly that their scanning patterns are substantially alike. The two-gun tube is suited for either simultaneous or sequential operation with each beam automatically scanning only its own color screen. A double unit gun with separate cathodes and common control-grid and anode elements can also be employed.

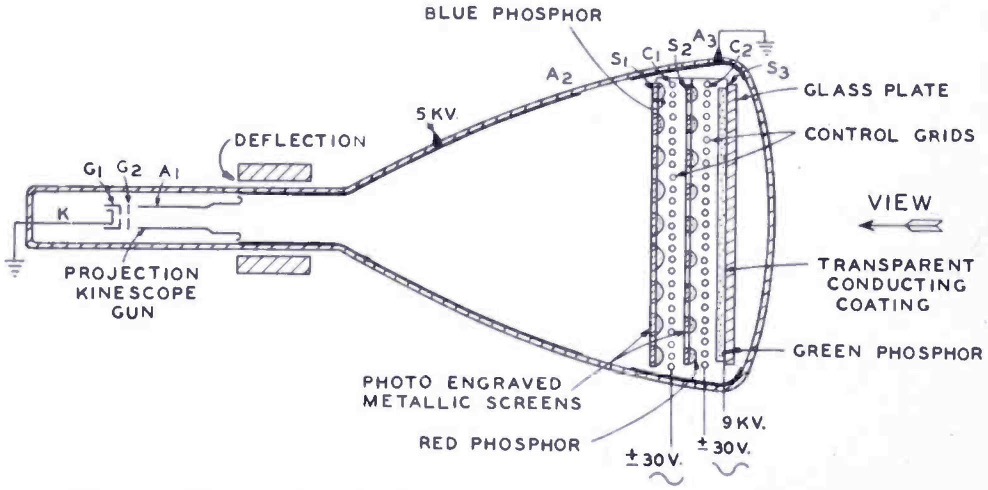

Fig. 4—Three-color single-gun grid-controlled color kinescope.

B. Three-Color Tube. Figure 4 shows the three-color single-gun arrangement, in which an added color control grid and phosphor screen are present beyond the screens shown in the corresponding two-color arrangement of Figure 2. Green, red, and blue phosphors are used here. The higher resolution desired in the green has suggested its location on the glass plate, while the red phosphor is uniformly settled on the next phosphor screen. The blue phosphor, least critical in resolution, is uniformly settled on the screen farthest from the viewer. Other factors, such as relative efficiency of the three phosphors, may in some cases suggest a rearrangement of the phosphor locations. For better efficiency for the blue light, which reaches the observer through the red screen, the transmission of the latter is chosen higher than that of the blue screen. Transmissions of 55 per cent to 60 per cent for the red and 35 per cent to 40 per cent for the blue give very nearly equal brightness to the observer; this will be discussed later. The color control grids C_1 and C_2 are again made of high-transmission stainless steel woven mesh.

In operation, when both C_1 and C_2 are made positive by say 30 volts, the beam penetrates both control screens and scans the green phosphor. If C_1 is positive and C_2 negative, the electrons are reflected before they reach C_2 and return mainly to scan the red phosphor. If C_1 is negative, the beam is reflected before it reaches it, and scans the blue phosphor. The screens are again all spaced as close together as possible, consistent with adequate voltage breakdown characteristics, to minimize the parallax seen by an observer appreciably off the axis of the tube.

For a sequential color presentation, the colors are keyed by sine-wave voltages on each of the two color-control grids with suitable phasing between the two waves. Alternatively, the color change may

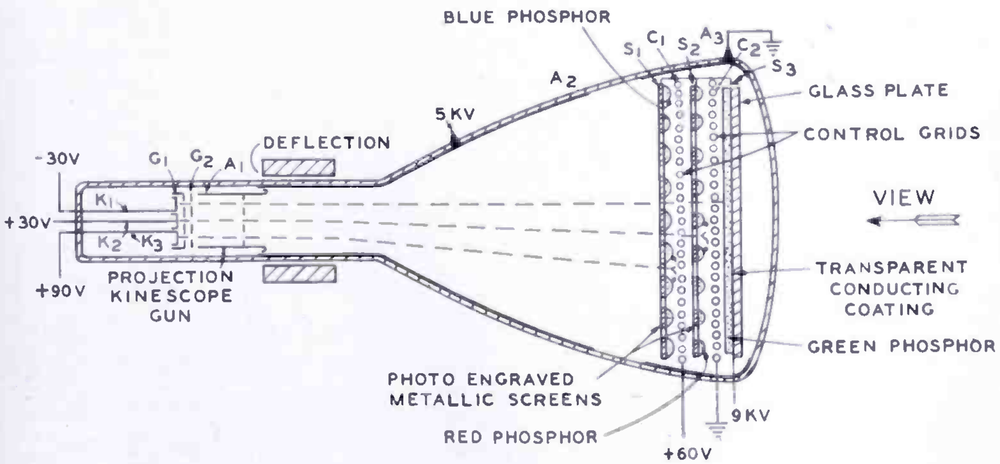

Fig. 5—Three-color three-gun grid-controlled color kinescope.

be effected by varying the gun potential while the two color-control grid voltages remain fixed. This has more advantage here than in the two-color case because of the greater reduction in capacitance, for it is not possible, with two color-control grids, to swing only their free-space capacitance. A simultaneous presentation with the single-gun tube is achieved by correct application of the color-control voltages to the two control grids.

Figure 5 shows a three-color tube using three separate electron guns for either simultaneous or sequential presentation. With the voltages shown, the beam from the cathode K_1, biased −30 volts, can penetrate both C_1 and C_2 to scan the green phosphor. The beam from the cathode K_2, biased +30 volts, can penetrate C_1 but not C_2, and will turn around just before reaching C_2 and scan the red phosphor. The beam from the cathode K_3, biased +90 volts, will be unable to penetrate either C_1 or C_2, will be reflected at C_1 and scan the blue phosphor. Thus, as in the two-gun two-color case, each gun scans its own color at all times that its beam is biased on.

Special guns containing three separate cathodes, a single control grid with three apertures, a single screen grid, and single first anode have been designed[2] and used in sealed-off three-color grid-controlled kinescopes. Each of the cathodes is spaced at a different distance from the common control grid of the gun to allow for the different biases put on the cathodes. Thus, a given voltage change impressed on the gun cathodes produces the same change in current from all three units of the gun.

III. Screen Mounting

Since a high voltage is needed on the phosphor screens to assure bright patterns, the spacing between screens and color-control grids should be sufficient to prevent breakdown. Large spacing, however, introduces more parallax. For a given spacing, parallax can be specified as a function of tube size and total viewing angle. While this will be discussed in more detail later, it can be said here that all these considerations make it desirable to have very flat screen surfaces tightly stretched to balance the pull of electrostatic forces between adjacent screens and to insure that no wrinkles are present which would lower the maximum permissible operating voltage.

The electrostatic force between two parallel screens for about ten kilovolts operating potential and a 9-inch diameter picture amounts to about 2 kilograms. The intermediate screens are subject to roughly this same force from each direction, so that the net force tending to pull them to one side is much reduced. The front screen is a rigid, immovable glass plate. The screen nearest the gun, however, must withstand the strong unbalancing force and should be relatively thick so as to be as rigid as possible. This thickness does not contribute to increased parallax, as it is beyond the last phosphor.

Mechanical tightening rings have been used for stretching both the woven color-control grids and the photoengraved phosphor-holding screens. In the simplest version, the screens were stretched by two concentric rings, with a radial spacing between them slightly greater than the flat stock thickness of the photoengraved screens, or slightly less than the lapped wire thickness of the woven grids. For experimental use, more complicated ring sets were designed to clamp the screens, and to permit easy assembly, disassembly, and local tighten-

[2] Designed by H. C. Moody and D. D. Van Ormer, RCA Victor Division, Lancaster, Pa.

ing around the periphery by means of small screws. In both cases, mica spacers were used to separate one screen from another.

By making use of the difference in expansion coefficients of the screen material and mounting rings, it is possible to obtain very tightly stretched screens soldered to these rings in a hydrogen furnace. This mounting means is light and uses a minimum of bulb space. Figure 6 shows a diagrammatic cross section of a three-color screen assembly using screens stretched by this method.

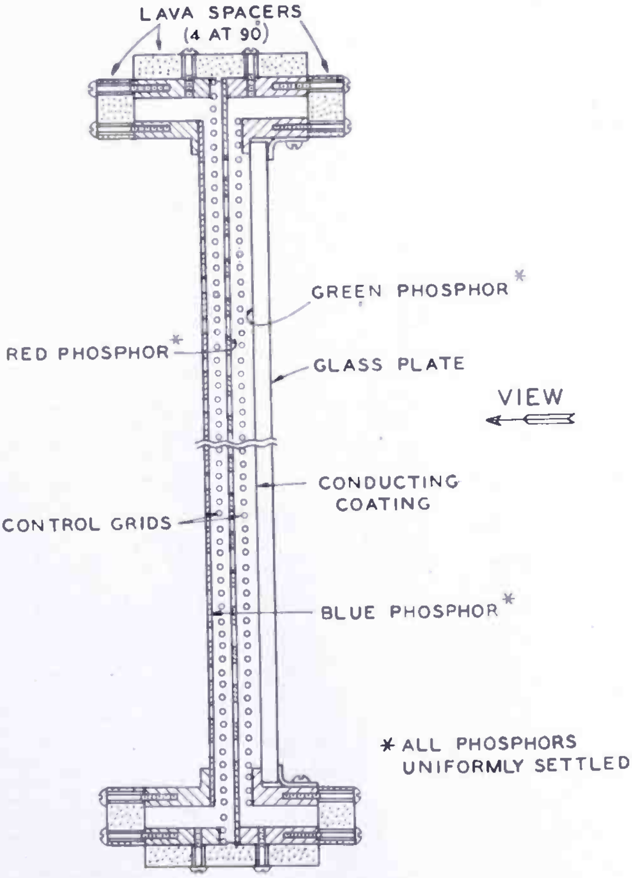

Fig. 6—Screen assembly, three-color grid-controlled color kinescope.

IV. Phosphor-Screen Design Considerations

A. Screen Material, Thickness, and Mesh. To avoid a slight moiré pattern between the red and blue phosphor screens in the three-color tubes, these two screens must have identical mesh spacings with no accumulative error. Also, the phosphors should be settled on a flat surface, with no phosphor in the openings to be encountered by the beam approaching from the gun. Since these considerations rule out woven wire screens, it was felt that photoengraved screens offered most promise.

Photoengraved screens of both copper and supernickel proved satisfactory, but preference was given to the latter because of its greater stiffness and brighter reflecting surface. Screen thickness of 0.006 inch proved to be a good compromise between stiffness and satisfactory screen fabrication as to transmission and uniformity of etching. Screens of excellent uniformity, etched from both sides, were commercially available. While the 60-mesh screen used in experimental tubes is capable of giving about 400 lines resolution in a 9-inch picture, one can choose a finer-mesh screen when higher resolution is desired.

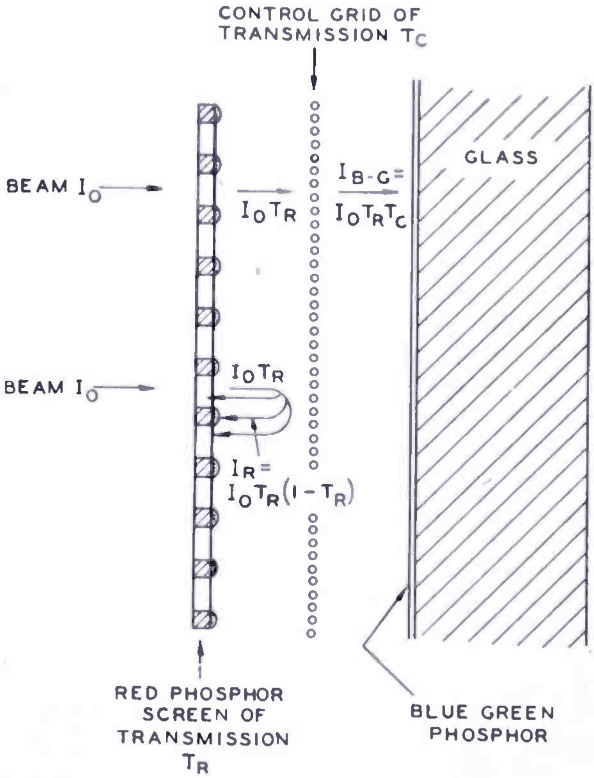

Fig. 7—Currents in two-color kinescope.

B. Efficiency versus Phosphor-Screen Transmission. It is of interest to determine the effects of the screens on the efficiency of utilization of the gun-beam current to produce light, as compared with a simple monochrome kinescope operating with the same beam and at the same voltage. The assumption will be made that, upon direction reversal, the beam will have a uniform density distribution over the screens on which it falls back. This has been closely verified experimentally.

1. Two-Color Case—The current penetrating the red screen is I_0T_R, where I_0 = beam current, and T_R = fractional transmission of the red screen (see Figure 7). To reach the blue-green screen, this current is attenuated by the control grid of transmission T_c, therefore

$$I_{BG} = I_0 T_R T_c. \tag{1}$$

On the other hand, for the reflected electrons, the current actually striking the red screen is given by

$$I_R = I_0 T_R (1 - T_R). \tag{2}$$

Furthermore, the light from the red screen is reduced by the control grid before it reaches the observer. If P is a performance factor to which the light reaching the front screen of the tube per unit beam current is proportional, then

$$P_{BG} = \frac{I_{BG}}{I_0} = T_R T_c, \tag{3}$$

$$P_R = \frac{I_R}{I_0} T_c = T_R T_c (1 - T_R).$$

The performance factor P_{BG} is linear with the red screen transmission, while that of the red screen, P_R, will be a maximum when $dP_R/dT_R = T_c(1 - 2T_R) = 0$. This gives

$$T_R = 0.5 \text{ or } 50 \text{ per cent (a broad maximum)}. \tag{4}$$

A common practical value for T_c is 60 per cent, for which

$$\begin{aligned} P_{BG} &= 30 \text{ per cent,} \\ P_R &= 15 \text{ per cent} \end{aligned} \tag{5}$$

are the performance factors for the two-color one-gun case; similarly

$$\begin{aligned} P_{BG} &= 60 \text{ per cent,} \\ P_R &= 30 \text{ per cent} \end{aligned} \tag{6}$$

for the two-color two-gun case.

Although the red efficiency indicated here on a basis of screen transmission alone is only half of that of the blue-green, several other factors enter into the relative output brightnesses of the two screens.

The blue-green phosphor is intrinsically somewhat more sensitive than the red and its thickness cuts down the red light passing through it slightly more than its own light. However, the blue-green phosphor can be settled in a thinner layer than usual so as to offer as little effect as possible on the efficiency and resolution of the red image. This reduces its effective efficiency. Also, because the red phosphor is scanned on its viewed side, and of more importance, because it is laid down on a bright reflecting surface, its brightness is enhanced. In summary then, the higher efficiency of the blue-green phosphor over the red, as determined by the screen-transmission equations, can be balanced by other factors, the principal one of which is the thickness of the blue-green layer.

2. **Three-Color Case**—In the three-color case, the considerably more involved efficiency equations, as determined by screen transmissions, take two forms, depending on whether the phosphor screen spacing is large or comparable with the screen mesh size. If the spacing is large, the attenuating effect of the red screen on the blue light which must pass through it is proportional to the simple red screen transmission factor, T_R. For close spacing, because of the red and blue screen alignment, the webs of the red screen directly cut off some of the light from the phosphor on the webs of the blue screen. This reduction in blue light is by a factor greater than the ratio of web area to total area, and is given by multiplying the light from the blue by the factor $(T_R - T_B)/(1 - T_B)$, which expresses the open area of the red screen directly opposite the blue webs to the fractional area of the blue webs.

The performance factors (based on screen transmission) will always be higher for the green than for the red and blue. But here again, the over-all performance of the green screen can be lowered to that of the other two, if desired, by reducing the amount of green phosphor deposited. The highest set of performance factors is obtained when the equations are solved under the condition that the blue performance factor be a maximum. In the practical case, the red screen transmission should be higher than the blue, but is prevented from reaching its optimum value by the maximum obtainable screen transmission. A typical transmission value for both T_R and T_c is 60 per cent. For this transmission, the optimum value of T_B from the equations is 50 per cent for wide spacing and 28 per cent for close spacing. The practical tube has more nearly approached the wide-spaced case for which the three performance factors are

$$P_B = 5 \text{ per cent},$$

$$P_R = 7 \text{ per cent},$$

$$P_G = 18 \text{ per cent}, \tag{7}$$

for the three-color single-gun case, and

$$P_B = 15 \text{ per cent},$$

$$P_R = 21 \text{ per cent},$$

$$P_G = 54 \text{ per cent}, \tag{8}$$

for the three-color three-gun case.

These performance factors take account of losses in beam passing forward through the screens, losses in effective beam passing back out of the holes in the red and blue screens after direction reversal, and losses in light passing out from the blue and red screens through the screens in front.

C. General Comments on the Phosphor Screens. In practice, during assembly the red and blue phosphor screens of like hole patterns are lined up by eye to sufficient approximation by means of a diffuse light passing through these two screens in series. These are the only two screens aligned. When the phosphors are settled on the screens, moderate care must be taken to insure that no phosphor lodges in the holes in the screen.

When the electrons are turned around to strike the red screen, a fraction of them pass back through the interstices of this screen. About half of these electrons pass back out through the holes in the blue screen towards the gun and cause no ill effect. Others, striking the blue phosphor, give rise to light reaching the observer when he should see only red. However, this spurious blue light is only about 10 per cent of the red, because it is excited by considerably fewer electrons and, after being produced, is attenuated further by having to pass through two more screens on the way out than does the red light. While this blue light is small, it can still be noticed with the present phosphors in the form of a slight dilution of the red.

V. Color-Control-Grid Design

It is desirable to have the color-control-grid transmission as high as possible from the standpoint of beam utilization efficiency and light transmission. On the other hand, a large number of mesh is advantageous for giving a low numerical cutoff (reflection) voltage. However, since screen transmission usually drops as one goes to a higher mesh number, a compromise between these factors must be effected. Color control grids of 230 mesh, stainless-steel woven screen etched to 60 per cent transmission have proved quite satisfactory.

A uniformly perpendicular approach of the scanning beam to the control grids will permit the use of minimum positive swing of the switching voltages on these grids. In addition to making the switching easier, this lowered voltage swing lessens the chances of primary electrons hitting these grids and giving rise to secondaries which can find their way to the wrong color screens. While a more open mesh minimizes this secondary electron effect, it increases the negative voltage swing required for complete reflection. Uniformly perpendicular approach of the scanning beam was accomplished with the use of an electron lens formed by splitting the graphite wall coating, as shown at A_2—A_3 of Figures 2-5. The lens action, coupled with the lens effect between A_3 and S_1, reduced the positive swing from over 100 volts to about 25 volts. An unpublished analysis of this lens effect by E. G. Ramberg predicts the same order of improvement. Because of the greatly reduced secondary-electron effects at this voltage, the control-screen mesh could be made finer, giving better negative control and thus lowering the negative voltage required for reflection. It was now found possible to pass uniformly from one color to another over the whole raster area simultaneously.

VI. Switching Considerations

No switching is required for multiple-gun operation as noted in Section II. For single-gun operation, a square-wave switching-pulse on the control grids is not necessary; sine-wave switching has been found satisfactory in both the two-color and three-color cases. The sine-wave subcarrier of the RCA color system was employed for this switching[3] using a 3.58-megacycle color rate. In operating a two-color switching device from a three-color signal, the driving circuit used for switching the grid-controlled color kinescope permits variation of both amplitude and phase of the sine wave. The most satisfactory operation with a two-color tube having a red and a blue-green screen has been with the tube switched to red to correspond with the red video signal and to blue-green in correspondence with equal parts of blue and green video signals as shown in Figure 8a. In addition to

[3] RCA Laboratories Division, "A Six-Megacycle Compatible High-Definition Color Television System", *RCA Review*, Vol. X, pp. 504-524, December, 1949.

the sine-wave amplitude and phase controls, a variable direct-current bias source is supplied to set the level of the control screen with respect to cathode potential. This has provided added adjustment to make up for differences between optimum positive and negative swings required for various experimental variations in the tubes. Generally, it has been found that a small positive bias is useful. Too large a bias will give poorer color rendition, however, by changing the time sharing between the colors as shown by the dotted curve of Figure 8a. A further improvement in color rendition has been observed when blanking is applied to the gun at the double frequency (7.16 megacycles) to blank during the time the sine-wave switching passes near zero.

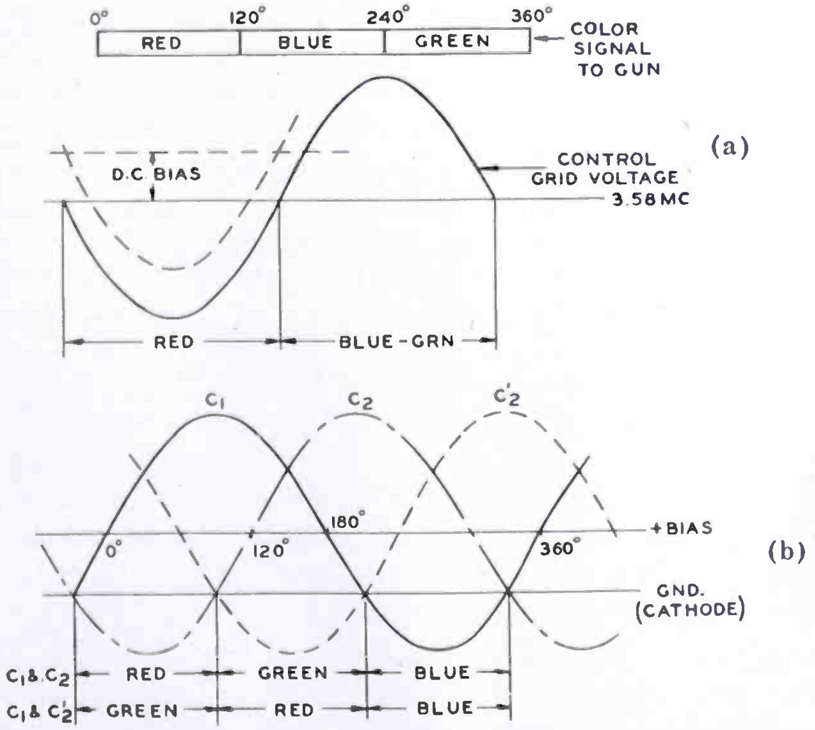

Fig. 8—Sine-wave switching of grid-controlled kinescope: (a) two-color; (b) three color.

The voltage polarity combinations of the two control grids in the three-color tubes for the various colors are:

	C_1	C_2
Green	+	+
Red	+	—
Blue	—	±

If one impresses a sine wave of a given amplitude and adjustable phase on C_1 (solid curve of Figure 8b) and another sine wave of equal amplitude and 120 degrees lag on C_2 (dot-dash curve), and applies a positive direct current bias of ½ of the sine-wave amplitude on both of these control grids, then the switching combinations given in the above table can be reproduced. This gives the sequence red, green, blue as shown. The opposite sequence is given when the sine wave on C_2 leads that on C_1 by 120 degrees (curve C_2').

A 3.58-megacycle sine-wave generator, with enough phase shift to allow adjustment of the phase of the color switching at the screens with respect to the color signal phase fed to the kinescope gun, applies the signal to C_1. Another sine-wave generator, whose phase is adjustable about that of the first generator, applies a sine wave to the second control grid, C_2. Thus, after the phase ϕ_2 is adjusted with respect to ϕ_1, the phase difference $\phi_1 - \phi_2$ does not vary when ϕ_1 is then changed to give correct color interlock between these switching voltages and the video signal to the gun. Other voltage arrangements are possible, but appear more complicated and/or make use of higher switching frequencies. Blanking at 11.4 megacycles applied to the gun near the switch-over time from one color to the next improves the color reproduction but with a slight reduction of brightness.

VII Experimental Results

Many tests of the grid-controlled color kinescope have been made in a demountable vacuum system, and sealed-off tubes have been built and operated with color pictures up to 8 inches in diameter. The kinescope resolution was observed to be about 300 lines on the front phosphor screen which the scanning beam strikes without reversal. A 15 per cent drop in resolution was noted when the beam was reversed in direction to strike the other phosphor screens. The use of higher mesh phosphor screens or the same mesh in a larger tube would improve the resolution. A single-gun tube had a measured brightness of a few foot lamberts using earlier, less efficient phosphors. The three-gun tubes have about three times more brightness than the single-gun versions. Improved phosphors would improve the brightness considerably.

The lowest satisfactory adjacent-screen spacing has been about 25 mils for 9 kilovolts operating voltage. Analysis of a simplified model for determining parallax effects has indicated for this spacing and 300-line green resolution, a 45-degree total viewing angle on a 12½-inch tube and 50 degrees on a 16-inch tube. However, in the latter case one might prefer to use a wider spacing, say 35 mils in order to use a higher accelerating voltage consistent with a larger size raster. This would reduce the viewing angle to about 40 degrees.

Both two- and three-color tubes were operated with the RCA color system signal.

VIII Conclusions

The grid-controlled kinescope has several desirable properties. First, since the phosphors are uniformly settled, there is no need for accurate settling of phosphor dots or lines. Second, there is no registry problem in the two-color version, and only at most a noncritical registry of two screens in the three-color arrangement. Third, the operation of the tubes is very insensitive to stray magnetic fields.

On the other hand, there exists the fundamental consideration of balancing parallax against brightness in the directly viewed tube. Improved stiffness and stretching of the screens can improve the tube operation in this respect. The parallax is considerably reduced by making use of a projection screen.

Acknowledgments

The writer wishes to express his appreciation for the support and encouragement of Albert Rose, under whose direction the work was carried out. In addition, credit is separately due to several groups and individuals for their participation: to R. W. Smith for his aid in the assembly of tubes, and to J. P. Smith, M. Topke, L. E. Flory, W. Pike, J. Dilley, and G. R. Gray for the design and building of the testing-circuit equipment.

DEVELOPMENT AND OPERATION OF A LINE-SCREEN COLOR KINESCOPE*†

By

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Summary—A color television receiver employing a single kinescope of the line-screen type has been developed. The kinescope screen consists of many hundred narrow parallel phosphor strips of the three primary colors, arranged cyclically. In the method investigated in greatest detail, the raster scanning lines are parallel to the phosphor strips. Circuit means are provided to cause the scanning lines to coincide with the phosphor strips of a single color. The beam is then deflected by a "stair-step" wave to the adjacent lines of the two remaining colors to generate color-dot areas in synchronism with the received color signal. The required registration of scanning lines with the screen elements is obtained by means of a servo circuit deriving control information from secondary-emission-signal areas on the kinescope screen. Various alternatives to this arrangement have also been investigated. Kinescopes of 16-inch envelope diameter have been employed to give color pictures of high horizontal definition and adequate color purity.

I. INTRODUCTION

AMONG the numerous means for portraying color images by a single kinescope, one that has long proved attractive to inventors has been the line-screen kinescope.[1,2] Undoubtedly the reason for such interest is the apparent simplicity of the picture tube. The major problem of securing the proper color images is then transferred to the circuit designer. In the experiments that were conducted, kinescopes were built and a number of circuit arrangements were investigated.

A kinescope of the line-screen type employs a luminescent screen consisting of narrow parallel strips or lines of phosphor materials emitting the three primary colors and arranged consecutively on the glass surface. In a typical tube of the experimental type to be described later, a rectangular piece of plate glass located within the kinescope envelope forms the viewing screen. On the appropriate surface of this plate are deposited several hundred strips of phosphor materials

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* Decimal Classification: R583.1.

† Reprinted from *Proc. I.R.E.*, October, 1951.

[1] R. Rüdenberg, U.S. Patent 1,934,821; issued November 14, 1933.

[2] M. von Ardenne, British Patent 388,623; complete accepted March 2, 1933.

parallel to one edge of the glass. The three colors are repeated cyclically: red, green, blue, and so on.

The design of the electron-optical system of the kinescope is such that the effective diameter of the electron beam at the screen is less than the width of each color phosphor strip or line. At any instant, then, the screen emits light of a color dependent upon the position of the beam with respect to the line structure. The problem becomes one of securing registration of the spot with a phosphor area of the correct primary color according to the color information contained in the received video wave.

Several scanning arrangements suggest themselves. One of these requires the orientation of the screen so that the horizontal scanning lines of the television raster are parallel to the phosphor lines on the screen. The size of the raster is chosen so that there is one scanning line for each group of three phosphor lines (i.e., a "triplet" of the three primary-color lines). Then, in principle, the scanning can take place so that the spot of light produced by the electron beam traverses successively all the lines of a single color during each field, making a pure color raster visible. If the centering adjustment is changed to displace the raster vertically by the center-to-center distance between adjacent phosphor lines, the entire screen will emit the second color. Of course, a further displacement by the same amount can then produce the third color.

Means must be provided for establishing this coincidence of scanning path with the phosphor lines and for changing the vertical centering in accordance with the color identification of the video signal. The circuits for accomplishing this constitute a control, or servo device, about which more will be said in the remainder of this discussion.

Other screen orientations and scanning arrangements have also proved to be useful. Reference is made to this subject in Section V of this paper.

The control information needed by the servo to specify the instantaneous position of the electron beam on the screen may be derived from various sources. Conductive surface paths on the screen represent one possible method. Another utilizes phototube pickup of light from the phosphor screen. A third depends upon contrasting secondary-emission areas on the screen surface. This last-named method is to be discussed in this paper.

The methods for obtaining correct registration of the beam may be of several types, such as:

1. Precision deflection with no servo control,
2. Continuous control during scanning,

3. Intermittent control, occurring only during a portion of the scanning cycle.

Because of the current importance of a single kinescope for color television reproduction, the major part of the discussion will refer to this use. It should be borne in mind, however, that some of the methods and results will find application in camera tubes, in monochrome receivers in which precision of geometric deflection must be obtained, in facsimile, in Ultrafax, in kinescope recording, in radar displays, and in such specialized uses as closed-circuit television systems where independent scanning standards may be established.

II. Kinescope Design

The idea of using phosphor lines of different colors for the presentation of color information on the face of a cathode-ray tube is old.[1,2] In the early state of the art it was realized that the making of the screen itself constituted one of the main problems. Experimental work on such kinescopes was undertaken at RCA some years ago to study and demonstrate properties of the screens. Early 9-inch kinescopes which were built revealed various shortcomings in the tubes and indicated some of the general problems remaining.

Many of these problems were solved by advances in design: an improved red phosphor[3] came into more general use, an electron gun capable of giving a much smaller spot diameter was developed,[4] and the process of aluminizing screens was brought out.[5] Screen charging was eliminated and increased brightness was obtained by this last-named development.

The kinescope tubes used in the present development have been of both the 9-inch and 16-inch size. These designations refer throughout to the maximum cone diameter. The smaller size tubes have all-glass envelopes and have been built experimentally to test principles to be incorporated into the larger metal-bulb type. The technique of building the 16-inch metal kinescopes has involved the solution of numerous mechanical and production problems described elsewhere.[6] For the tubes considered here, however, the screen is not assembled from

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[3] H. W. Leverenz, "An Introduction to Luminescence of Solids," p. 147, John Wiley and Sons, Inc., New York, N. Y., 1950.

[4] D. S. Bond and V. J. Duke, "Ultrafax," *RCA Review*, Vol. X, pp. 99-115, March, 1949.

[5] D. W. Epstein and L. Pensak, "Improved Cathode-Ray Tubes with Metal-Backed Luminescent Screens," *RCA Review*, Vol. VII, pp. 5-10, March, 1946.

[6] B. E. Barnes and R. D. Faulkner, "Mechanical Design of Aperture-Mask Tri-Color Kinescopes," *Proc. I.R.E.*, Vol. 39, pp. 1241-1245, October, 1951.

several parts that must be properly registered together, as is the case in the shadow-mask color kinescope.[7] The discussion will be concerned mainly with the 16-inch tubes. A drawing of a typical tube is shown in Figure 1.

A. Design of 16-Inch Kinescope. The metal bulb is similar to that used in the commercial 16AP4 kinescope except that it is divided in a plane near and parallel to the tube face. The screen can then be assembled on its mounting plate and attached inside the rear section of the metal bulb after the conical magnetic shield of high-permeability material has been inserted. The front annular section of the bulb, with the clear-glass face plate sealed to it, is welded to the conical bulb section after these assembly operations have been completed.

The secondary-emission control signals required for the servo system to be described later are picked up on the collector electrode near the screen, as shown in Figure 1. The electrode is an insulated metallic strip about ¼ inch wide, supported at right angles to the screen and located adjacent to one side of the secondary-emission signal area. A connection is brought out through an insulated lead in the cone.

In accordance with usual practice, a conductive coating is placed on the inside of the flared portion of the glass neck. However, a ring of uncoated glass is left adjacent to the seal to the outer metal cone. A difference of potential can thus be established between cone and neck to provide an electrostatic lens which may be required for some purposes.

The cylindrical portion of the neck is about 1.5 inches outside diameter, thus allowing considerable lateral adjustment of the surrounding magnetic deflection yoke, which is 2 inches inside diameter.

Vertical electrostatic deflection is employed in the color-registration circuits tested to supplement the main magnetic deflection in the vertical plane. It is much more practical to include electrostatic deflection because of the very-high-frequency components present in the control signals. The total deflection angle required in the electrostatic portion is less than 0.5 degree. Consequently, the separation of the electrostatic plates is determined mainly by the beam diameter. Rectangular plates are located between the gun and the magnetic-deflection-field region, as shown in Figure 1. These are accurately centered with respect to the precision-bore tubing constituting the neck. At a second-anode voltage of 18 kilovolts, only a 6-volt potential difference

[7] H. B. Law, "A Three-Gun Shadow-Mask Color Kinescope," *Proc. I.R.E.*, Vol. 39, pp. 1186-1194, October, 1951.

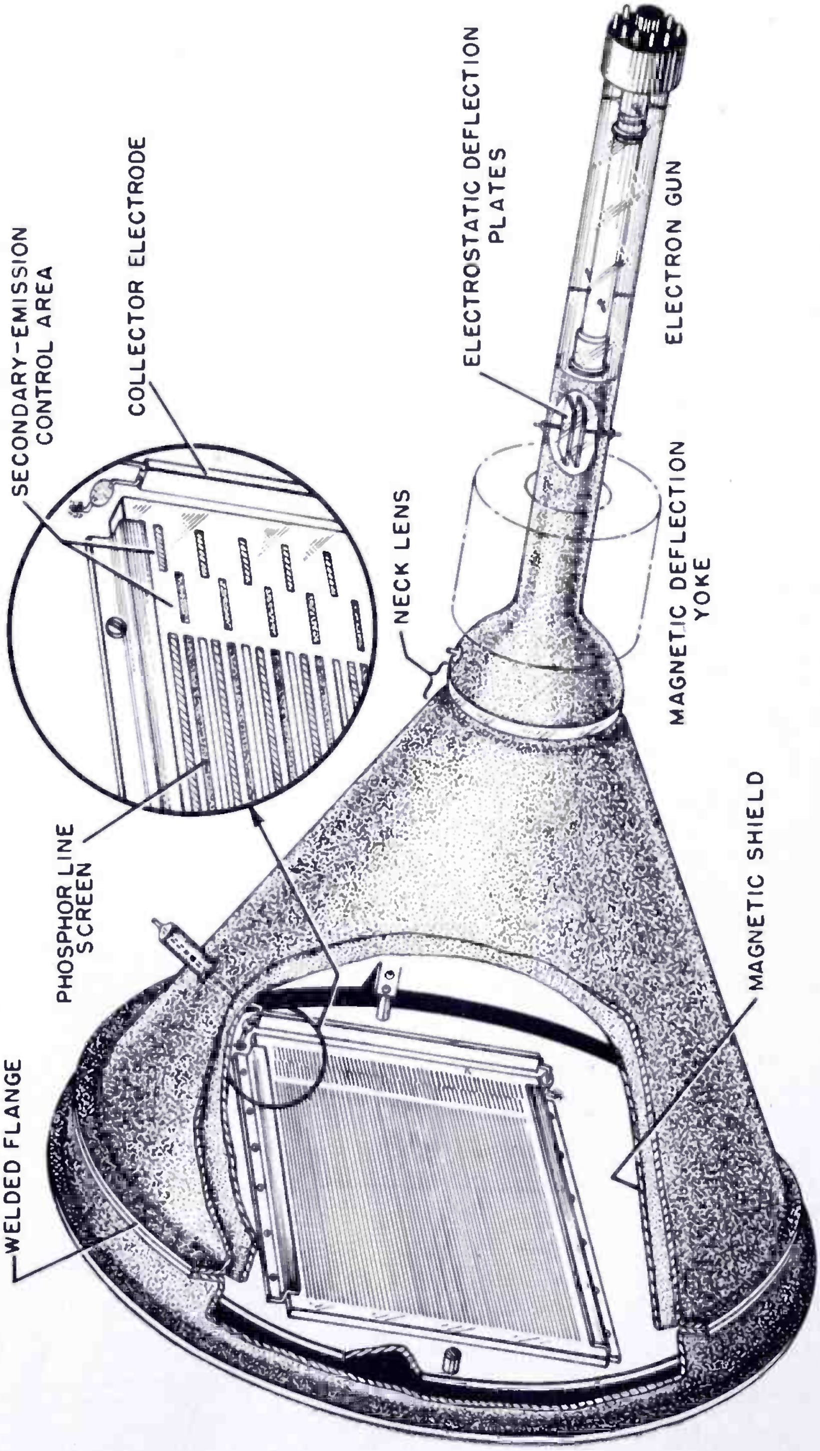

Fig. 1—Sixteen-inch line-screen kinescope.

between the deflection plates is required to shift the beam from one color line to the next.

B. Screen Deposition. Accurate deposition of the parallel fine phosphor lines has been achieved through two satisfactory methods. In the first method, the screens are made by settling the phosphors through a metal mask. The latter consists of a grid of parallel wires stretched across a frame. The wires are milled off flat on one side to allow closer contact with the glass plate on which the screen is to be deposited. The spacing between adjacent wires is such as to give an unmasked area the width of the phosphor strip of one color. After one color has been deposited, the mask is moved along the plate and normal to the lines. The lines of the second phosphor are then settled in the proper location, after which the process is repeated for the remaining phosphor. The lines produced by this settling method are particularly even and uniform, and the edges are straight and sharp.

The second method employs a silk-screening technique very similar to that used for other three-color kinescopes.[8] The screens for the 16-inch tubes were all made by this process. A number of advantages were found for this method of screen production, principally the ease of producing the larger size screens in quantity.

Screens for the 9-inch tubes are 4.5 by 6.5 inches in size and contain 450 lines. Each phosphor strip is 0.010 inch wide and adjacent strips are tangent. Thus, a triplet of three colors occupies 0.030 inch of screen height. The width of a triplet in the 16-inch tubes is also made 0.030 inch. There is a total of 720 lines on the screen of the 16-inch tubes, to conform to the arbitrary scanning standards discussed in Section IV *A* below. The screen size is 7 by 10.5 inches. It was found desirable to make each phosphor line 0.007 inch wide and leave a dark line 0.003 inch wide between adjacent colors. Slight defocusing or spot displacement is then more tolerable because the beam cannot strike adjacent color lines.

With all the screens used, the phosphor on the useful picture area was coated with a thin film of organic material and then aluminized in the conventional manner.[5] The phosphor materials used for blue and green are silicates. Cadmium borate was chosen for red.[3] More efficient red phosphors have subsequently been developed.

C. Secondary-Emission-Signal Production. Some of the control arrangements for use with line screens require a good secondary-emission signal of special shape. Information on suitable materials for produc-

[8] N. S. Freedman and K. M. McLaughlin, "Phosphor-Screen Application in Color Kinescopes," *Proc. I.R.E.*, Vol. 39, pp. 1230 1236, October, 1951.

ing contrasty signals at 18 kilovolts is rather scarce since secondary-emission devices usually operate at much lower potentials. At the beginning of this work, it was observed that there was sufficient difference between the emission from the aluminum on the back of the three different phosphors to give a picture showing the line structure of the tube. As a rule the cadmium borate lines stood out fairly strongly against the others. The reason for this difference was not fully investigated, but it appeared to be largely due to the roughness of the aluminum produced by the granular nature of the phosphor material. In other words, the signal was largely derived from the difference in secondary emission of rough and smooth aluminum. The available signal was further enhanced by using smooth aluminum as the surrounding area and rough aluminum on phosphor as the signal area. The required surfaces were obtained by silk screening the desired signal area with cadmium borate and then aluminizing this area directly without the application of an organic film. Each of the first tubes built in this manner produced a signal that was judged to be reasonably satisfactory at the time.

While the signals from rough and smooth aluminum were fairly good, they were not as large as could be desired. A number of experimental tubes were made in which the signals from various other contrasting surfaces were observed under actual operating conditions.

One type of surface was particularly attractive. It was chosen because it gave a good signal and, at the same time, could be readily produced and registered with the phosphor lines. This pattern consisted of dashed lines of bare glass surrounded by smooth aluminum on glass. These bare-glass portions were obtained by a rather simple technique. The silk-screen process was used to deposit phosphor lines and short dashed lines in the required location. The whole screen, including the dashed lines, was then filmed, aluminized, and air-baked to remove the organic film. In order to obtain the bare-glass area, the phosphor in the dashed-line portion was brushed off. This operation also removed the aluminum on this portion but did not affect the aluminum on the bare glass.

D. Electron Gun. The earlier work on line-screen kinescopes had indicated the necessity for an electron gun of exceptionally fine focus. This is evident from the figures given for line width. It was actually found that the effective beam-spot size at any point on the screen must be less than about 0.008 inch. An improved gun structure to meet these requirements had meanwhile been developed for Ultrafax.[4]

The improved electron gun is of the electrostatic-focus type. The magnification of the electron-optical system is reduced by employing a gun structure of almost twice the length of that of the RCA 5TP4 projection kinescope. The spherical aberration of the final electrostatic lens is minimized by a reduction in beam diameter in this lens. This stopping down reduces the usable beam current, but the maximum current remains adequate. Care was taken to insure symmetry of the electron-lens system: the metal tubing for the anode lens was held to close tolerances on roundness, and precision-bore glass tubing was used for the neck to permit accurate centering of the gun with spacing legs.

E. Focus and Geometric Distortion. The required spot diameter of 0.008 inch for the 720-line 16-inch kinescopes could be readily achieved over the major part of the screen area. At the corners, particularly in the marginal area of the control pattern, focus was not entirely adequate with the conventional arrangement of focusing potentials. Part of the difficulty was due to changes in required ratio of first- to second-anode potentials at the extremes of deflection. This was corrected by electrical focus modulation produced by varying the first-anode potential. Further improvement was made by including a weak cylindrical lens in the electron-optical system to correct spot ellipticity or to produce deliberately an elliptical spot with its major axis horizontal. For the usual video band width, this latter condition did not impair the horizontal resolution. The lens was produced by operating the *pair* of electrostatic deflection plates some 500 to 600 volts above second-anode potential.

As shown in the diagram of the metal-cone tube in Figure 1, provision was made for producing an electrostatic lens (the "neck lens") between the flared portion of the glass neck and the metal cone. It had been determined previously that most of the pincushion shape of the raster could be removed by modifying the field distribution of the deflection yoke in the correct manner. However, it is desirable to have some electrical control over the amount of field modification to compensate for variations from yoke to yoke. With the deflection yoke as finally designed for this arrangement,[9] there still remained a slight amount of pincushion distortion. This could be completely eliminated by a ratio of cone voltage to neck voltage of about 1.2. When this voltage ratio was changed to 1.5, the horizontal edges of the raster could be made very slightly barrel shaped. In any case, the total bending produced was not large enough to affect picture geometry

[9] A. W. Friend, "Deflection and Convergence in Color Kinescopes," *Proc. I.R.E.*, Vol. 39, pp. 1249-1263, October, 1951.

perceptibly, but the effect was nevertheless of importance in obtaining proper colors.

III. Precision Deflection Method of Registration

The possibilities of achieving a satisfactory result with a three-color line-screen kinescope by accurate registration of the lines of the scanning raster with the corresponding screen lines were investigated in some detail. The purpose was threefold: to discover the lengths to which this method can be carried in the present state of the art, to develop elements needed in the circuits to be described in Sections IV and V, and to demonstrate how picture quality for other television applications can be bettered.

Kinescopes having 450 phosphor lines, i.e., 150 in each of the primary colors, served as the starting point. With the lines horizontal and parallel to the scanning lines, the requirements of precision deflection are almost entirely confined to the vertical-deflection channel and the magnetic-deflection yoke. The raster height must remain constant, and the scanning lines must be equidistant. A departure from either of these conditions by an amount sufficient to misplace the scanning beam vertically by one-half the separation of two adjacent phosphor lines causes a very prominent color change. Geometric precision to better than one part in 1,000 is thus needed even for these relatively coarse line screens.

It is instructive to note the analogy between the measurement of such departures from geometric exactness of scanning and the measurement of departures from perfect flatness in optical surfaces by means of light interference fringes. The well-known test for flatness of a glass surface involves bringing it into contact with a similar optically flat surface and observing the uniformity of the interference fringes in monochromatic light. Departures from a plane by a fraction of a wave length of the light produce readily observed distortion of the fringe pattern.

In the case of the kinescope, a screen pattern of color fringes can be deliberately produced due to nonlinearity of vertical scan, incorrect size, or geometric pattern distortion. This pattern is extremely sensitive to small defects. A typical situation that can be set up experimentally might be one in which vertical-deflection velocity is correct over the major part of the scan, but where considerable pincushion effect is present. Then at the corners of the screen there is a series of color fringes while the central zone across the screen is of a single color. A vertical displacement of the raster of 0.010 inch causes the single-color area to change from one primary color to a second. A vertical displacement might be due to change in centering adjustment, hum signals, motorboating in the vertical-deflection circuit, interlace, and the like. The picture is quite sensitive to any of these effects. The color pattern of fringes then gives quantitatively the displacement of the scanning path from a straight line. Photographs of the face of a line-screen kinescope showing the effects of incorrect adjustments are given in Figure 2.

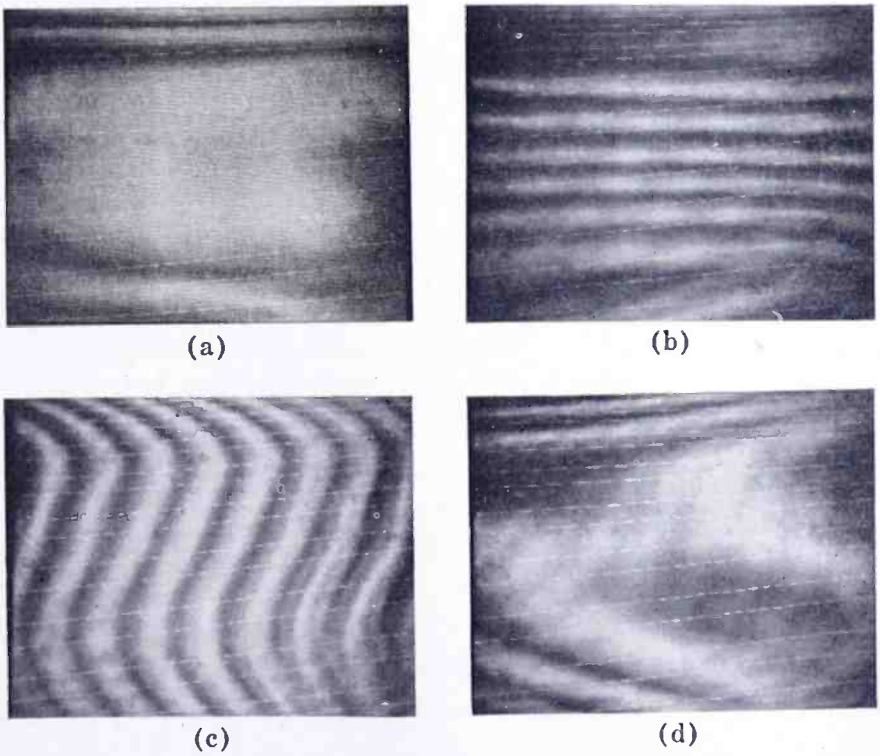

Fig. 2—Typical color fringe patterns of misregistered rasters on line-screen kinescope. (The bright narrow retrace lines should be ignored.) (a) Slight nonlinearity of vertical deflection. Maximum displacement error 0.8 per cent. (b) Vertical size incorrect by 3 per cent. (c) Deflection yoke rotated 1.5 degrees. Sweep linearity same as in (a). (d) Deflection-yoke axis not coincident with electron-gun axis.

Tests were conducted on a television video system of arbitrary scanning standards with the 450-line kinescopes. The receiver vertical-deflection system, shown in Figure 3, was designed to be as linear and as stable as was practicable. A saw-tooth wave of good linearity is generated across capacitor C_1, which in turn is charged from a constant-current source through resistor R_1. This source includes diode V_2 and cathode-follower stage V_3. The saw-tooth voltage across resistor R_2 is fed back through capacitor C_2 to the high-potential end of R_1. The potential of this latter point thus rises at approximately the same rate as the plate of V_1 to maintain constant current through R_1. Diode

V_2 isolates R_1 from the B supply during this part of the cycle. This "bootstrap" circuit has been utilized rather extensively in the past.[10]

A three-stage amplifier follows the saw-tooth generator. This may be regarded as a wide-band audio-frequency amplifier passing a fundamental of 40—60 cycles and the large number of harmonics necessary to reproduce the saw-tooth wave. Since the current wave through the vertical-deflection yoke should be a reproduction of the generator saw tooth, the current through a low resistance R_4 is sampled, and the signal is fed back to the first amplifier stage. The signal is phased to give negative feedback around the entire amplifier loop.

The output stage is push-pull to reduce direct-current core saturation in the output transformer. A balancing control in the cathode circuits of the amplifier tubes in this stage is needed to reduce residual dissymmetry in the two plate currents. The apparatus is operated with a carefully regulated B supply, and the heaters of the tubes are fed from a direct-current source. It has been found feasible to obtain linearity within 0.3—0.5 per cent with stable operation. After careful adjustment, the linearity can be maintained somewhat better than this for brief periods of time.

Scanning standards were established with the horizontal-scanning frequency 150 times the vertical rate. Thus, a few lines on the screen are not scanned because of the time lost in vertical retrace.

This discussion makes it obvious that it is necessary to correct vertical linearity further for 450-line tubes. Accordingly, a deflection wave of the desired shape was synthesized. This was done by correcting the deflection produced by the circuit of Figure 3 by a series of adjustable voltage waves generated successively during each vertical scan cycle. The diagram of Figure 4a illustrates the manner of accomplishing this result.

A counter chain, dividing down from horizontal- to vertical-repetition frequency, controls the receiver vertical-deflection unit previously described. The final divider provides at the same time 10 pedestal waves occurring as shown in Figure 5a. The amplitude and the tilt of the top of each can be controlled independently. The 10 waves are combined to give a synthesized wave like that of Figure 5b, and this is applied to the electrostatic vertical-deflection plates. One will note that the main vertical deflection is magnetic and that only the correction is accomplished by electrostatic deflection. A method of obtaining the pedestals from the counter chain at points A_1, A_2, . . . A_{10} has

[10] T. Soller, M. A. Starr, and G. E. Valley, "Cathode Ray Tube Displays," pp. 135-138, McGraw-Hill Book Company, New York, N. Y., 1st ed., 1948.

been described by Grosdoff.[11] Gain and tilt controls and the coupling amplifier for each pedestal channel are shown in Figure 4b. Each of the 10 channels requires one-half of a double triode tube.

Although adjustments were critical, it was found possible by this arrangement to obtain a raster of uniform color with the 450-line kinescopes. Power-supply voltages were regulated, the kinescope was shielded magnetically, and provision was made to secure uniform focus of the spot over the entire screen. Adjustment of the manual centering control would cause the raster to go cyclically from red, to green, to blue, and so on.

This latter adjustment suggests immediately a means of producing

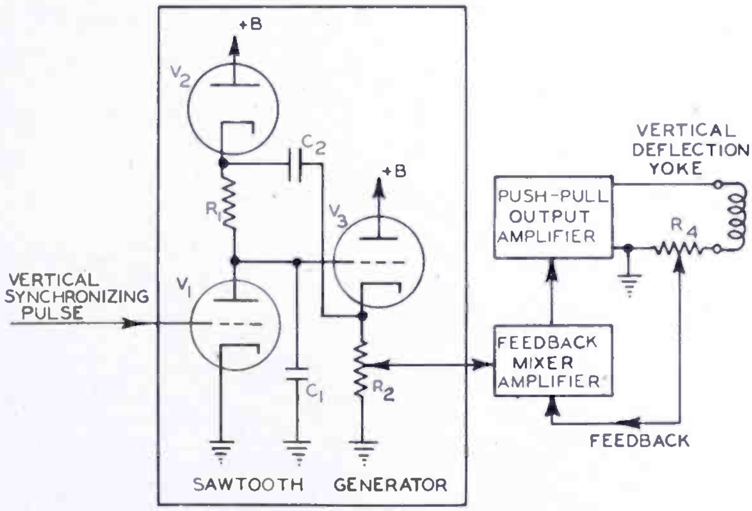

Fig. 3—Vertical-deflection circuit.

automatically the three color pictures in time sequence. Tests were conducted with the RCA color system[12] in which the color subcarrier frequency was of the order of several megacycles. This system permitted a dot-sequential type of presentation. It is obvious how frame- or line-sequential signals can also be accommodated.

In Figure 6a, the color-commutation method is shown for a dot-sequential presentation. The commutation-frequency oscillator G operates in synchronism with the color-system subcarrier. In the present case this frequency f_c was chosen to be 2.0 megacycles so

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[11] I. E. Grosdoff, "Electronic Counters," *RCA Review*, Vol. VII, pp. 438-447, September, 1946.

[12] "A Six-Megacycle Compatible High-Definition Color Television System," *RCA Review*, Vol. X, pp. 504-524, December, 1949. Also "An Analysis of the Sampling Principles of the Dot-Sequential Color Television System," *RCA Review*, Vol. XI, pp. 255-286, June, 1950. In these papers the *color subcarrier* frequency is identified as the *sampling* or *commutation* frequency.

as to be consistent with the arbitrary scanning standards adopted for test purposes during the early phase of this project. It can be synchronized and phased with the color subcarrier either by a "burst" of a signal of frequency f_c during line-blanking time or by direct connection with the transmitting terminal for laboratory purposes. Pulses are generated from the sine-wave output of G and used to trigger two multivibrators M_1 and M_2. Each of the latter produces a single pulse of length adjustable to one third of a period of f_c for each trigger pulse, returning to its initial condition until another pulse is received. A delay line L retards the pulses fed into M_2 by one third of a period of f_c. The output of one multivibrator is inverted in

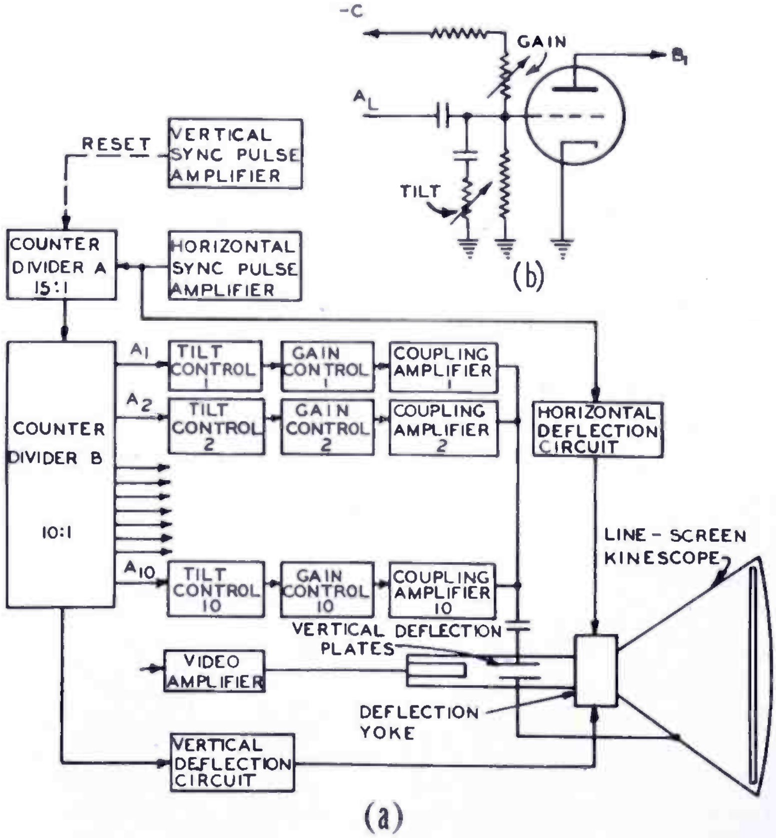

Fig. 4—Deflection circuit for synthesizing vertical-deflection wave. (a) Block diagram. (b) Typical pedestal channel.

phase and combined with the other. The wave-forms at the various points in Figure 6a show how the final desired "stair-step" wave is generated. This latter signal is applied to the vertical-deflection plates shown, and has the correct amplitude to cause the spot to coincide successively with three adjacent phosphor lines. The deflection action is illustrated in more detail in Figure 6b.

The composite video signal is fed to the kinescope grid in the usual fashion. It was possible to obtain a color picture of over 35 foot-lamberts high-light brightness on the 4.5-by-6.5-inch screen at a second-anode potential of 18 kilovolts. Color purity was judged to be satisfactory.

Careful attention to the winding arrangement and current distribution in the vertical coils of the deflection yoke[9] reduced the initial pincushion distortion to about one half of a color fringe at the corners. This very small geometric distortion was then eliminated (or could be overcompensated to give barrel distortion) by the converging electron lens at the apex of the bulb cone described in Section II *E*. Each scanning line was straight to considerably better than 0.005 inch throughout its 6.5-inch length. The precision deflection system and the vertical-linearity compensator gave a vertical deflection that was linear to about one part in 1,000.

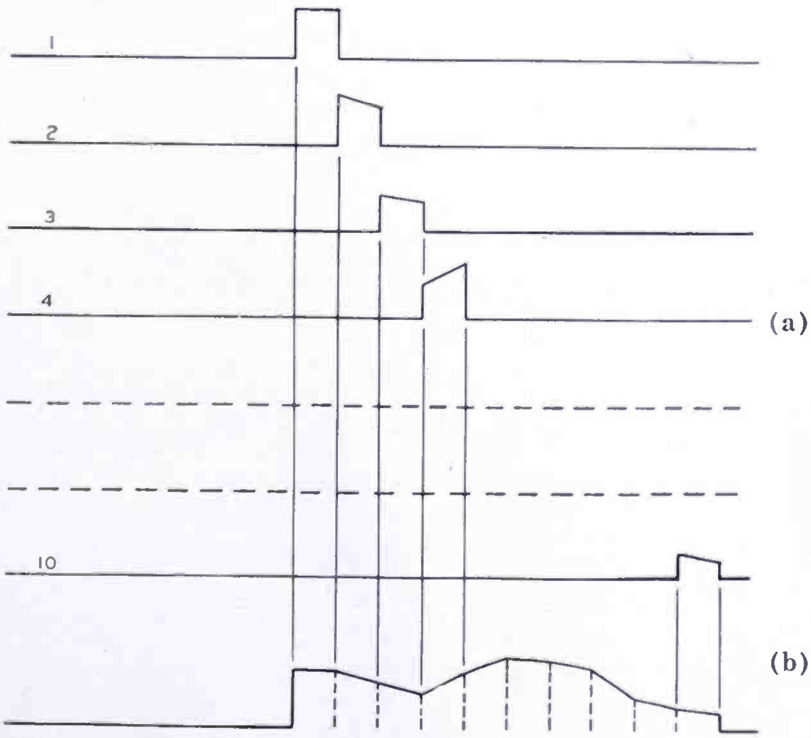

Fig. 5—Synthesized vertical-deflection wave. (a) Typical pedestals in 10 individual channels. (b) Combined wave.

IV. Aided-Tracking Registration Method

A. Noncumulative-Control Method. It became evident that the method just described has limitations as to the number of scanning and phosphor lines that can be registered with the required precision. Adjustments were somewhat critical for the 450-line kinescopes and the scanning standards chosen. For a noninterlaced picture on the 525-line monochrome standards of broadcast television, 262.5 lines of each color would be needed if no allowance were made for vertical blanking. Actually, about 240 lines of each color (or 720 total) would be required in such a system where odd and even fields are superimposed. For a full interlaced color picture with 525-line standards, 480 groups of phosphor lines on the screen would be needed, more than a threefold increase over the 9-inch experimental tubes discussed. A noninterlaced picture of half the theoretical limiting vertical resolution offered an initial goal to determine the further possibilities of the line-screen-kinescope method. Accordingly, screens having 240 groups of color lines were employed.

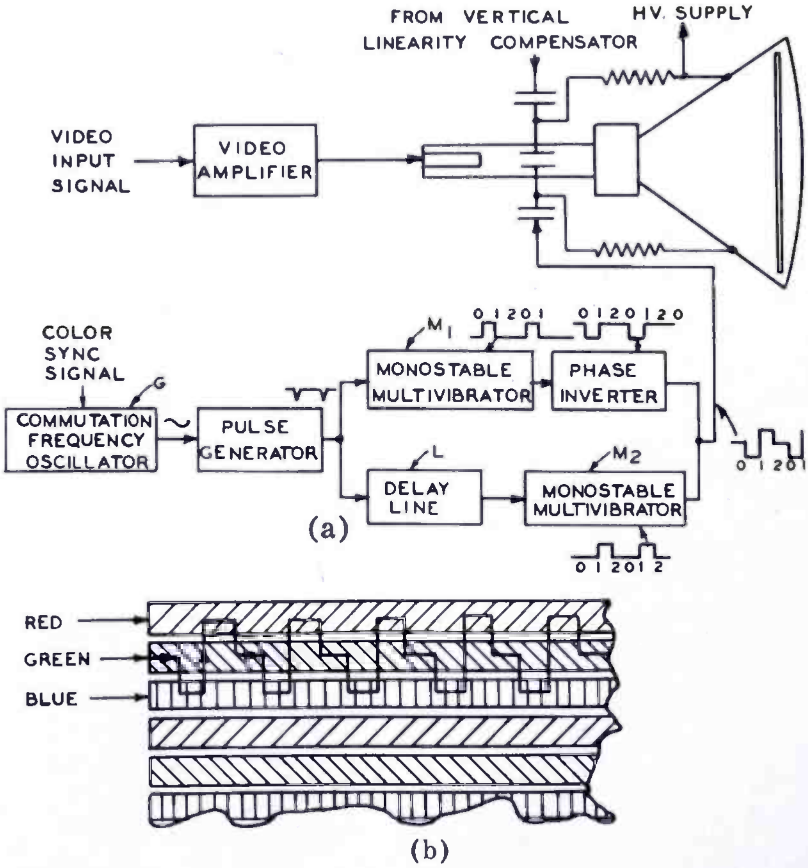

Fig. 6—Color commutation method. (a) Stair-step generator circuit. (b) Deflection path of electron beam on line screen.

A servo circuit was developed to control the vertical deflection of the beam so as to maintain registration with the proper color lines. For the moment, one can limit the problem to that of obtaining a single-color raster (e.g., green) by means of the servo with no color multiplex video signal applied. Then the other two colors can be obtained by the supplementary stair-step deflection illustrated in Figure 6. Contrasting secondary-emission areas on the kinescope screen provide the information as to the beam position with respect to the chosen green phosphor lines.

Appreciable variations in control information due to the range of beam currents encountered during picture modulation must be avoided. A control circuit must operate down to black level and provide correct color registration in low brightness portions of the picture as well as in high lights. No restrictions on contrast range should be imposed by the color control means.

To meet these requirements a "control area" having a characteristic secondary-emission pattern is placed on the left-hand margin of the phosphor screen and covered with an opaque mask on the viewer's side. The beam current is brought up to a value corresponding to full brightness level during the latter part of horizontal-blanking time as the beam scans this marginal area. The characteristic pulse signals picked up by the secondary-emission collector indicate whether the beam is correctly registered with the beginning of the green phosphor lines or, if not, the sense and the magnitude of the deviation. Vernier deflection is then supplied by the vertical-deflection plates to start the beam in proper register as it begins to traverse the visible phosphor area. No further control is applied for the duration of that scanning line. Reliance is placed upon the freedom from geometric distortion, from stray fields, or from other sources of disturbance in the vertical-deflection circuit.

Control signals are derived from a screen having secondary-emitting areas, shown diagrammatically in Figure 7a. A series of rectangular strips A_B is arranged in a vertical column, each strip being in the same horizontal plane as a light-emitting blue phosphor line or strip L_B. Similarly, there are strips A_R placed on the axes of the corresponding red phosphor strips L_R. The vertical column of A_R areas is displaced to the right of that of A_B areas, as is evident from the figure. There are no control areas to correspond to the green phosphor strips L_G, the green lines being of the arbitrarily chosen color with which the scanned raster is to coincide.

The electron-beam spot S is keyed on to "white" during the interval of pulse 3 shown in Figure 7a, i.e., for the duration of the traverse of the control area at the beginning of each horizontal-scanning line. If the spot starts at position S_1, it encounters neither an A_B nor an A_R control area but strikes L_G along axis XX'. No control signal is generated to deflect the beam vertically. On the other hand, if the beam starts below this desired position, at S_2 or S_3, for example, it generates a secondary-emission signal of magnitude dependent upon the departure from XX' as the spot crosses an A_B region. Departure from XX' in the opposite direction (S_4 or S_5) causes the generation of a similar pulse as the beam crosses an A_R region. In either case the magnitude of the signal increases with vertical departure from XX' until the beam is centered on an A_B or an A_R area. The *sense* of the

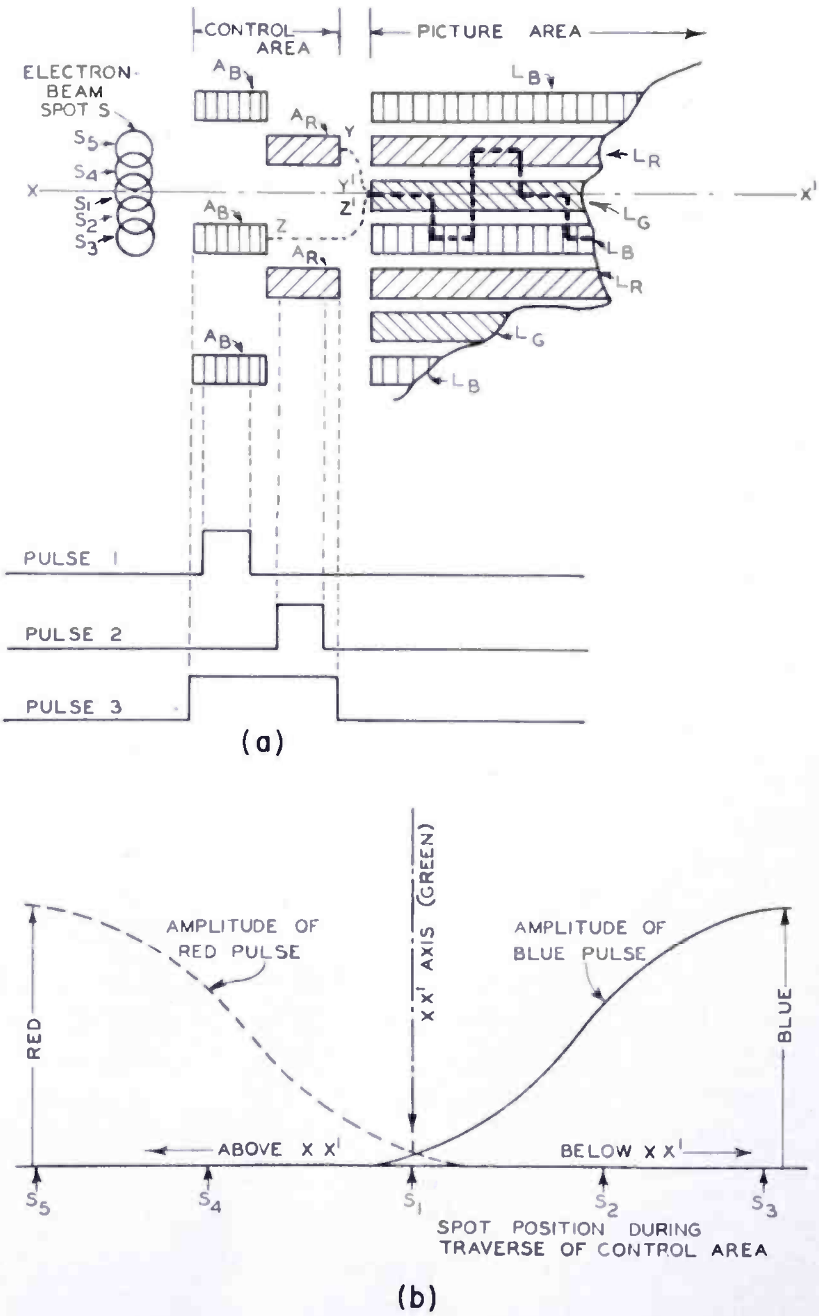

Fig. 7—Control-signal generation process. (a) Beam scanning path in control and picture areas. The times of occurrence of pulses 1, 2, and 3, referred to spot travel, are shown. (b) Amplitude of "red" and "blue" pulses as a function of vertical misregistration of beam in control area. Spot positions $S_1 \ldots S_5$, shown in (a), are indicated along the abscissa axis.

departure is determined from the difference in time of occurrence of the two types of pulses. For convenience, the pulse due to the scanning of an A_B area will be called a "blue" pulse and, similarly, for A_R, a "red" pulse. The servo device will be called upon to sample the amplified secondary-emission signal at two time intervals, corresponding to pulses 1 and 2 in Figure 7a, and to compare signal amplitudes so obtained. The continuous nature of the signals obtained is illustrated in Figure 7b. In practice, it is found that there is just sufficient overlapping of the spot on adjacent strips to cause a small pulse signal from *each* area when the spot is on the axis XX'.

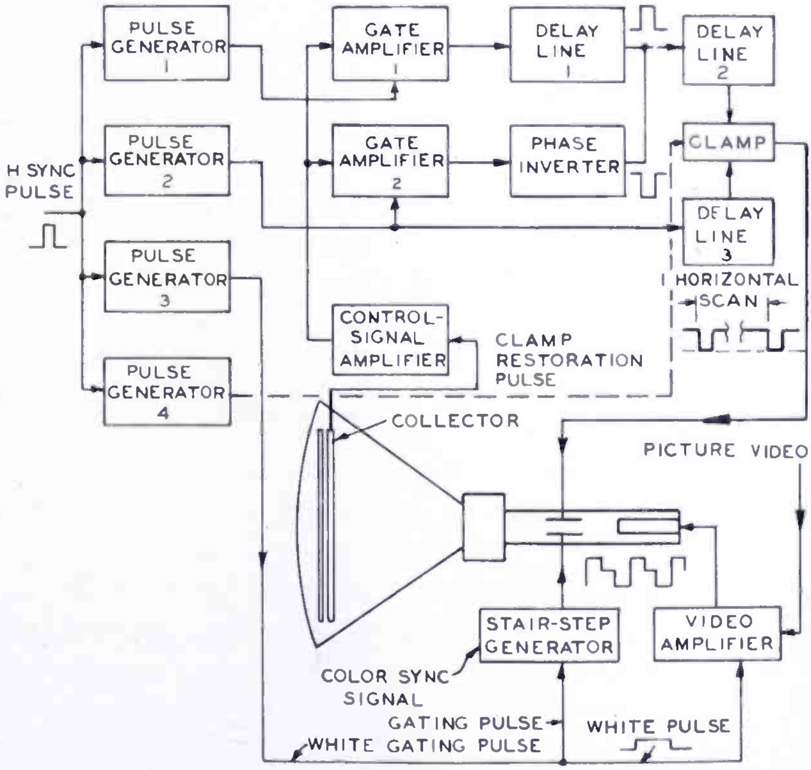

Fig. 8—Aided-tracking circuit employing noncumulative control.

A diagram of a basic servo employing this type of control information is presented in Figure 8. The relative order of occurrence of the pulses is shown in Figure 9. In the former illustration, there are four pulse generators. Each is triggered by one edge of the horizontal synchronizing pulse, and each may contain a delay circuit—a multivibrator to produce a control pulse of adjustable delay in the actual apparatus—and a pulse multivibrator. All pulses occur during the "back-porch" interval of horizontal blanking. One may neglect for the moment pulse 4, the clamp restoration pulse. It will be observed that pulse 3, the white gating pulse, supplies a signal to the video amplifier to turn the kinescope beam on full as the spot traverses the control area. At the same time, this pulse gates off the stair-step generator.

The signal from the secondary-emission collector is amplified and applied to two gate amplifiers. The input wave at the latter has a typical form given by *s* of Figure 9. The two relatively flat-topped portions of unequal amplitudes are generated as the beam scans A_B and A_R.

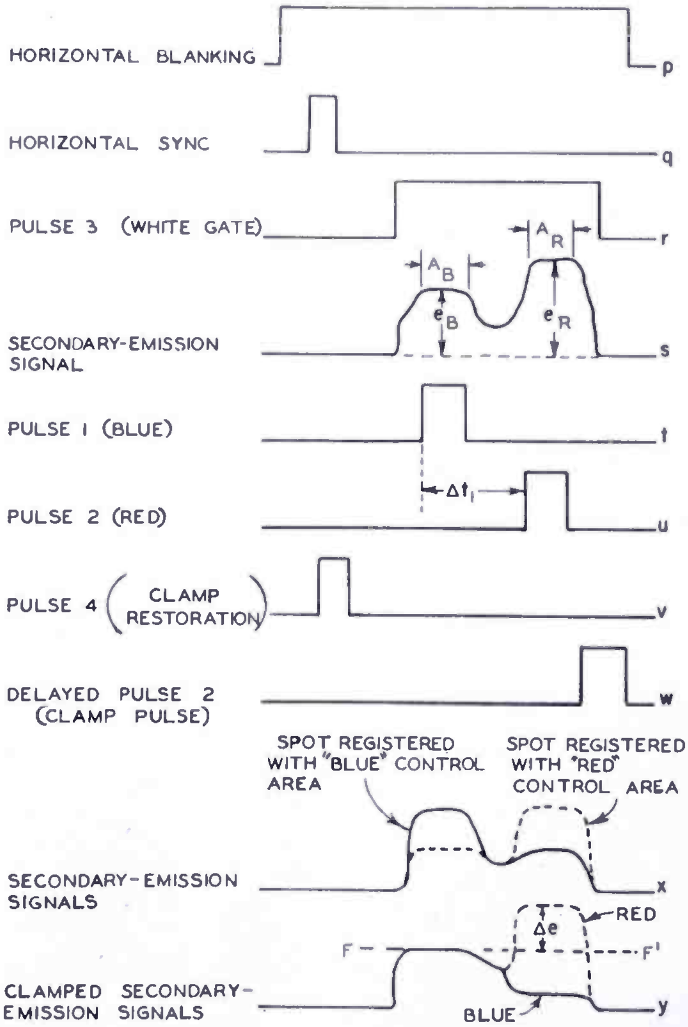

Fig. 9—Diagram of pulses in aided-tracking circuit.

A sample of the secondary signal is passed through gate amplifier 1 at the time of occurrence of pulse 1, while a second sample passes through gate amplifier 2 at the time of pulse 2. These pulses occur at the time of scanning the two control areas. The first signal (the "gated blue signal") is delayed by Δt_1 (see Figure 9) by means of a delay line and combined with the second signal (the "gated red signal") inverted in phase. Thus, at the input to the clamp circuit of Figure 8 the differential signal indicates the magnitude and sense of the vertical error in initial beam position. The signal is retarded by delay line 2 by approximately the pulse width, while pulse 2 itself is delayed and fed into the clamp circuit to establish the direct-current axis at the time of occurrence of the differential signal. The clamp circuit is of the double-keyed type described by Wendt.[13] Then, for the duration of one horizontal-scan interval, the potential applied to the kinescope deflection plate by the clamp will equal the differential signal. The beam is thus deflected along a typical path YY' or ZZ' to coincide with XX' in Figure 7a.

A little consideration will show that in the circuit just described it is necessary to restore the clamp circuit to its initial condition before a second line is scanned. In this manner a false vertical correction on alternate scanning lines can never be established, an effect that would result in color "pairing." Accordingly, in one arrangement a clamp restoration pulse (pulse 4 shown as v in Figure 9) is caused to occur before pulses 1 and 2 at the beginning of each scanning line to establish a fixed potential on the output circuit of the clamp. The beam is then in its uncorrected position as it begins its sweep through the control area, and the operation of the servo is not influenced by the history of the previous scan.

B. Cumulative-Control Method. Several improvements over the previous arrangement were next considered for the experimental color receiver. At the beginning of each scan the servo mechanism of the method described in Section IV *A* retained no information as to the previous correction required. Then, when progressively greater corrections were needed on successive scans, a condition would be soon reached in which deflection by more than the width of a color triplet was required. The control circuit did not accomplish this, however, but gave the smallest possible deflection to arrive at the correct color. A gap or an overlap in the scanning pattern then resulted. It was also noticed that the amount of correction provided depended upon the secondary-emission ratio of control areas A_B or A_R. In experimental tubes considerable variations in this ratio were sometimes observed. Less dependence on screen uniformity would be very desirable.

A method of improving servo operation utilizes a cumulative control in which the correction voltage applied to the deflection plates for one scanning line is reapplied at the beginning of the next scanning line before the beam sweeps across the control region. The control

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[13] K. R. Wendt, "Television DC Component," *RCA Review*, Vol. IX, pp. 85-111, March, 1948.

circuit then determines the *incremental* correction required to provide precise registration of the second scanning line. The servo device may thus be said to have a "memory."

A circuit of this type may be capable of accumulating correction information corresponding to several color cycles on the screen so that no discontinuities in the pattern occur. The second problem, that of screen uniformity, is much diminished since it is only the increment of signal on each scan, after the first, that is dependent upon control-area secondary emission.

A circuit arrangement having this type of "memory" is shown in block diagram form in Figure 10, with further details of the memory circuit in Figure 11.

As the beam scans the control area, pulse 3 keys the beam on full and cuts off the stair-step generator as in the earlier system. The secondary-emission signal shown as curve s in Figure 9 is redrawn as curve x to show the conditions of the spot initially in register with an A_B area ("blue") and an A_R area ("red"), respectively. In this circuit the control-signal clamp is keyed on by pulse 1 at the time the beam crosses the A_B region to establish a fixed direct-current axis FF' of curve y in Figure 9. Then, when the control-signal gate amplifier is keyed on by pulse 2 as the beam crosses the A_R region, the voltage Δe is developed with respect to this established direct-current axis. The quantity Δe may be of either polarity, depending on the relative magnitudes of e_B and e_R. It will be noted that the operation is not influenced by the amplitudes of e_B or e_R, but only by the difference Δe.

The difference signal is amplified and delayed as before. Clamp 1 brings the deflection plates to the same potential at the time the control pulse emerges from delay line 2. Then, for the remainder of that horizontal-scan cycle, the deflection plates maintain a voltage equal to that of the amplified difference-signal appearing at clamp 1. During the time of scanning the picture area, the stair-step wave is superimposed on this signal.

The memory clamp (like clamp 1 except with its double-keyed diode near ground potential instead of substantially at second-anode potential) delivers a similar voltage to the memory gate amplifier. Grid G_1 of this latter maintains a bias or pedestal voltage of this pulse amplitude starting at the time of occurrence of the delayed pulse 2 (curve w of Figure 9) and continuing through the beginning of the next scanning line until the occurrence of the next delayed pulse 2. When a new pulse 2 (not delayed) is applied to G_3 (Figure 11), this pedestal voltage is amplified and appears in the output of the memory gate amplifier. The output is thus proportional to the deflection-plate

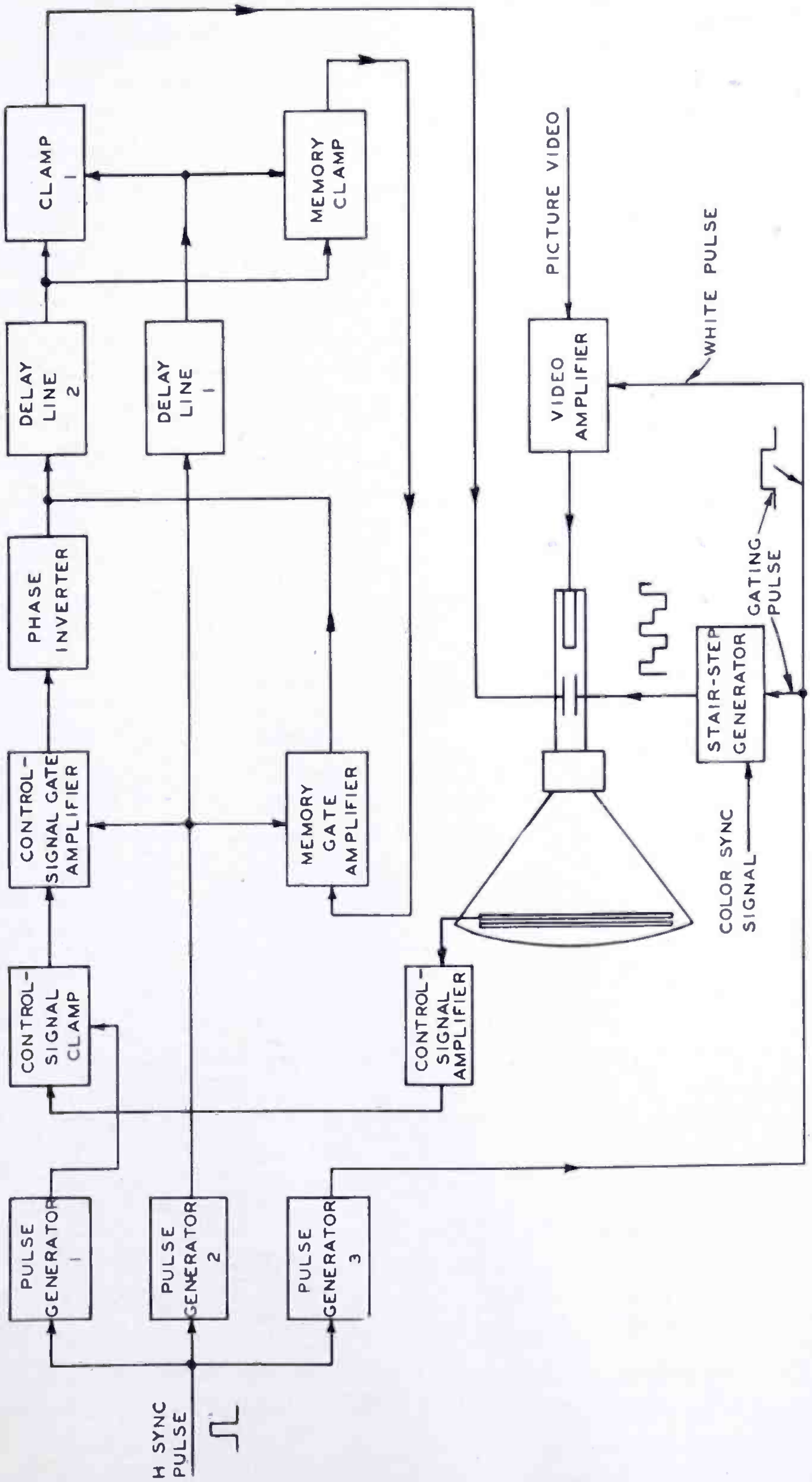

Fig. 10—Aided-tracking circuit employing cumulative control ("memory").

signal applied for the previous scanning line. The signal is added to the new signal from the control-signal gate amplifier and fed into delay line 2. The phase inverter of Figure 10 is required to combine these signals in the proper polarity.

Each gate amplifier used in the experimental apparatus uses a type 6AS6 pentode. This type is particularly suitable because of the high transconductance between the suppressor grid G_3 and the plate. The bias $-C_2$ (in Figure 11) is sufficient to cut off the tube until pulse 2 (of positive polarity) is applied to the suppressor.

The receiver employing the cumulative-control method proved easier to adjust and maintain in color registration than its predecessors. Mention may be made of a number of refinements that were incorporated to improve picture quality.

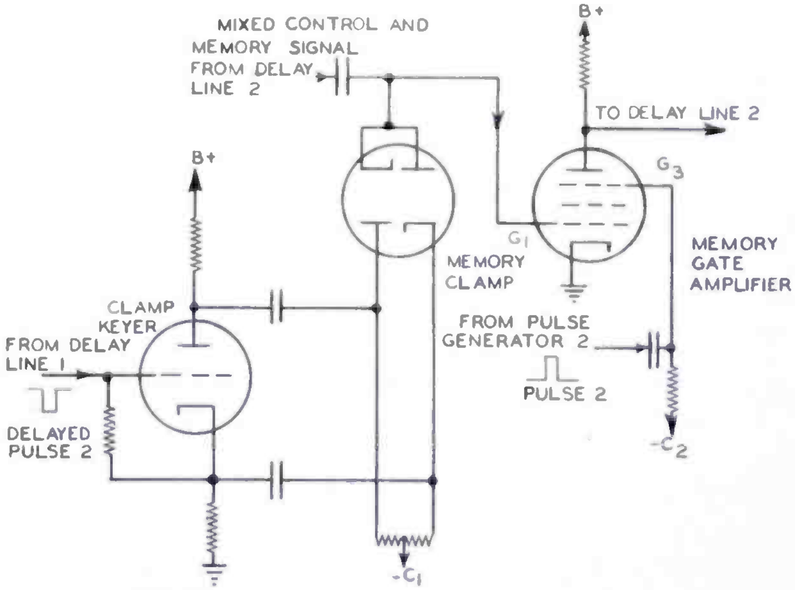

Fig. 11—Memory circuit used in Figure 10.

When the subcarrier frequency f_c was increased from 2.0 to 3.58 megacycles, the stair-step generator was changed from the multivibrator system to a combination of clipper stages, a delay line, and a wide-band video amplifier. While this gave a fairly good wave form, each rise time was a substantial portion of the total period. By the introduction of a circuit tuned to $3f_c$ inserted in the kinescope cathode lead and driven from the 3.58-megacycle color-synchronizing signal through a tripler stage, substantial freedom from color dilution was achieved despite the fact that the shape of the stair-step wave was not ideal.

Focus-modulation voltage was utilized to improve spot sharpness at the corners of the raster. The horizontal-deflection wave generated a parabola of 200—300 volts that, in turn, was applied to the first anode of the kinescope. Focus modulation in the vertical direction was also tried but later omitted because of the minor additional improvement it contributed.

The 525-line picture was deliberately converted into one having no interlace, i.e., *odd* and *even* fields were superposed. This process of "de-interlacing" was made necessary because, as was previously mentioned, the screens employed only 240 color-line triplets. A 30-cycle square-wave generator phased with vertical synchronizing signals furnished a voltage to the vertical-deflection circuit to make successive fields coincide.

Brightness of blue and green phosphors was deliberately reduced to maintain color balance with the relatively inefficient cadmium borate red phosphor available at the time. A receiver using a 16-inch line-screen kinescope with these phosphors was found to give a dot-sequential color picture of high-light brightness of 5—15 foot-lamberts at 18 kilovolts. Color purity was satisfactory when all the precautions described were taken. While the aided-tracking system required careful adjustment, correct color phase could be maintained over substantially all the picture area. Some difficulty was encountered because of the lack of adequate secondary-emission signals from the extreme top and bottom parts of the screen control areas.

Horizontal resolution through the video portion of the receiver was very substantially higher than in current commercial television equipments because the usual limitations of kinescope spot size, defocusing, and the like, had been much reduced. This condition held true over the entire raster area.

The three color images were precisely registered horizontally. The red and blue pictures were displaced up and down, respectively, by just 0.010 inch from the green picture. At normal viewing distances the registration of the three images appeared exact.

The very nature of the color registration process required that the vertical linearity appear perfect as far as the observer could tell from picture geometry.

V. Picket-Fence Registration Method

Brief mention may be made of another method of securing color registration. It was considered to be rather attractive because of its potential simplicity, particularly with the RCA color system.[12]

The name *picket-fence method* indicates clearly the orientation of the phosphor strips on the screen. The lines are vertical and spaced apart by the mean horizontal distance scanned by the electron spot during the time of one color element. (This applied to a presentation not incorporating dot interlace. In case dot interlace is employed there are *two* color triplets in such a scanning distance.) Then if the beam scans the screen with perfect horizontal linearity and size and if the starting phase is correct, the beam will coincide with a phosphor line of the correct color at the time the video modulation of the beam corresponds to that same color. The screen thus inherently performs the function of the color demodulator. The distance between centers of a triplet of color lines can be very nearly the same as for the 720-line screens previously described. The relation of strip width to scanning-spot diameter involves the duty cycle of the multiplexing process.

In the picket-fence arrangement, the stringent requirements on vertical deflection and yoke geometric distortion are removed, and the stair-step generator is omitted. The full vertical resolution of a line-interlaced picture is obtainable. On the other hand, additional requirements may be imposed on the precision of *horizontal* scan. Alternatively, a servo operating throughout the scanning time may accomplish the required color registration. When such a servo is used, the information as to instantaneous beam position must be furnished to the control device regardless of beam-current amplitude.

Considerable progress has been made during the course of this project on servo devices of two types:

1. Circuits in which the *color information* is *independent* of the receiver operation and in which the horizontal deflection is controlled by the servo.

2. Circuits in which the *deflection* is *independent* of the servo, while the receiver color commutation is governed by the control means.

A discussion of such methods would be too extensive for inclusion in the present paper.

VI. Conclusion

Line-screen three-color kinescopes have been built in sizes up to 16 inches diameter. The phosphors can be deposited either by settling or by silk-screening. Tubes of 720 lines were produced by the latter method. Precautions in the electron-optical system are required to insure uniform sharp focus. The kinescopes are comparatively simple and appear to be well-adapted to factory production.

Among the various methods employing line-screen kinescopes described here, the aided-tracking system of color registration offered about the most satisfactory system studied in detail. The improvement of cumulative control in the servo system was found very desirable. The circuits are somewhat elaborate, but a picture of high horizontal definition and of adequate color quality results. Improvements in the production of secondary-emission surfaces to give greater and more uniform contrast may be expected to improve color purity and simplify the adjustment of the servo circuit controls.

The methods of securing color registration are potentially useful in other applications where geometric exactness of the picture is required. Circuits suitable for the smaller earlier tubes, described in Section III, should be valuable for many of these uses.

PHOSPHOR-SCREEN APPLICATION IN COLOR KINESCOPES*†

By

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Summary—*A technique has been developed whereby fine-detail printed patterns of color phosphors are deposited onto a glass surface suitable for use as the viewing screen in a color reproducer of the cathode-ray type. The phosphors, suspended in a lacquer, are "squeegeed" one color at a time through a stainless-steel-mesh-supported gelatin stencil. The lacquer is subsequently entirely removed by simple bakeout in air. The glass plate is rigidly fixed by vacuum onto a table which can be accurately adjusted in two horizontal perpendicular directions. Exact position of the glass on the table is indicated by two dial gauges; the accuracy attained is such as to intermesh the three color-phosphor patterns to better than 0.001 inch over the entire area. Phosphor screens have been made in substantial quantities for several types of color kinescopes and have given very satisfactory performance.*

INTRODUCTION

TELEVISION reproducing tubes of the cathode-ray type make use of luminescent materials, or phosphors, which are deposited on the glass viewing screen. In the past, such phosphors have been dusted, sprayed, or settled in a uniform layer on the electron-beam side of the faceplate. Of these methods, the most popular is the settling process, which although relatively slow, has led to the highest degree of screen uniformity and minimum optical contact. The latter is desirable because it reduces halation. The phosphors used in black-and-white kinescopes are mixtures of color phosphors which produce white light when they are simultaneously excited. In a kinescope for reproducing color pictures, it is necessary to use separate color component phosphors; normally, three such phosphors, red, green, and blue, are used. Most of the methods employed in color kinescopes require an accurately intermeshed pattern of these color phosphors; the patterns take the form of thin lines, dots, or other arrangements. Although it has been found possible to produce appropriate phosphor screens for color kinescopes by settling the phosphors through special masks, the length of time involved in a three-step settling process made it very desirable to investigate other methods.

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* Decimal Classification: R 720.

† Reprinted from *Proc. I.R.E.*, October, 1951.

This paper describes the successful application of printing techniques to the deposition of phosphor patterns on flat surfaces, such as glass or metal. The work was initiated because it appeared to be essential to quantity production of a color kinescope. For simplicity, the discussion will be confined to deposition on glass of patterns of the dot type and of the line type which are described in other papers.[1, 2] The method which was successfully developed for these purposes is based on the technique known as "silk-screen printing."[3] This process involves the use of a stencil through which the phosphors are forced.

In the printing of a line screen (i.e., one having adjacent narrow lines of different color phosphors) with a set of three different color phosphors, a stencil having only one set of lines may be used. By accurately moving the glass plate a predetermined distance underneath the stencil in a direction perpendicular to the lines, it is possible to print a second and third set of color lines. For the dot pattern, a single stencil is also used, but, depending on the geometry of the array, it may be necessary to move the glass plate in two directions for the other two colors. Accurate intermeshing of the three colors, of course, requires careful relocation of the stencil for each printing step and a means whereby the glass can be moved in two directions beneath the stencil. Because commercial equipment of sufficient accuracy and versatility was not available, the necessary equipment for this printing operation was designed and built.

A printing medium containing the suspended phosphor particles, which would permit printing on a nonabsorbent surface such as glass or metal without affecting the operation of the tube, was also developed. Before the phosphor plate could be used, however, all constituents of this medium which would affect tube operation were completely removed from the glass plate after printing. During experimentation with various printing media, the only compromises made were those which affected printing qualities; no compromises were made which affected tube operation.

As for the printing itself, the geometry of the color kinescopes under consideration required a precision of an order of magnitude greater than that required for four-color commercial printing, and such precision was, in fact, obtained.

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[1] H. B. Law, "A Three-Gun Shadow-Mask Color Kinescope", *Proc. I.R.E.*, Vol. 39, pp. 1186-1194, October, 1951.

[2] D. S. Bond, F. H. Nicoll and D. G. Moore, "Development and Operation of A Line-Screen Color Kinescope", *Proc. I.R.E.*, Vol. 39, pp. 1218-1230, October, 1951.

[3] J. I. Biegeleisen and E. J. Busenbark, SILK-SCREEN PRINTING PROCESS, McGraw-Hill Book Co., Inc., New York, N. Y., 1941.

Typical pattern dimensions for the line screen are a line width of 0.007 inch with a 0.030-inch spacing between line centers. For the dot pattern, dot diameters are used ranging from 0.017 inch with dot centers spaced at 0.030 inch, to a dot size of 0.010 inch with dot centers spaced at 0.018 inch. The figures given are for the pattern of a single color.[4] The pattern is printed to conform to the original photograph over the entire array to better than 0.001 inch.

Technique Considerations

For the printing of either the line or the dot patterns, the development of a suitable process was simplified because a single stencil could be used for all three colors. After preliminary work, but before the design and development of printing equipment, it was found necessary to solve two fundamental problems:

1. whether the stencil or the glass plate should be moved with respect to the other, and
2. whether consecutive plates should be printed with one color at a time by removing the glass plate from the table after each color, or whether each plate should be printed with all three colors without removing the plate from the table.

Since the stencil frame would always be large compared to the glass plate, it seemed reasonable that greater precision could be obtained by movement of the smaller glass plate, rather than the larger, bulkier stencil frame. This principle was followed throughout.

As for printing the glass plates completely or consecutively, the decision was dictated by circumstances. Only small quantities of tubes were needed at the start of the developmental program. In addition, only a few printed plates were to be made from each stencil. It was obvious, therefore, that complete printing of each plate would be satisfactory, at least during the development stages. It was advantageous, too, because having the glass clamped to the printing table for the entire printing of the three colors eliminated the need for registration which would occur if the glass plate had to be replaced on the table before each color pattern could be printed.

Printing Equipment

The first printing table was of wood and had a hinged stencil frame such as is used in conventional silk-screen printing. A micrometer-head screw feed was used for adjusting the glass plate, but accuracy

[4] When all three colors are printed, lines of different colors are separated by 0.003 inch. In the dot patterns, the dots become tangent.

required ground-glass edges or the cementing of the glass to a machined plate. The hinged stencil proved too inaccurate until locating pins were used. A further difficulty was that even the finest silk used by silk-screeners had too little open area for rapid printing. An all-metal table having a lathe-type cross feed and a vacuum suction system for holding the glass plate was then built. Dial gauges were used to indicate the position of the glass plate to better than 0.001 inch. Stainless-steel mesh, 165 by 165 strands to the inch, woven with wire 0.0019 inch in diameter and having an open area of 47 per cent, was then adopted, supplanting silk for all further work.

A third table (Figure 1) is a prototype of several later tables. In this table clearances and movements in the cross-feed unit are eliminated. The platform on which the glass plate is supported is roughly 20 per cent larger than the maximum dimensions of the glass plate. Both edges of the platform along the length have V-shaped grooves machined in the thickness. Along each side of the V groove a machined-steel block with a similar V groove is placed. Hardened and ground steel balls are interposed between the two grooves so that the platform is, in effect, supported by large steel balls. One of the two V blocks alongside the platform is adjustable so that clearances can be made practically zero while the platform remains free to move along one axis. To permit movement in the horizontal plane in a perpendicular direction, the two V blocks and platform assembly are mounted on a larger steel plate with similar V grooves and V blocks oriented at an angle of 90 degrees to the V grooves of the platform. To control the movement of the lower steel plate and platform, a lathe-type cross feed is inverted and fastened to it. The actuating device for the platform permitting movements in both directions is supported by the frame of the table (Figure 2). In this table also, the position of the platform (and of the glass plate) is determined by calibrated dial gauges rigidly mounted to the frame of the table. With this type of table, accuracy of the order of 0.0005 inch has consistently been attained over a considerable period of time.

An all-metal stencil frame was designed which clamps the stainless-steel mesh on four sides between two aluminum bar clamps. The clamping bars are tightened and adjusted by a bolt arrangement. With this metal frame it is possible to get the mesh relatively uniform and sufficiently taut and also to tighten or adjust the mesh tautness periodically. A set of locating holes is used to position the metal stencil frame on the printing table. Four threaded and hardened bushing-type inserts are bolted to the stencil frame. These inserts are accurately aligned with four hardened and ground bushing inserts

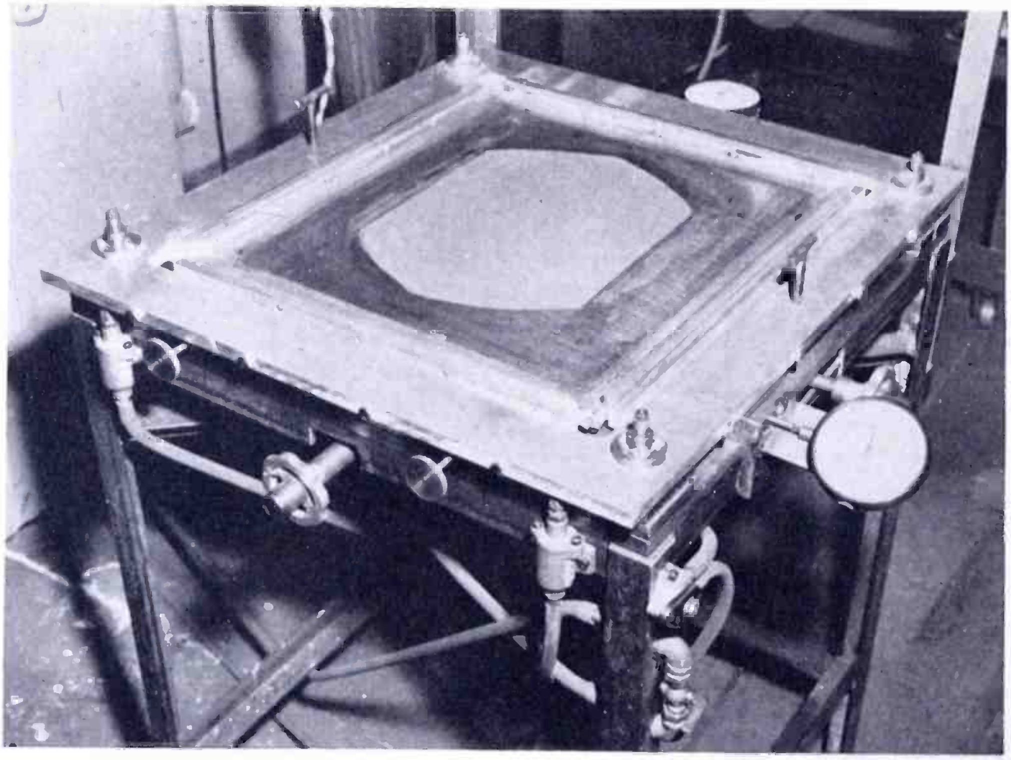

Fig. 1a — Printing table with stencil frame in position.

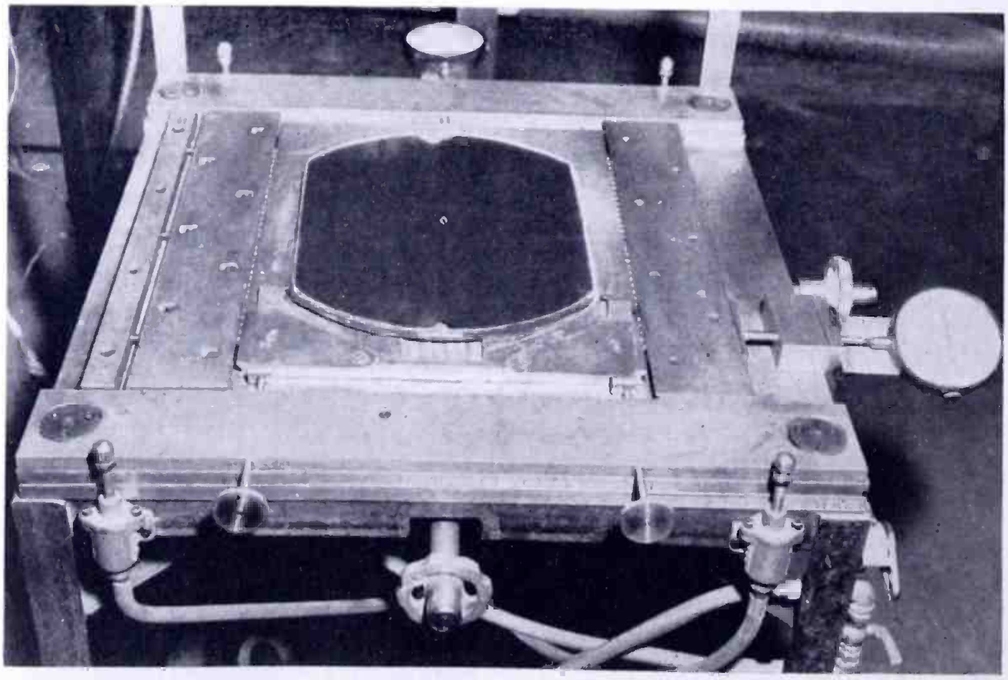

Fig. 1b — Printing table with stencil frame removed. Two air pistons are visible in front.

in the table. An adjustable pin having a fine thread for easy height adjustment is precision fitted to each stencil-frame insert. This pin also has a conical-shaped end which fits concentrically into the inside top edge of the hole in the printing-table insert. The height of the stencil frame is adjusted by rotating these pins in the stencil frame. The conical ends of the pins, fitting into the table inserts, maintain the desired stencil frame location. Everything except the hardened steel inserts and pins are made of aluminum to keep weight to a minimum. With this arrangement it is possible to relocate the stencil frame exactly at all times and to print as many as seven coats of the same pattern in registry, with removal of the frame after each coat. A 30-power magnifying device is used to determine registry; the accuracy of registration is considerably better than 0.001 inch.

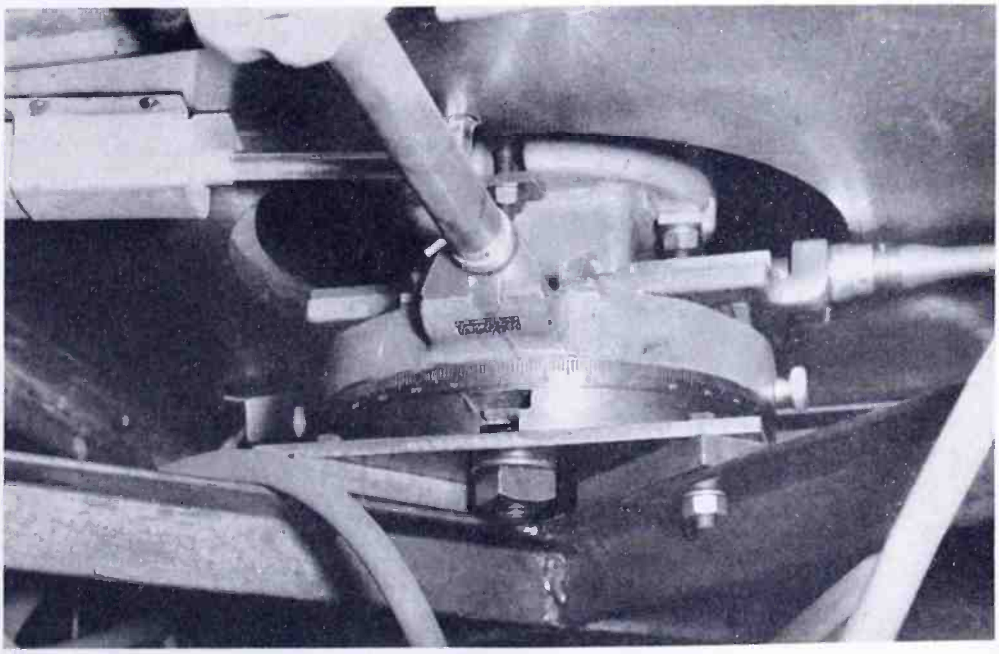

Fig. 2 — Close-up of cross-feed mechanism for positioning phosphor-dot plate on printing table.

Preparation of Gelatin Stencil

The exact reproduction of a pattern requires a suitable stencil as well as satisfactory printing equipment. At the start, gelatin stencils were made by means of the conventional "temporary" transfer technique. In this process a pigmented gelatin coated onto a paper backing is first sensitized in dichromate solution and then placed wet on a temporary transfer sheet to which it adheres. With a pigmented gelatin, the final thickness of the dry gelatin stencil is wholly dependent upon the amount of light during exposure. Because of the light-scattering characteristics of the pigment, fineness of detail can be lost by overexposure. Thus, proper exposure depends primarily upon the type of pattern; the thickness of the gelatin stencil, which controls, to some extent, the thickness of phosphor deposit, becomes of secondary importance. Materials made by several manufacturers were tried and a suitable, reliably consistent material was found.

At first, clear cellulose nitrate 0.005 inch thick was used for the temporary transfer sheet. Because the final printed plate must be accurate, the choice of the transfer sheet material is important. Since the coefficient of thermal expansion of cellulose nitrate[5] is high ($12\text{-}15 \times 10^{-5}/°C$), it became apparent at this stage that the use of this material greatly increased the problems of temperature control. To minimize these problems, it was decided to substitute Vinylite since it has a lower thermal expansion coefficient of $7 \times 10^{-5}/°C$. The use of this material resulted in the printing of many successful plates.

Distortions were still troublesome, however, even with the Vinylite support, and eventually led to abandonment of the temporary-transfer process. The direct transfer was in moderate use in the silk-screen industry at that time. In this process, the gelatin is placed directly on the glass photographic positive plate, and the glass plate supports the gelatin. The glass photographic plate is first coated with a thin layer of clear lacquer to protect the water-swelling emulsion. When the lacquer is completely dry, the lacquer coating on the emulsion side of the glass photographic plate is waxed to permit easy separation of the gelatin from the glass plate after the gelatin has dried. The wet, sensitized gelatin and paper backing is "squeegeed" on to the emulsion side of the photographic plate. The photographic plate is in direct contact with the gelatin except for the intermediate lacquer coating.

A Kodalith glass photographic plate, exposed to produce black dots in the emulsion at locations corresponding to the dots of phosphor to be printed, is used for exposure of the gelatin. Kodalith glass plates are highly satisfactory because of the extremely high contrast characteristics of the Kodalith emulsion. Glass plates, rather than film, are used for accuracy. The preparation of patterns on the photographic glass plates is part of the technique for each particular type of color kinescope. Procedures for making the dot pattern for the tri-color aperture-mask tube are discussed in an accompanying paper.[1] The configuration of patterns for the line-screen tubes, which are made on photographic glass plates by use of a special ruled-glass master, are discussed in another accompanying paper.[2]

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[5] Cellulose acetate is equally unsatisfactory; its thermal coefficient of expansion is approximately $15 \times 10^{-5}/°C$.

For exposure, a carbon arc lamp is placed 80 inches from the sensitized gelatin for approximately 3 to 4 minutes. The gelatin in contact with the photographic plate is then developed in tap water at approximately 45°C. The water dissolves the unexposed gelatin beneath the paper and permits the paper backing to be lifted off. Continued washing of the gelatin dissolves all the unexposed gelatin leaving behind only the light-exposed, insoluble chromated-gelatin. At this stage, the gelatin stencil is ready to be transferred to the metal mesh. Before actual transfer, however, it is first necessary to bring the photographic plate support and the gelatin to the proper dimension by soaking them in a controlled-temperature water bath. Since the thermal expansion coefficient of glass ($0.9 \times 10^{-5}/°C$) is so much less than that of Vinylite, controlled dimensions are more easily achieved and maintained when the direct transfer techniques are used. The conventional method of placing the metal frame on top of the wet gelatin, often causes up to a 0.002-inch error in a 10-inch length. To eliminate this, the metal frame is positioned upside-down and the gelatin carefully placed on top of the mesh with only the weight of the glass plate bearing down on the gelatin. The gelatin is then dried in air with the help of a fan. This improved technique of placing the gelatin on the stencil eliminates any consistent, measurable distortion.

The mesh on the stencil frame can be used repeatedly with only minor adjustments of the tension of the mesh from time to time. To clean the stencil gelatin from the mesh, glacial acetic acid is used, followed by hot water rinsing. An alternative technique for washing off the gelatin uses a solution containing 5 per cent sodium carbonate, 1 per cent potassium silicate, and 2½ per cent hydrogen peroxide.

Printing Considerations

A discussion of some dimensional distortions occurring during conventional printing is necessary before proceeding to the improved mechanics and procedure of the printing technique used for the phosphor application. Initially, the printing technique was almost an exact duplication of the technique used in the silk-screen process. For instance, the gelatin stencil frame was located and adjusted so that the stencil was spaced from 1/32 of an inch to 3/16 of an inch above the glass plate on which the pattern was to be printed. During printing, when the squeegee is being drawn across the stencil, the squeegee actually displaces the mesh-supported gelatin downward so that the gelatin stencil just below the edge of the squeegee contacts the glass plate. In the usual silk-screen process this spacing between the stencil and the work permits sharp printing and causes a spring action which provides a good release of the stencil from the work being printed. This distortion of the mesh and gelatin stencil does not appear to cause noticeable errors in commercial screen-process work. However, with the precision needed for phosphor plates of color kinescopes, this distortion of the mesh screen is serious because it results in an elongated pattern caused by the progressive drawing of the squeegee across the stencil. This elongation is as high as 0.005 inch over the pattern length of approximately 12 inches and is proportional to the spacing between the stencil and the printed plate. In addition to the uniform distortion caused by the uniform spacing between the stencil and the glass plate, errors were found which were caused by nonuniform stencil-to-glass spacing over the area of the pattern. Accordingly, it appeared necessary to keep the spacing between the glass plate and the stencil uniform and at a minimum. At best, with accurate adjustment of the position of the stencil above the glass plate, a pattern may be printed that has a small but uniform elongation.

To eliminate the effect of this pattern elongation caused by stretching of the stencil, a compensating factor was introduced into the stencil. The stencil, before transfer to the mesh, was cooled below room temperature in a temperature-controlled water bath. A uniform contraction of the pattern in both directions resulted. Since the printing caused a distortion in one direction only, this added compensation by uniform contraction of the gelatin was, of course, only an approximation, and was termed "compensated printing." It was difficult, indeed, to reproduce by this printing technique, patterns which did not deviate from the original by more than 0.001 inch.

The difficulties of producing accurate printed reproductions, even with the refined techniques which were developed, prompted an investigation intended to improve fundamentally the printing process rather than merely to refine the compensated-printing technique. The successful method evolved is termed "noncompensated printing." It is obvious that the printing should be done, if at all possible, with no distortion of the stencil during actual squeegeeing. It is not then necessary to shrink the stencil to compensate for pattern elongation. In the noncompensated printing technique, the stencil is adjusted to be in contact with the glass plate so that pressure of the squeegee during printing causes no distortion in the stencil. Only light pressure of the squeegee during the printing operation is required, since it is no longer necessary to distend the mesh-supported stencil. At the four corners of the metal stencil frame, four air pistons are mounted on the printing-table frame in contact with the stencil frame. By actuating the four air pistons simultaneously, it is feasible to raise the entire frame uniformly and quickly above the glass plate. This operation provides a clean break of the gelatin stencil away from the glass plate, and results in a sharply printed pattern. This noncompensated technique has two desirable advantages over the compensated technique:

1. It is not necessary to shrink the gelatin.
2. Since the mesh is actually never distended either during printing or during transfer of the stencil to the mesh, nonuniform tensions in the mesh are not a cause of distortions. The accuracy of the pattern printed by this technique has been consistently better than 0.001 inch, which is about the limit of measurement over a large pattern.

Printing Medium

A printing ink or paint, hereinafter referred to as "phosphor-printing medium," has been developed especially for printing phosphor plates for use in color kinescopes. The basic requirements of the phosphor-printing medium are as follows. The phosphor-printing medium must dry rapidly to minimize flow or spread on the glass after the pattern is printed. Rapid drying has a second advantage: inasmuch as consecutive printings are made on the same glass plate with different colored phosphor-printing media, it is possible to print second and third coats of the same phosphor without long waiting times. A further requirement of the phosphor-printing medium is that it must be capable of being easily and thoroughly cleaned from the stencil between colors to avoid contamination of one phosphor with the next. Most important in the formulation of the phosphor-printing medium is the avoidance of "poisoning" of the phosphors by the addition of foreign materials which reduce their light-emitting efficiencies. For this reason, the use of metallic salts or other inorganic constituents, such as "drying," "tacking," or "shortening" agents, must be completely ruled out since most common materials used for these purposes would seriously impair the light output of the phosphors. Moreover, any materials mixed with the phosphor powder in preparing the phosphor-printing medium are preferably removed after printing and before assembly into a color kinescope; only the phosphor powders are then left on the glass phosphor plate.

Because chromated gelatin is the stencil material, a lacquer is used as the base for the phosphor-printing medium. A viscous solution of ethyl cellulose in amyl alcohol is used for the lacquer base. The phosphor printing medium is prepared by mixing phosphor powder with the lacquer base. During the drying of the printed plate, the amyl alcohol evaporates, leaving behind the phosphor powder suspended in ethyl cellulose. The ethyl cellulose is subsequently completely removed by baking in air so that only the pure unaffected phosphor powder remains. Although difficulties were experienced with some special phosphor powders which were contaminated by extremely small traces of metal impurities present in commercial ethyl cellulose, the phosphor materials most widely used are not so affected. While particle size of the pigments used in commercial letterpress printing is generally less than one micron, the phosphor particle size used in the present phosphor-printing medium is generally larger than two microns.

PRINTING PROCEDURE

A chemically cleaned glass plate and the stencil frame are placed in position on the printing table. The four alignment pins are carefully adjusted so that the gelatin stencil just contacts the glass plate evenly over the surface of the glass. Depending upon the pattern being printed, the glass plate is aligned so that its locating marks are aligned with registry marks in the gelatin stencil. For the dot pattern of the aperture-mask tri-color kinescope, for example, a 50-power microscope is used so that the stencil pattern can be aligned with the glass plate to within ± 0.001 inch. When vacuum is applied, the glass plate is clamped to the table platform. The position of the glass plate is rechecked with the microscope and any further necessary adjustments are then made. The dial gauges, which locate the platform position, are adjusted to zero so that they can give the exact location of the glass during all subsequent printing operations.

The apparatus is now ready for printing the first coat. A stainless-steel spatula is used to apply the phosphor-printing medium across the top of the screen. A neoprene squeegee is used to squeegee the phosphor-printing medium across the stencil. By this method, the pattern is printed on the glass plate in much the same manner as that of silk-screen printing. As the stroke is completed, an air valve is depressed which actuates the four air pistons. The pistons quickly and uniformly raise the stencil above the glass plate. The stencil frame is removed from the table and placed in a screen-cleaning hood. At the cleaning position, the stencil is carefully cleaned with industrial cleaning tissues saturated with amyl acetate to insure freedom from color contamination. Absorbent paper-toweling sheets are placed underneath the stencil to absorb both the solvent and the phosphor powder. The screen is washed a minimum of three times; fresh tissues and absorbent paper sheets are used each time. During the cleaning operation, a bank of infra-red lamps is pivoted into position on the printing table to dry the phosphor pattern printed on the glass plate. For the second color position, the table movements are adjusted so that the proper dial gauge readings are obtained. The cleaned stencil frame is replaced on the printing table so that the alignment pins are in correct position. Squeegeeing, printing, and cleaning are then repeated for the second color, and finally for the third color.

Several coats of phosphor may be applied to each set of color dots in order to build up the amount of actual phosphor powder in each dot, although present practice permits good results with one coat. To print sharp dots, the gelatin stencil openings should be in contact with the actual surface being printed. The first patterns printed, therefore, must not interfere excessively with making good contact. To prevent interference, it is desirable to print one coat of each of the three colors before the second-coat printings are made. Under white light the three different color phosphors appear white and it is impossible to distinguish the three different phosphors from each other. Under ultraviolet radiation of the proper wavelength, however, the phosphors will fluoresce in their respective colors. Ultraviolet radiation, therefore, is used to check for contamination of the printed phosphor plates and for over-all uniformity of appearance of the printed pattern.

Early in the printing sequence, the first printed dot pattern is checked to uncover any inaccuracies due to errors in either the gelatin stencil or the printing-frame adjustments. After the first single pattern array is printed on the glass plate, the plate is removed from the printing table and checked for accuracy and freedom from distortion on a lightbox against a glass-plate photographic negative of the original pattern. The emulsion side of the negative is placed in contact with the printed phosphor pattern. The entire pattern is carefully scrutinized with a 30-power microscope; if any misregistration is observed, the stencil is considered unsuitable. It is conservatively estimated that any errors in excess of 0.001 inch are thus detected.

The possibility of pattern moiré arose early in the program. It may be recalled that the width of the printed line in the line pattern was approximately 0.007 inch. This narrow line width is not far different from the spacing of the supporting mesh strands which are spaced on 0.0061-inch centers; the wire strands of the mesh are 0.0019 inch in diameter. If the lines of openings in the stencil are not exactly parallel to the strands of mesh, a "beat" pattern could be set up between the phosphor lines and the strands of mesh and an over-all moiré pattern on the printed phosphor plate would result. To eliminate such moiré, it is important that the lines of openings in the stencil be placed at an angle of 45° to the direction of the mesh strands.

A similar moiré possibility could exist in some dot patterns in which the phosphor dots are in straight parallel rows. In the preferred dot pattern for the shadow-mask color kinescopes, there are rows of dots at angles of 60° to other rows of phosphor dots. For this dot pattern, several preventive means can be employed. First, moiré can be radically reduced by mounting the stencil so that one set of parallel rows of dots is at an angle of approximately 7° to the strands of mesh. For practical reasons, the mesh is mounted at an angle of 7° to the stencil frame and the gelatin stencil is placed so that its long axis is parallel and perpendicular to the directions of table movements. The very small residual moiré effect is then eliminated by printing the second coat of phosphor dots in a dot location adjacent to the first printed-dot location. Thus, when the second coats of the three color patterns are printed, the table movements cause the second coat to be deposited on the same color phosphor but on adjacent dots. Because the geometry of the pattern array is regular and even, adjacent dot printing does not result in any inaccuracies in the pattern.

Processing of Printed Phosphor Plates

The following processing steps take place after printing. In order that the ethyl cellulose be removed completely from the printed plate so that only phosphor powder remains, the printed phosphor plate is baked (oxidized) in air at 425°C for approximately a half hour. After bakeout, a pattern of phosphor powder not bonded in any way to the glass remains on the glass plate. At this stage the glass plate must be handled carefully and kept free of drafts because the powder can be easily disturbed. A bond is provided by gently spraying a fine mist consisting of an aqueous solution of potassium silicate onto the phosphor pattern and the glass plate. When dry, the silicate acts as a bonding agent, bonding the phosphor particles to each other and to the glass. When bonded, the powder is not easily wiped or blown off the glass plate.

The next operations are concerned with providing a metal backing for the viewing screen (a thin, reflective aluminum film deposited on the glass plate over the phosphors). The plate is first "filmed" by means of a special technique.[6] In the filming process, the plate is completely immersed in water, phosphor side up, and a specially pre-

[6] D. W. Epstein and L. Pensak, "Improved Cathode-Ray Tubes with Metal-Backed Luminescent Screens", *RCA Review*, Vol. 7, pp. 5-10, March, 1946.

pared nitrocellulose solution is then floated on the surface of the water. While the film is drying, the water level is lowered until the film, floating on the surface of the water, is deposited on to the glass plate over the phosphor powder. After the filmed plate is dried, it is trimmed and placed in a vacuum jar. Under high vacuum a reflective aluminum film is then evaporated on top of the nitrocellulose film. The phosphor plate is rebaked in air at 425°C for a short time to remove the nitrocellulose film. The phosphor plate is then ready for operation in a color kinescope.

ACCURACY CONSIDERATIONS

The accuracy necessary for the printing of the color phosphor has been achieved without unduly complicated equipment. On the printing table, the ways of the cross-feed are machined to a high precision. Four adjustable hardened and ground steel dowel-pins and four hardened and ground steel bushing-inserts, handlapped together in sets, maintain accurate positioning of the stencil frame. Dial gauges are used to position the table and the glass plate to an accuracy of better than 0.001 inch. Accurate temperature control and constant humidity in an air-conditioned area provide for constant conditions of gelatin exposure and gelatin drying. Likewise, temperature control keeps the dimensions of glass photographic plates and the parts of the printing equipment constant and reproducible. Careful comparison of the printed pattern with a glass-plate photographic negative in contact with the printed pattern, by means of a conventional 30-power microscope, gives an accurate determination of any errors which may occur in stencil making or printing. It is a conservative estimate that the accuracy maintained for the printing techniques described is better than ± 0.001 inch over printed patterns of the order of a foot in size.

ACKNOWLEDGMENT

The successful development of the processes described in this paper has been due to the cooperation and work of many. A sincere acknowledgment is due to G. Wolfe, E. V. Space, A. E. Chettle, W. J. Bachman, D. Pearson, E. J. Smith, S. Kozar, and many other members of the Tube Development Shop at the Harrison, New Jersey plant of the RCA Tube Department. Special acknowledgment is made to Mr. H. Rosenthal of RCA Laboratories Division for, among other things, his work on dot moiré and to L. J. Caprarola, also at Harrison, who originated the vastly improved "noncompensated" printing technique. Mention should also be made of the help given by Mr. Masi of the Francis A. Masi Company, Newark, New Jersey, during the early experimental stages. It was in his shop that one of the authors received indoctrination in the art of silk-screening, and it was there that gelatin stencils for some of the early tubes were made.

THREE-BEAM GUNS FOR COLOR KINESCOPES*†

By

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Summary—*The three-beam gun assembly for the aperture-mask tri-color kinescope consists of three guns located so that their axes are mutually parallel, equidistant from, and spaced 120 degrees about the axis of the assembly. The No. 4 grids open into a large common cup. The three electron beams are converged to a point on the aperture mask by an electrostatic lens formed between the large cup and the conductive neck coating. The focus of the individual beams is controlled mainly by the voltage applied to grid No. 3. The potentials of grids No. 3 and No. 4 may be varied in synchronism with the scanning frequencies to maintain beam focus and convergence over the entire screen area.*

The individual guns, of glass-beaded construction, are held in position by support spacers welded to eyelets around the gun cylinders. Many standard-type gun parts and manufacturing procedures are used. The beam spacing and gun placement are related to the design dimensions of the screen assembly. The guns are positioned with accurately machined, three-fingered fixtures which use the gun apertures as reference positions.

Separate leads for the cathodes and grids No. 1 and 2 of the three guns permit adjustment of the grid drive characteristics so that the ratios of the three beam currents are constant with grid drive. Thus, correct color is maintained independently of changes in brightness.

A variation of the parallel-beam type of gun uses a single set of cylinders in which triple-aperture discs are placed in appropriate positions. The final cylinder, which contains no aperture disc, forms, with the neck coating, an electrostatic converging lens. An arrangement of mechanically converged guns, used with magnetic dynamic convergence, is also described. Another type of gun, designed for a minimum neck diameter, employs electrostatic divergence of the beams before convergence. Still another type of construction is the "coincident-crossover" gun in which the beams may be focused and converged by a common lens system.

Introduction

THE design and construction of several types of three-beam gun assemblies for color kinescopes, particularly those for use with the shadow-mask phosphor-dot screen, are discussed in this paper. Other papers in this series[1,2] describe the operation and use of

* Decimal Classification: R138.311 × R583.15.

† Reprinted from *Proc. I.R.E.*, October 1951.

[1] R. R. Law, "A One-Gun Shadow-Mask Color Kinescope", *Proc. I.R.E.*, Vol. 39, pp. 1194-1201, October, 1951.

[2] H. B. Law, "A Three-Gun Shadow-Mask Color Kinescope", *Proc. I.R.E.*, Vol. 39, pp. 1186-1194, October, 1951.

these gun assemblies, as well as single-beam guns, in color kinescopes of the shadow-mask type. The salient feature of the three-beam gun assembly is the availability of a separate and independently controlled beam of electrons for excitation of each of the phosphors in the screen. Thus, the intensity of each of the three primary colors may be varied independently of the other two.

Initial experimental tubes[2] used mechanically converged guns, i.e., the assembly was constructed with the guns tilted toward the tube axis at an appropriate angle. In pilot-plant production, however, it was considered advisable for reasons discussed in this paper to use the parallel-gun type of construction with an electrostatic beam-converging lens.

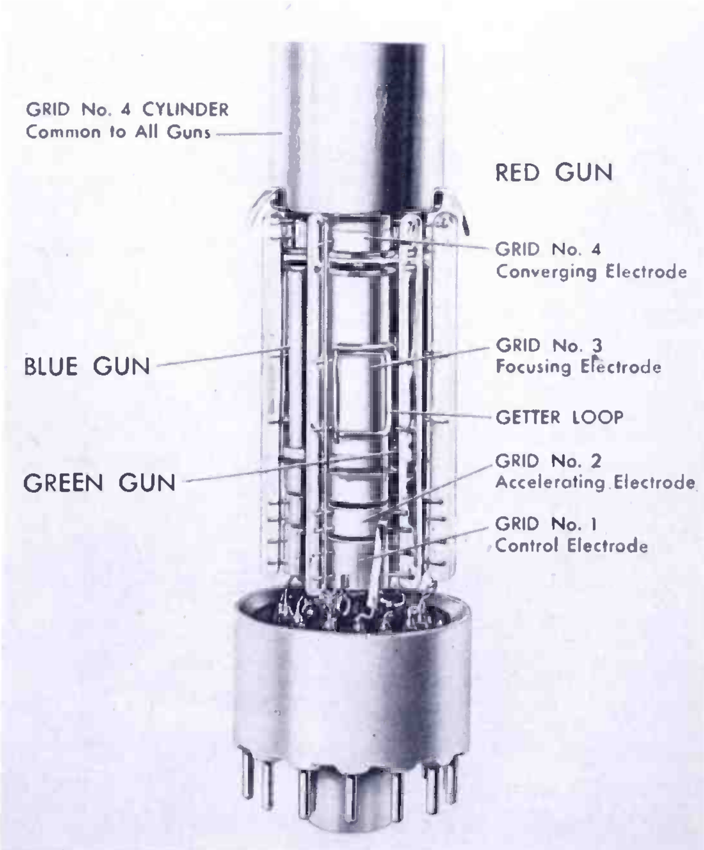

Fig. 1—Photograph of three-beam gun used in RCA color kinescopes.

Design Features

The three-beam gun assembly (Figure 1), which was used in color kinescopes for the 1950 demonstrations of the RCA color television system,[3, 4] consists of three similar guns located so that their axes are mutually parallel, equidistant from the axis of the assembly, and spaced 120 degrees about the latter. This construction permits accurate alignment of the three guns by means of a parallel-membered, three-fingered jig; it is a compact arrangement mechanically, requiring a tube neck diameter of only two inches. The design of the guns is a modification of a conventional cathode-ray tube gun design, and consists of an indirectly heated cathode, control grid, cup-shaped grid No. 2, a grid No. 3 containing a beam-masking aperture, and a grid No. 4. Beyond this point, there is somewhat less resemblance to conventional guns. The small-diameter grid-No. 4 cylinders of the three guns open into a common cup of large diameter, and are connected to it electrically. The grids No. 3 for the three guns are connected to each other internally; the cathodes, control grids, and grids No. 2 of the individual guns use separate leads. The three heaters are connected internally in parallel. Connections to all gun electrodes are brought out through a 14-lead stem and a base filled with plastic to provide insulation between leads for high voltage operation of the tube. A conductive coating on the inner surface of the neck is connected internally to the metal envelope and the screen assembly.

When the tube is in operation, an electrostatic electron lens is formed between the common grid-No. 4 cup and the neck coating by the potential difference between these electrodes. This lens serves to converge the three originally parallel electron beams to a point on the aperture mask of the screen assembly.[2] In performing this function, the converging lens also tends to focus each of the three beams. The major beam-focusing action, however, which permits sharp focus of the individual beams at the point of beam convergence on the mask, is supplied by a separate lens for each beam formed between grids No. 3 and No. 4. With this arrangement it is possible to control beam focus and beam convergence separately by adjustment of the voltages applied to grid No. 3 and grid No. 4.

Because the aperture mask and screen are flat, the distance that the beams travel between gun and screen varies during the scanning cycle. If the converging-lens potentials which produce beam convergence at the screen center were constant, they would tend to overcon-

[3] T. R. Kennedy, Jr., "RCA Shows All-Electronic Tube as Key to Color Television", *The New York Times*, March 29, 1950; "New Color Television Tube Seen Bringing Color Programs to the Home", *Radio Age*, Vol. 9, pp. 3-5, April, 1950.

[4] "Improved RCA Color TV", *Tele-Tech*, Vol. 10, No. 1, pp. 31, 59, January 1951; "RCA Improves Color in Latest Showing", *Broadcasting*, pp. 73, 77, December 11, 1950; see also Jack Gould, "RCA Exhibits Improved Color; Complicating of the T.V. Battle Seen", *The New York Times*, December 6, 1950.

verge the beams at the edges of the screen. For this reason, a dynamic-convergence potential of proper wave shape, in synchronism with the scanning frequencies, may be applied to grid No. 4 in order to obtain best convergence at all points on the screen.[5] It may also be desirable to vary the grid-No. 3 voltage dynamically in a similar fashion to obtain best beam focus over the entire screen area.

The converging-lens shape and, hence, its action are affected by the depth of the grid-No. 4 cup if the depth is appreciably less than the diameter of the cup. A shallow cup would permit the lens field to extend into the small-diameter portions of the electrode, and would distort the beams astigmatically. However, by having the depth of the cup nearly equal to or greater than its diameter, this effect is avoided because the converging-lens field barely reaches the bottom of the cup and is not appreciably affected by the three separate openings in its lower surface.

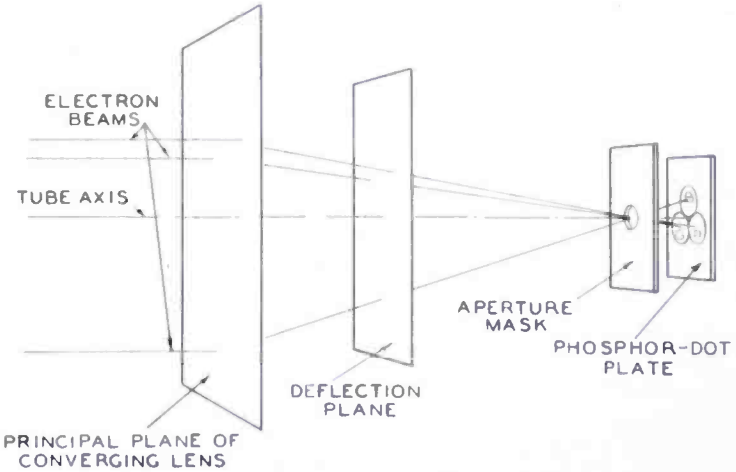

Fig. 2—Diagram illustrating three-beam convergence.

Since the proper functioning of the aperture-mask-screen assembly depends upon the accuracy with which the three beams pass through the "color centers" in the deflection plane,[6] it is important that the separation between the three gun axes, the distance from gun to deflection plane, and the distance from deflection plane to screen be properly set (Figure 2). The latter distance is determined by the size of screen and maximum deflection angle desired for the tube. The distance between gun and deflection plane is adjusted so that, when the deflecting yoke is in position, there is sufficient space between it and

[5] A. W. Friend, "Deflection and Convergence in Color Kinescopes", *Proc. I.R.E.*, Vol. 39, pp. 1249-1263, October, 1951.

[6] D. D. Van Ormer and D. C. Ballard, "Effects of Screen Tolerances on Operating Characteristics of Aperture-Mask Tri-Color Kinescopes", *Proc. I.R.E.*, Vol. 39, pp. 1245-1249, October, 1951.

the gun to avoid interaction between the yoke field and the converging-lens field. Considerations governing the separation of the beams in the deflection plane (i.e., the location of the color centers) are covered in another paper in this series.[2] With these parameters set, then, the necessary separation between gun axes could be determined if the location of the principal plane of the converging lens were known. Actually, a reasonable value for gun separation was chosen for a first approximation and the principal plane position computed from operational measurements. A second approximation, based on these results and consisting of adjustment of either the gun separation or the distance from the gun to the deflection plane, then gave sufficiently accurate results. For the diameters and voltage ratios used for the converging lens, the principal plane of this lens lies about midway down the grid-No. 3 cylinders, some three inches below the top of the gun. Figure 3 shows how the position of the principal plane is determined. Small errors in beam positioning may be corrected by adjustment of three small external magnets placed near the three guns.[5]

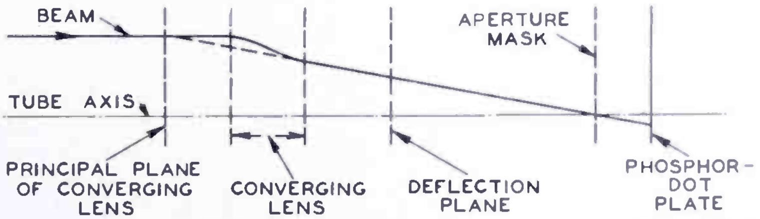

Fig. 3—Diagram of beam convergence, showing method of determining location of principal plane of converging lens.

Fabrication of the Three-Gun Assembly

The design and method of fabrication of the three-gun assembly are determined for the most part by the space considerations of the completed tube, particularly those of over-all length and neck diameter. To permit the minimum neck diameter for the desired beam spacing at the deflection plane, the three beams are made parallel up to the converging lens. Because of its ready availability, standard-size tubing, one half inch in diameter, is used for the gun elements. Since the standard method of gun-element support, using either two supports 180 degrees apart or three supports 120 degrees apart, does not permit the desired beam-to-axis spacing before convergence of 0.415 inch, three standard-type guns could not be used for the assembly without certain changes.

The position of each gun axis is determined by means of an accurately machined, three-fingered fixture which uses the apertures rather than the outer parts of the electrodes for reference. This fixture permits the use of nonprecision, production-type, support elements and spacers.

Thus "floating" on this positioning fixture, the cylinders are secured by glass beading or welding. The first method of intergun support considered was an all-beaded construction in which all the separate elements of the complete gun assembly (with the exception of the common grid-No. 4 cup) are placed on the positioning fixture and beaded 120 degrees apart (Figure 4). The grid-No. 4 cup is then positioned by another fixture and welded to the grid-No. 4 cylinders. This type of construction has the advantage that all elements of the assembly can be isolated electrically.

The method adopted later, which offers greater mechanical stability, consists of beading the individual guns with two beads each, 120 degrees apart, as subassemblies. The subassemblies are then positioned on the positioning fixture and the floating positioning system again used. With the subassembly guns positioned parallel to each other, their apertures serving as references, the guns are secured in place by welding an eyelet collar, fitted around the cylinder of a supporting gun

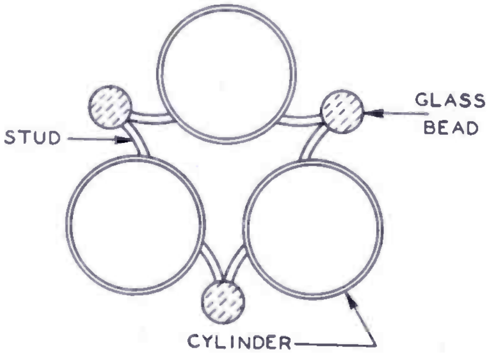

Fig. 4—Three-gun structure having all-beaded support.

element, to a loose-fitting support spacer. After the plane of support has been determined by welding one eyelet to its supporting gun element and welding all of the eyelets to the support spacer, the two remaining eyelets are welded to their respective gun elements. This procedure permits accurate positioning without the use of precision-made cylinders and spacer parts. In the early trials of this method it was found that the intergun supports placed between the control grids provided a loop which absorbed too much of the radio-frequency power intended for degassing of the cathode-grid assemblies on exhaust. To isolate the control grids electrically and to prevent overheating due to this absorption of power, the position of the intergrid supports was changed from the No. 1 grids to the lower part of the No. 3 grids. The bottom of the grid-No. 4 cup serves as the second support spacer; the positioning procedure described above is used in placing and securing both spacers.

The heater-cathode-control-grid assembly is the standard structure used on all RCA beaded-type electron guns. Grid No. 2 is a drawn cup with its edge rounded and electropolished. The rolled edge is omitted to provide liberal electrical separation of these cups after assembly. Since this part is positioned by its aperture on the beading fixture, the lower beading stud is placed as close as possible to the bottom of the cup, and made slightly longer than the upper stud in order to minimize the torque encountered when the gun is beaded. The ends of the cylinders for grids No. 3 and No. 4, which form the focusing lens for individual beams, have rolled edges of small radius. The top edge of the grid-No. 4 cup is rounded and electropolished, rather than rolled, to allow use of a cup of maximum diameter which would provide adequate breakdown separation from the neck coating.

In the color kinescope, both the gun alignment and the distance between the gun and screen are controlled in production so that in operation the beams will pass through the deflection plane in such a manner[6] that both pure color and proper beam convergence are readily obtainable. For these controls, seals for both the neck tubing and gun are made with the help of fixtures which align the neck and gun properly with respect to the color-screen mounting posts.[7]

Light Output and Color Control

In the design of the gun assembly, the operating characteristics of each phosphor determine the required drive characteristics of the corresponding guns. The drive characteristics of each gun are controlled so that correct color is maintained independent of changes in brightness. When a black-and-white picture is reproduced by the color kinescope, the color temperature of the whites and grays, from the high lights down to the deepest shadows, is essentially constant. Because the phosphors used in tri-color kinescopes show negligible current saturation in the range of current densities used, the achievement of constant color temperature requires only that the ratios of the three beam currents be held constant over the desired brightness range. The drive characteristics of each gun are controlled by adjustment of the potential differences between the cathodes, control grids, and grids No. 2, all of which are provided with separate base-pin connections. With this flexibility it is not even necessary to maintain close mechanical tolerances to produce the control characteristics required of each gun.

Since the drive characteristics depend directly on certain phosphor

[7] B. E. Barnes and R. D. Faulkner, "Mechanical Design of Aperture-Mask Tri-Color Kinescopes", *Proc. I.R.E.*, Vol. 39, pp. 1241-1245, October, 1951.

characteristics, a consideration of the characteristics of the phosphors used in the tri-color kinescope is of interest. The following table shows the relative efficiencies of the phosphors and the relative luminosities of the three colors needed to produce white.

Phosphor	*Relative Luminous Efficiency*	*Relative Luminosity to Produce 7300° K White*
Red (zinc phosphate: manganese)[8] . . .	25.3	82.5
Green (zinc silicate: manganese)	100.0	100.0
Blue (zinc sulfide: silver and calcium-magnesium silicate: titanium)	26.6	40.0

It would appear from the above table that current equalization to produce white could be accomplished by adjustment of the phosphor efficiencies. Lowering the efficiencies of the blue- and green-emitting materials might appear, at first glance, to be a simple solution. Such reduction of phosphor efficiencies would, however, require a compensating increase of total beam current to maintain light output. Even though the requisite video drive might be available for this purpose, there is a further limitation, namely, aperture-mask expansion due to the increased heating.[7]

When the phosphor efficiencies are not adjusted, the difference between the "red-gun" and the "green-gun" currents needed to produce white will result in slightly different optimum focusing conditions at high current levels. However, over the range of currents used in the tri-color kinescope, independent focus control of each gun (for example, by means of separate grid-No. 3 leads) or gun modifications are not required for satisfactory results.

Developmental Three-Beam Gun Types

During the course of the development of the three-beam gun, several other types of gun construction and operating principles were investigated.

A variation of the parallel-beam type of gun consists of a single set of electrodes, in which each aperture disc contains three apertures, spaced 120 degrees about the center. Three cathodes are enclosed in a common control-grid cylinder having an aperture located above each cathode; a triple-aperture disc serves as grid No. 2, and triple-aperture discs are likewise used in the grid-No. 3 cylinder, both at the lower end

[8] A. L. Smith, "Luminescence of Three Forms of Zinc Orthophosphate: Mn", *Jour. Electro-Chem. Soc.*, Vol. 98, pp. 363-368, September, 1951.

and near the upper end. Above grid No. 3 is a grid No. 4 consisting of a simple ring; the conductive neck coating, metal shell, and screen assembly are connected internally. A compound field produced by the potentials on grid No. 4 and the neck coating penetrates the apertures near the top of grid No. 3, providing beam-focusing action. As the beams pass into the grid-No. 4 region, they meet a common convergence field produced by the penetration into grid-No. 4 cylinder of the field produced by the neck-coating potential. Raising the grid-No. 4 voltage increases the beam-focusing action and reduces the converging action; lowering this voltage, of course, produces the opposite effects. There is, therefore, a point at some distance in front of the gun, at which beam focus and beam convergence occur simultaneously; the center of the aperture mask is located at this point. This gun is especially suitable when the three beams must be so closely spaced that the use of a separate set of cylinders for each beam is not feasible. The gun requires a relatively small dynamic-convergence voltage; this voltage produces little defocusing of the beams. Fabrication of this gun presents mechanical problems, however, if separate grid-No. 1 and grid-No. 2 controls are required for the three beams. Furthermore, the aperture method of focusing subjects the beams to spherical aberration of considerable magnitude. Masking of the beams and focusing action must be accomplished by a separate set of triple apertures in order to avoid the entrance of secondary electrons (from the edges of the masking apertures) into the convergence field.

The parallel-gun structure described at the beginning of this paper (Figure 1) allows a considerable degree of flexibility in tube and screen dimensions and has certain practical mechanical advantages in assembly. However, development of a special jig has recently demonstrated a practical method for accurate assembly of the guns in a tilted position with respect to the axis of the structure. The angle of tilt is adjusted so that, when the gun is sealed into the tube neck at the proper distance from the deflection plane, the three beams pass through the respective color centers. Minor deviations from the desired alignment may be compensated for in the same way as deviations in the parallel-gun type.[6] The mechanically converged type requires no electrostatic converging lens, so that the three grid-No. 4 cylinders may be connected directly to the conductive neck coating (without use of a common cup) and thus operate at the voltage of the final electrode. Beam focusing is accomplished entirely by the lenses between grids No. 3 and No. 4. The advantages of this gun assembly as compared with the parallel-gun type are an increase in grid-No. 3 potential with consequent improvement in gun efficiency, the elimination of a converging lens, and a reduction in the maximum potential on the leads brought out through the base. This gun structure, however, has a slightly increased maximum diameter. Dynamic convergence must, of course, be supplied electromagnetically.

Another type of gun, designed for a minimum neck diameter, employs electrostatic divergence of the beams before convergence. This feature permits electrical adjustment of the beam-convergence angle and of the beam spacing at the deflection plane in the finished tube. Electrostatic divergence is accomplished by a lens formed by the combination of a flat aperture disc and a cylinder. The close spacing of the disc and cylinder flattens the normally converging portion of the lens so that essentially only the diverging portion affects the beams.

Still another type of construction being developed is the "coincident-crossover" type gun. Its operation and construction are based on the principle that, if the beams appear to originate from the same source, i.e., have coincident crossover points either real or virtual, a common electron-optical system can be used to focus and converge all beams. An additional feature of the gun is that the divergence of the beams from the crossover point can be controlled electrically, thus making it possible to adjust in the finished tube the positions of the beams in the deflection plane.

ACKNOWLEDGMENTS

Many persons have contributed to the development described in this paper. For guidance and for ideas in three-beam gun design, the authors are particularly indebted to L. B. Headrick and L. E. Swedlund; for indispensable supporting work in means for fabricating the gun, to N. L. Graham; and for development of a practical method for assembling mechanically converged guns, to V. M. Hutchison. Much of the work would have been ineffective without the development of adequate testing equipment, for which credit is due to P. A. Richards, R. W. Hagmann, P. M. Kelly, and D. J. Ransom.

MECHANICAL DESIGN OF APERTURE-MASK TRI-COLOR KINESCOPES*†

By

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Summary—*The alignment requirements of the aperture-mask color kinescope, combined with the necessity of maintaining the alignment of aperture mask and glass phosphor plate during the operation of sealing the viewing-screen assembly within the tube, have resulted in the development of new assembly methods and techniques. The aperture mask of copper-nickel alloy is stretched tightly on one side of the spacer frame and the phosphor-dot plate is loosly clamped on the opposite side; alignment of the two parts is maintained by a fixed pin at one end of the frame and a sliding pin at the other. The two-piece metal-shell construction permits insertion of alignment fixtures for glass-neck and electron-gun sealing prior to the installation of the screen assembly. A reference plane is provided for these operations by screen-assembly mounting posts inside the shell. An internal high-permeability magnetic shield is also fastened to these posts. The final envelope seal is made by welding together the flanges on the two shell sections by means of an inert-gas arc. These flanges help to protect the tube faceplate and viewing-screen assembly from mechanical and thermal damage during the welding operation.*

Introduction

THE primary mechanical design task in producing a direct-view large-screen color kinescope of the aperture-mask type was the development of methods and techniques for proper alignment of the aperture mask, phosphor-dot plate, and electron gun. This paper discusses both the techniques developed for producing the major sub-assemblies of viewing-screen parts and envelope parts, and also the method used for the alignment, final assembly, and processing of the complete tube.

In the course of the developmental work on techniques and methods for constructing aperture-mask tri-color kinescopes, a number of developmental tubes have been made. These, in general, are similar in appearance to the 16AP4 kinescope, but have a welded flange near their large ends as shown in Figure 1. They have been made in both one-gun and three-gun versions, and with over-all lengths of either 25¹⁵⁄₁₆ inches or 33½ inches. All have a picture size of approximately 9×12 inches with rounded ends.

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* Decimal Classification: R583.15.

† Reprinted from *Proc. I.R.E.*, October, 1951.

The one-gun tube uses either a standard 5TP4 mount or a special short mount,[1] while the three-gun tube uses a special mount with parallel beams entering an electrostatic convergence electrode.[2] The deflection angle in each case is 45 degrees. The beam-to-axis spacing in the deflection plane is approximately 0.3 inch, the distance from the deflection plane to phosphor screen approximately 14¼ inches, and the convergence angle, therefore, 1° 14′.

The major components of the three-gun kinescope are given in the cross-sectional sketch of Figure 2. A magnetic shield of high permeability material is mounted inside the tube envelope to prevent beam distortion and resulting color dilution by stray magnetic fields. The

Fig. 1—External view of three-gun tri-color kinescope.

phosphor screen is printed in a geometrical pattern on a flat glass plate,[3] which is assembled in conjunction with the aperture mask and then mounted within the tube.

The one-gun and three-gun tubes first demonstrated in Washington, D. C. in March 1950,[4] used aperture masks with approximately 117,000 apertures, 0.012 inch in diameter, spaced on 0.030-inch centers. A green, blue, red phosphor-dot group was utilized with each aperture

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[1] R. R. Law, "A One-Gun Shadow-Mask Color Kinescope", *Proc. I.R.E.*, Vol. 39, No. 10, pp. 1194-1201, October, 1951.

[2] H. C. Moodey and D. D. Van Ormer, "Three-Beam Guns for Color Kinescopes", *Proc. I.R.E.*, Vol. 39, No. 10, pp. 1236-1240, October, 1951.

[3] N. S. Freedman and K. M. McLaughlin, "Phosphor-Screen Application in Color Kinescopes", *Proc. I.R.E.*, Vol. 39, No. 10, pp. 1230-1236, October, 1951.

[4] T. R. Kennedy, Jr., "RCA Shows All-Electronic Tube as Key to Color Television", *The New York Times*, March 29, 1950.

making a total of approximately 351,000 color dots. The spacing between the aperture mask and the phosphor-dot plate was approximately 15/32 inch. The phosphors used were willemite (Zn_2SiO_4:Mn) for the green, blue-emitting silicate (CaMg $(SiO_3)_2$:Ti), and red-orange-emitting borate (2CdO:B_2O_3:Mn). These were applied by "silk-screening" techniques[3] and then aluminized. Didymium glass filters were used in front of the tubes to improve the color of the red phosphor. These tubes were operated with the RCA color television system in circuits previously described[5] and using special deflecting yokes.[6]

In December 1950, an improved three-gun tube was demonstrated in improved circuits.[7] The number of apertures in the mask had been

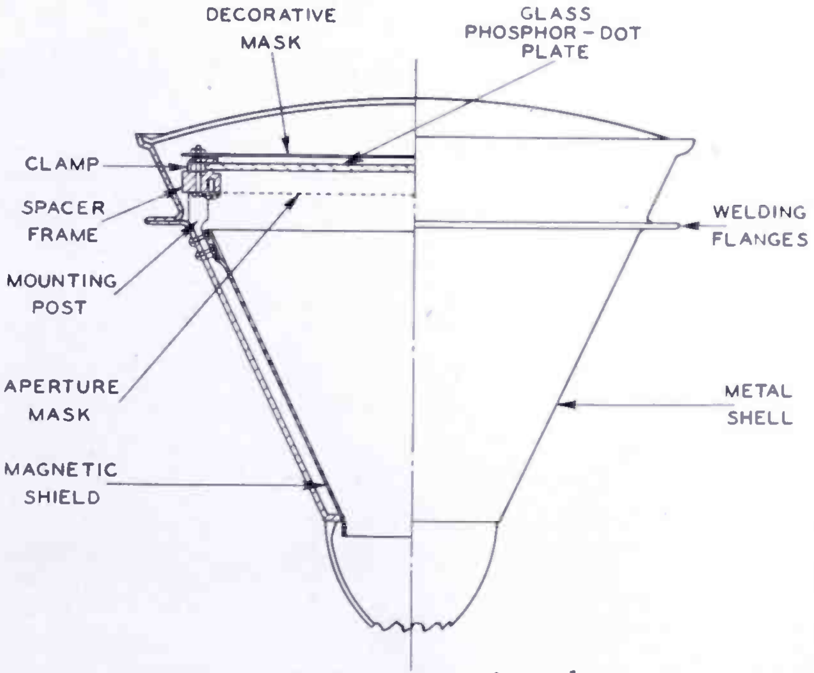

Fig. 2—Cross section of envelope.

increased to 195,000 by reducing the aperture diameter to 0.009 inch, and the spacing between aperture centers to 0.023 inch. The resultant number of color dots was approximately 585,000. The spacing between the aperture mask and phosphor-dot plate was approximately ⅜ inch. The convergence angle remained 1° 14′. The picture color and light output had been improved through the use of two new phosphors. One was a blue-emitting sulfide (ZnS:Ag) mixed with a blue-emitting silicate (CaMg $(SiO_3)_2$:Ti), and the other was red-emitting phosphate

[5] RCA Laboratories Division, "General Description of Receivers which Employ Direct-View Tri-Color Kinescopes", *RCA Review*, Vol. 11, pp. 228-232, June, 1950.

[6] A. W. Friend, "Deflection and Convergence in Color Kinescopes", *Proc. I.R.E.*, Vol. 39, No. 10, pp. 1249-1263, October, 1951.

[7] Jack Gould, "RCA Exhibits Improved Color; Complicating of T.V. Battle Seen", *The New York Times*, December 6, 1951.

($Zn_3(PO_4)_2$:Mn). The use of the new red-emitting phosphor eliminated the need for the correcting didymium glass filter. A high-light brightness of over 20 foot-lamberts was obtained and the finer dots, together with improved receiver circuits, resulted in freedom from objectionable dot structure or noticeable moiré effects. The number of apertures, when corrected for the lost area due to the curved sides of the picture mask, correspond to approximately 215,000 for a full rectangular raster and provided resolution capabilities in excess of those obtained with present black-and-white standards. The color pictures with this tube are bright, have high detail resolution, good color fidelity, and freedom from objectionable effects due to the dot structure.

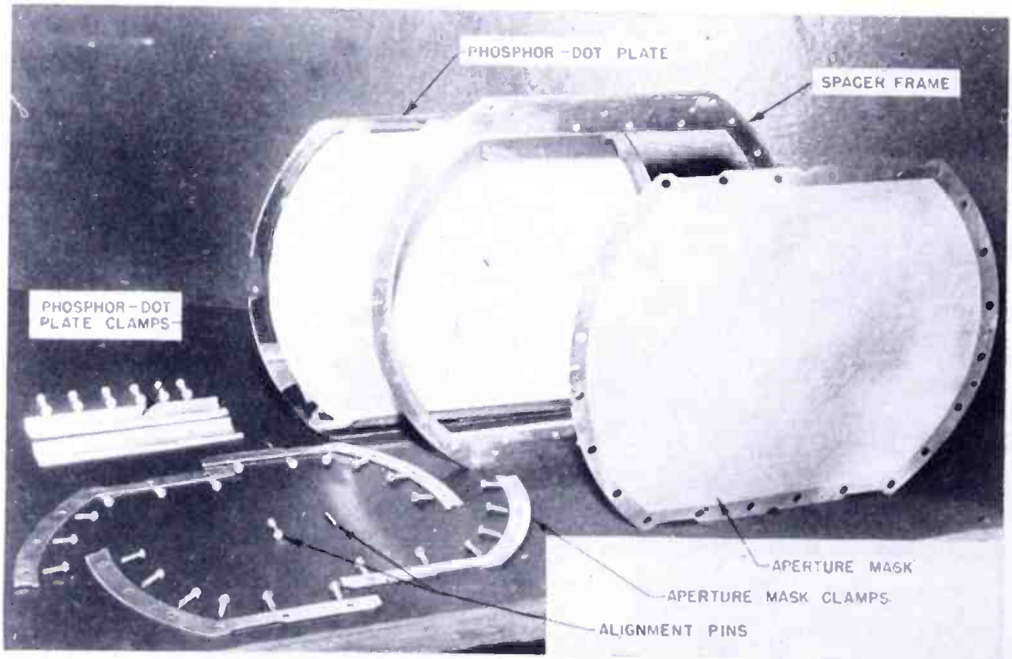

Fig. 3—Viewing-screen assembly—exploded view.

VIEWING-SCREEN ASSEMBLY

The viewing-screen assembly consists of three major parts: the aperture mask, the phosphor-dot plate, and the spacer frame. The spacer frame serves to hold mask and phosphor-dot plate in correct positions. These parts are shown in Figure 3. In the initial design of the viewing-screen assembly, considerable attention was given to the registration required between the aperture mask and phosphor screen, and to those operational and processing considerations which affect this registration. Analysis of the screen-assembly problem indicated that the apertures of the aperture mask should be properly aligned with the dots in the phosphor-dot plate to insure color purity, and that the edges of the apertures should be very thin to prevent beam restriction at wide deflection angles. The required aperture edge thinness was obtained through the use of a photoengraving process as mentioned by H. B. Law.[8] The holes are tapered to a feathered edge which acts as a very thin mask with respect to the electron beam. Holes made with taper on both sides of the mask to give a feather edge in the center have been made by etching in registry from both sides.[9]

During tube operation, the aperture mask receives approximately 85 per cent of the beam current, which heats the mask and causes it to expand. If this expansion is not compensated for, the mask may buckle and color nonuniformity may result. To overcome this problem, the "hot-blocking" manufacturing technique was developed. With a temperature difference between the aperture mask and steel frame slightly higher than that encountered in tube operation, the mask is expanded and then clamped to the frame. On cooling, the mask contracts and remains under tension.

This operation requires a frame which is strong enough to withstand the tension of the mask without serious distortion. Because size limitations of available mask materials prevented the initial use of a circular frame with its balanced stress system, a frame, illustrated in Figure 4, was designed. To compensate for the increased bending of the flat sides under load, they are made wider than the curved ends. The increased width of the flat sides also proved useful for mounting purposes. Because the glass phosphor-dot plate is mounted against the side of the frame opposite the aperture mask, the frame also serves as a spacer to give the correct distance between the aperture mask and the phosphor-dot plate.

Supernickel, a 70-30 copper nickel, is used for the aperture mask because it has a sufficiently high yield point to withstand the stress applied during "hot blocking". In addition, it is readily etchable by photoengraving techniques (a practical way of economically producing masks with the required number of holes), and it has a coefficient of thermal expansion close to that required in the assembly. During tube exhaust, the entire envelope and screen assembly goes through a 400° C heating-and-cooling cycle. An aperture-mask material is therefore required which has a higher coefficient of thermal expansion than that of the low-carbon-steel spacer frame. During the heating-and-cooling cycle, the mask expansion should always be greater than the frame expansion, even though the frame temperature, due to its greater thermal mass,

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[8] H. B. Law, "A Three-Gun, Shadow-Mask Color Kinescope", *Proc. I.R.E.*, Vol. 39, No. 10, pp. 1186-1194, October, 1951.

[9] Masks of this type have been made by the Buckbee Mears Co. of St. Paul, Minn.

is considerably higher than that of the mask during cooling. If, during the cooling portion of the cycle, the aperture-mask contracts more than the frame, the possibility exists of exceeding the elastic limit of the mask material. This condition would result in distortion of the mask pattern, and, in turn, could then lead to color nonuniformity.

The proper alignment of the aperture mask and phosphor-dot plate requires special attention because of the difference in expansion of the spacer frame and phosphor-dot plate during exhaust. In some constructions, this alignment could be controlled by sealing the phosphor-dot plate directly to the spacer frame. In this instance, however, this method is not practical because of the flatness required to maintain the necessary parallel relationship between the plate and the aperture mask.

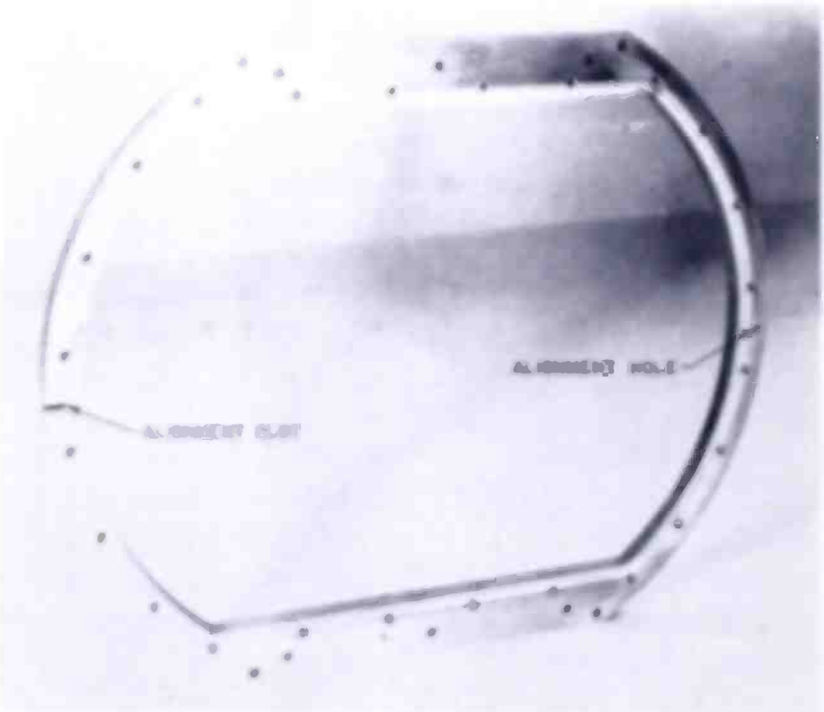

Fig. 4—Spacer-frame.

The solution developed for this problem is the use of an expansion joint between the glass plate and spacer frame. As shown in Figure 5, the joint consists of a fixed pin through the glass and frame at one end of the assembly. At the other end, a pin is fixed in the glass plate and allowed to slide in a slot in the frame. The maximum play between the glass plate and the frame is 0.001 inch. The holes are drilled in the glass plates under water with an undersized diamond drill; they are drilled halfway from one side and completed from the other. A plus tolerance of 0.0005 inch in hole diameter is held by reaming the drilled holes to size.

During "hot blocking", temporary pins in the spacer frame hold the aperture mask in proper alignment. Steel clamping segments 1/16 inch thick are assembled over the border of the mask by means of clamping screws. The unit is then placed in the "hot-blocking" press which consists of two electrically heated platens, one mounted on the ram of the press and the other on the bed of the press. Air or hydraulic pressure brings the upper block down against the aperture mask; the mask is squeezed flat as it is expanded by the temperature rise. The clamping screws are then tightened to hold the aperture mask in place on the spacer frame. After the unit is removed from the press, the contraction of the mask on cooling tightens it on the frame.

This aperture mask as clamped to the spacer frame is then photographed in a unit known as a "lighthouse" which is described in an accompanying paper.[8] This photograph is then used to prepare a gelatin stencil. After the phosphor plate is printed with its phosphor-dot pattern and aluminized,[3] it is placed over the registry pin which has been

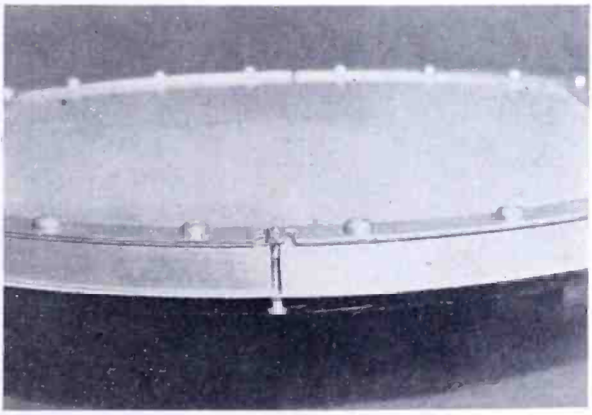

Fig. 5—Expansion joint.

fitted and pressed into the corresponding mask-frame unit. The sliding pin is then fitted into place through the hole in the glass plate and the slot in the spacer frame. Nuts are used to lock the sliding pin. Support clamps with glass fibre cushions are used to hold the glass phosphor-dot plate snugly against the frame. The viewing-screen assembly is then ready to be placed in the tube envelope.

Envelope Assembly

The choice of materials and the techniques used to incorporate the viewing-screen assembly into a tube are determined to a large extent by the physical properties of the phosphor-dot plate. Preliminary work, in which a small-sized phosphor-dot plate $4\frac{1}{2} \times 6$ inches was sealed into a glass envelope, indicated that this method would present problems due to the stress effects of sudden changes in temperature, or the high temperature necessary to make either a direct glass-to-glass seal or a frit-typ seal. In addition, the weight of a large screen assembly required a strong mounting to hold it in position during tube processing and shipment.

With these considerations in mind, two methods were investigated. The first was the use of a direct glass-to-metal seal in which the viewing-screen assembly was thermally isolated by an aluminum foil cap placed between this assembly and the sealing area. Air was circulated to cool the assembly. Although this method has possibilities, it presented difficult processing problems.

The second method was to cut the metal shell apart, insert the screen assembly in the lower portion, and then weld the two parts together without allowing the temperature inside the bulb to rise appreciably. The chief problems encountered in this development were to provide the required stress isolation between the welding area and the glass seals and to develop a technique for making vacuum-tight welds with the high-chromium steel used for the shell. Investigation showed that a shielded-arc weld using an inert gas such as helium or argon would produce vacuum-tight welds, provided the initial fit between the parts to be welded was good. The development of a practical envelope, therefore, resolved itself into the design problem of providing a good fit between the parts and of isolating the stress between the weld and the faceplate glass seal. Butt and lap welds proved unsuccessful because the parts to be welded could not be properly backed up and also because either type of weld provided so little stress isolation. The use of flat flanges, which could be clamped together while the edges were being welded, solved the problem.

The metal shell used for type 16AP4 kinescope had tentatively been chosen because of its availability, size, and suitability for the desired 45-degree deflection angle. In addition, the conical shape of this shell minimized the amount of stress isolation required between the weld and the faceplate. The developmental design finally utilized for the assembly is illustrated in Figure 6. Two metal shells, cut to proper lengths, have flanges spun at adjacent edges and trimmed to size. During the welding of the flanges, a bending moment is produced at the faceplate seal due to thermal expansion of the flanges. This effect is minimized by the conical shape of the shell and by cooling the flanges during the welding operation by means of heavy copper rings clamped to the flanges.

Alignment and Assembly of Tube

A reference plane for the alignment of all parts is established by four posts mounted inside the lower shell section. These posts, which are bolted and then welded to the shell, are machined to the proper height. They are then drilled in a jig and tapped for accurate location of the mounting bolts. The machined post ends provide a reference plane for the alignment of fixtures used for the neck-and-funnel sealing operations and for the alignment of subassemblies in the final assembly of the tube. A master drill jig is used to drill the mounting and locating holes in the spacer frame, the mounting posts, the "light house," and the assembly jigs.

After the posts are mounted and the reference plane is machined, the glass neck is sealed to the lower shell section. Since the conductive coating to be applied to the inner surface of the neck forms part of the electron-optical system, accuracy in size and roundness of the neck is required. Because of lack of demand, tubing is not currently produced in commercial quantities within the required tolerance of ±0.001 inch

Fig. 6—Metal envelope.

on the inside diameter. It was advisable, therefore, to rework available tubing by shrinking it onto a steel mandrel. This operation is performed by heating the glass on the mandrel and using a vacuum to pull the glass into contact with the mandrel. The metal, of course, shrinks more in cooling than the glass and this frees the tubing. This tubing is spliced to a glass funnel and then sealed to the lower metal shell. The fixture used for neck sealing consists of a heavy metal disc and a strong central post. The fixture is bolted to the mounting posts so that the axis of the reference plane coincides with that of the fixture. The desired alignment between the axis of the neck and that of the reference plane is obtained during sealing by the fit between the neck and mandrel. After the envelope is washed, the inner walls of the glass funnel and the upper neck are coated with graphite by standard methods and baked to remove all volatile material.

The fixture used for sealing-in the electron-gun assembly is similar to that used for the neck-sealing operation except that it has a tip which fits into the common grid-No. 4 cup of the electron gun. In use, this fixture is also bolted to the mounting posts; the gun assembly is then slipped down over the alignment fingers to the proper position. This fixture locates the gun assembly at the proper distance from the reference plane and orients it radially and axially, during the sealing operation, with respect to the position the phosphor-dot arrays are later to take in the tube.

The magnetic shield, which is required to properly shield the electron beam from stray magnetic fields, is fastened inside the envelope to the mounting posts. This shield, made of 50 per cent nickel-iron alloy, is annealed in a dry-hydrogen atmosphere in order to obtain high permeability.

The viewing-screen assembly is then bolted to the mounting posts. A decorative mask, made of flat blackened metal, is used to frame the useful screen area and to conceal screen assembly parts which would otherwise introduce reflections when the picture is viewed. In the final assembly stage, the upper shell section with sealed-in faceplate is clamped over the mounted viewing-screen assembly. The tube is then placed in a rotating fixture for the welding operation; the seal is made by an inert-gas arc weld in one continuous operation to eliminate the possibility of leaks which might occur if the welding operation were interrupted.

The tube is then exhausted by modified conventional cathode-ray-tube methods. During the exhaust process, particular attention is paid to the heating and cooling rates to prevent the expansion of the frame from exceeding that of the mask.

Acknowledgment

In addition to help in this project from authors of other papers in this series, the mechanical design herein described was aided by ideas and suggestions of G. S. Briggs, M. J. Grimes, H. R. King and C. P. Smith of the RCA Victor Division, Lancaster, Pa., and R. R. Law of the RCA Laboratories Division, Princeton, N. J.

EFFECTS OF SCREEN TOLERANCES ON OPERATING CHARACTERISTICS OF APERTURE-MASK TRI-COLOR KINESCOPES*†

By

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Summary—*The two basic requirements for proper operation of the aperture-mask tri-color kinescope are that the deflection center and the color center of each of the three beams be coincident, and that the beams converge to a point at the aperture mask. Dimensional deviations which occur in manufacture are discussed in terms of variations from the condition of coincident deflection and color centers.*

The effects of manufacturing variations in the placement of the aperture array and phosphor arrays relative to each other are divided into two general types: the displacement of an array or part of an array within its plane, and the displacement perpendicular to the plane of an array.

If the displacement within a plane is uniform in magnitude and direction, a uniform shift of the position of the color centers within the color plane results. If the displacement is not uniform, or contains a rotational component, each section of the screen has a unique color center resulting in a confused or enlarged color center for the entire screen.

With the second type, the displacements normal to the plane of the array, uniform stretching or contraction of either array can be included because these variations in dimensions cause the color centers to be displaced normal to the plane of the screen.

Complete compensation can be made in the finished tube for those manufacturing variations which affect only the position of the color centers. Such compensation is made by altering the path of each electron beam before it reaches the deflection plane so that it passes through the displaced color center, and by placing the deflecting yoke so that the plane of deflection coincides with the displaced plane of color centers. The limitations in establishing suitable tolerances for the variations are chiefly those imposed by the envelope and gun dimensions, since beam convergence and freedom from neck shadow must be maintained.

Tolerances on dimensions affecting diffusion of the color centers have been carefully considered in the design of the screen assembly because variations in these dimensions cannot be compensated for by simple means in the finished tube. An allowance for these variations has been made by the use of apertures of smaller size. In this manner, the effects of variations in phosphor-dot size and shape on hue and intensity are, for practical purposes, eliminated.

Also discussed are the variations due to a tilt of the phosphor-dot plane, the aperture plane, or both planes with respect to the tube axis.

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* Decimal Classification: R583.15.

† Reprinted from *Proc. I.R.E.*, October 1951.

Introduction

THIS paper discusses the effects on the operating characteristics of the aperture-mask tri-color kinescope of deviations from the design center values encountered in the manufacture of the screen assembly and the placement of the screen and gun assemblies in the envelope. The relative importance of these deviations and compensating measures possible in the completed tube are considered.

In the process of setting up the aperture-mask color kinescope, either for operation of the tube or for analysis of the screen assembly, the concept of a "color center" is useful. A color center may be defined as any point in space, determined by the geometry of the screen assembly, from which an observer could "see," through the aperture mask, only the phosphor dots of a particular color. In the tri-color tube, the positions of the three color centers, one for each color of phosphor, determine the "color plane" parallel to the plane of the screen. In the color plane there exists an array of color centers. It would be possible to see only the phosphor dots of a particular color from any one of these color centers, but only the set which is nearest and symmetrically located with respect to the central axis of the screen assembly is of interest.

If the three electron beams deflected by a common yoke field are considered, the three centers of deflection will determine the "deflection plane." If the position of each deflection center coincides with that of a color center, then each deflected beam will excite only the phosphor dots of a particular color. The manufacturing deviations in the production of the screen assembly and its placement with respect to the electron guns can be interpreted in terms of the effects on this condition of coincident deflection and color centers.

In the completed tube these centers are not accessible, i.e., they are within the tube envelope. Therefore, the relative positions of the deflection centers and the color centers must be determined from the effects produced on the viewing surface of the screen. Ideally, the projections of the electron beams through the apertures of the mask onto the phosphor plane coincide with the phosphor dots. The problem thus becomes one of interpreting a three-dimensional system in terms of the effects observed on a two-dimensional surface.

The two basic requirements for the proper operation of the aperture-mask color kinescope are that the deflection center and the color center of each of the three beams be coincident, and that the beams converge to a point at the aperture mask. These two conditions insure pure color fields in proper registry.

The effect of manufacturing deviations in the placement of the aperture array and phosphor arrays relative to each other may be divided into two general types: the displacement of an array or part of an array within its plane, and the displacement perpendicular to the plane of an array.

Uniform Displacements Within Plane of Array

If the displacement of the aperture array within its plane is uniform in magnitude and direction, the dimensions of the projected array are not affected since the aperture array is made of equally spaced apertures and the two arrays are parallel. The result is merely a uniform shift of the position of the color centers within the color plane.

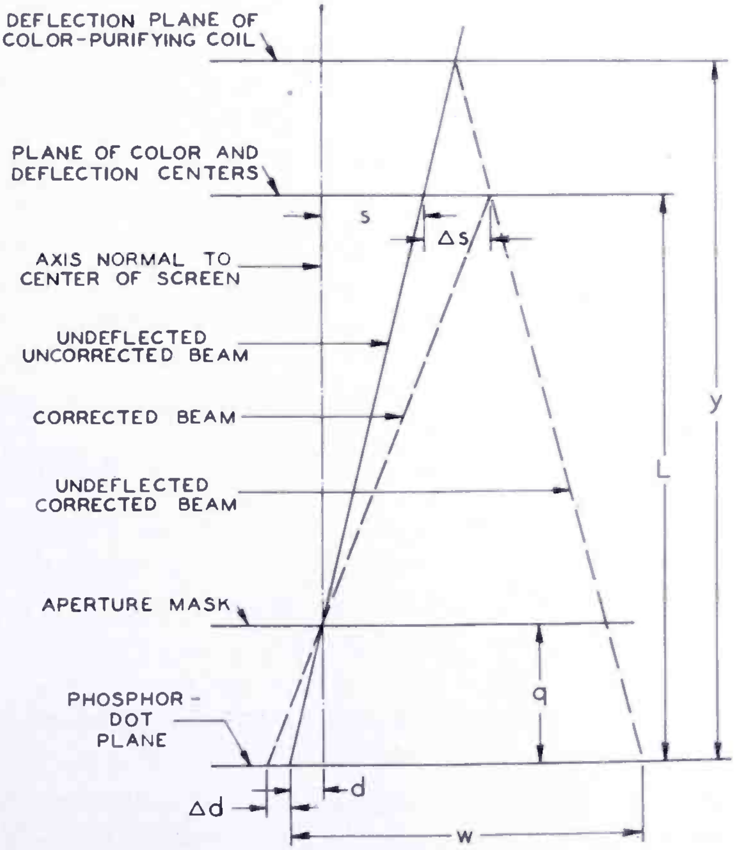

Fig. 1—Plane normal to the screen and passing through both a color center and the axis normal to the center of the screen.

Figure 1 shows a plane normal to the screen and passing through both a color center and the axis normal to the center of the screen. From this figure, the following relation may be obtained:

$$\frac{d}{q} = \frac{s}{L-q}, \tag{1}$$

so that

$$\frac{\partial s}{\partial d} = \frac{L-q}{q} = \frac{\Delta s}{\Delta d}. \tag{2}$$

In these relations, d is the distance between the center of a phosphor dot and the center of the three-dot cluster or trio of which it is a part, s is the distance between the axis normal to the center of the screen and the color center, L is the distance between the color plane and phosphor plane, and q is the aperture-plane-phosphor-plane spacing.

The above relation shows a magnification factor between s and d such that a variation in location of a phosphor dot with respect to its masking aperture is magnified to an apparent change in s by a factor of $\dfrac{L-q}{q}$.

It is possible to correct for the manufacturing deviations in dimension d by deflecting the electron beam before it reaches the deflection plane in order to make it pass through the displaced color center. This correction can be conveniently made by means of the controlled magnetic field of a coil located on the neck of the tube. This coil is known as the color-purifying coil.

The amount of displacement of the color center is a convenient indication of the misalignment between aperture and phosphor dot.

Again, reference to Figure 1 shows that

$$\frac{w}{y} = \frac{\Delta s}{y-L}, \tag{3}$$

where w is the distance between the undeflected focused spot of the corrected beam and the undeflected spot of the uncorrected beam, y is the distance between the phosphor screen and the deflection plane of the color-purifying coil, and Δs is the displacement of the color center resulting from a displacement Δd of the phosphor dot.

Substitution of the expression for Δs from Equation (2), in Equation (3) gives

$$\frac{w}{y} = \Delta \mathrm{d} \frac{L-q}{q} \left(\frac{1}{y-L} \right),$$

or, if $$\frac{L}{q} \gg 1,$$

$$\Delta d = w \left[\frac{q\,(y-L)}{yL} \right]. \tag{4}$$

The value of the quantity in the brackets for the tubes described[1] is about 3×10^{-3}. L and q are known from the screen design, while w and y can be measured easily within the required accuracy.

The current required in the color-purifying coil to cause the beam to pass through the color center is adjusted, with the screen under examination through a microscope of approximately 40 power, so that the beam, during the scanning cycle, lands squarely on the proper phosphor dot.

If the position of each dot in a trio is correct with respect to the other two dots so that d is correct, a displacement of this trio with respect to its aperture is a displacement of the axis of the color centers from the axis normal to the center of the screen. The relative positions of the color centers remain the same, and the amount of the displacement of their axis is equal to the shift of s.

This method of analysis and correction may be used for displacements from the design center in a direction parallel to the plane of the aperture array as a result of deviations in the locations of the aperture mask, phosphor-dot plate, entire screen assembly, and the electron guns.

Nonuniform Displacements Within Plane of Array

If the displacement is not uniform or if it contains a rotational component, each section of the screen has a unique color center, and therefore a confused or enlarged color center for the entire screen results. This effect can be visualized by considering for each aperture a ray passing through its center and the center of its phosphor dot. For a particular color, all such rays should meet at a single point, which has been defined as the color center. If, for example, the aperture array is now rotated with respect to the phosphor array, the rays connecting the aperture and phosphor-dot centers no longer will meet at a single point. They now define a circle of confusion in the color plane, the diameter of which depends upon the angle of rotation. Since each point within the circle will be the color center of a particular aperture, it would not be practical to have the deflection center coincident with such a group of color centers.

Thus far, the color center has been considered as a point; however, since the electron beam passing through the color plane has a finite

[1] B. E. Barnes and R. D. Faulkner, "Mechanical Design of Aperture-Mask Tri-Color Kinescopes", *Proc. I.R.E.*, Vol. 39, No. 10, pp. 1241-1245, October, 1951.

diameter, the system, for optimum operation, must be designed on the basis that the diameter of the color center is the same as the beam diameter.[2] This color center is composed of an infinite number of points, from each of which it is possible to "see" only a part of each phosphor dot of a particular color. When viewed from all of these points within the color center, however, the entire phosphor dot is visible. The beam, therefore, when deflected from the color center, excites the entire dot.

Since it is impractical to completely correct the entire screen for nonuniform displacements, an allowance for such deviations is made in the screen design. As referred to in H. B. Law's paper,[2] the optimum diameter of a color center is equal to M and the diameter of the phosphor dot to R. R is held to its optimum value while the diameter of the masking aperture is made slightly smaller than optimum. Changing the diameter of the aperture changes the diameter of the color center. When x is eliminated from Equation (4) given in the paper by H. B. Law,[2]

$$\frac{M+R}{R-B} = \frac{L}{q},$$

so that

$$\frac{\partial M}{\partial B} = -\frac{L}{q},$$

where B is the aperture diameter. Therefore, decreasing the size of the aperture increases the size of the color center. When the beam diameter no longer completely fills the color center, the entire phosphor-dot area will not be excited. By allowance for a finite beam diameter in this manner, the changes in hue and intensity resulting from variations in phosphor-dot size and shape are, for practical purposes, eliminated. The ratios of the three beam currents are adjusted so that faithful reproduction of a given hue and intensity is obtained.[3]

Displacements Perpendicular to Plane of Array

For the second type of effect, which is the result of the manufacturing deviations in dimensions normal to the plane of the screen, uniform stretching or contraction of either array is included, because the effect on the performance of the tube is the same.

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[2] H. B. Law, "A Three-Gun Shadow-Mask Color Kinescope", *Proc. I.R.E.*, Vol. 39, No. 10, pp. 1186-1194, October, 1951.

[3] H. C. Moodey and D. D. Van Ormer, "Three-Beam Guns for Color Kinescopes", *Proc. I.R.E.*, Vol. 39, No. 10, pp. 1236-1240, October, 1951.

From the equation[2]

$$\frac{1}{D} = \frac{1}{a} - \frac{1}{3s},$$

s is unchanged if D, the distance between centers of phosphor trios, and a, the separation of aperture centers, are unchanged. Therefore, from the equation[2]

$$q = \frac{La}{3s}, \quad \text{or} \quad \frac{L}{q} = \frac{3s}{a},$$

it is evident that the ratio of L to q is a constant. For the tubes described[1], the value of $\frac{L}{q}$ is approximately 38, so that changes in the value of q mean that L must change by an amount 38 times as great. Manufacturing variations in q are compensated for by locating the deflecting yoke so that the plane of deflection coincides with the displaced plane of color centers resulting from the change in L. Without this compensation, the effect of variations in dimension q on the relative position of the projected beams with respect to the phosphor dots can be obtained from Figure 2 which shows that

$$\frac{f + \Delta f}{L} = \frac{h}{L - (q + \Delta q)}, \tag{5}$$

where f is the distance from the axis of the color centers to the center of a particular phosphor-dot trio, Δf is the distance between the center of the phosphor trio and the center of the three projected beams, and h is the distance between the axis of the color centers and the center of the masking aperture associated with the trio. Then,

$$f = L \tan \theta, \qquad \text{and} \qquad h = (L - q) \tan \theta,$$

where θ is the angle of deflection from the color-center axis to the phosphor-dot trio. When these expressions are substituted for f and h in Equation (5),

$$\frac{L \tan \theta + \Delta f}{L} = \frac{(L - q) \tan \theta}{L - (q + \Delta q)},$$

or

$$\Delta f = L \tan \theta \left[\frac{\Delta q}{L - q - \Delta q} \right]. \tag{6}$$

Since Δq is very small compared to $L - q$, Equation (6) may be written

$$\Delta f = \Delta q \left(\frac{L}{L - q} \right) \tan \theta. \tag{7}$$

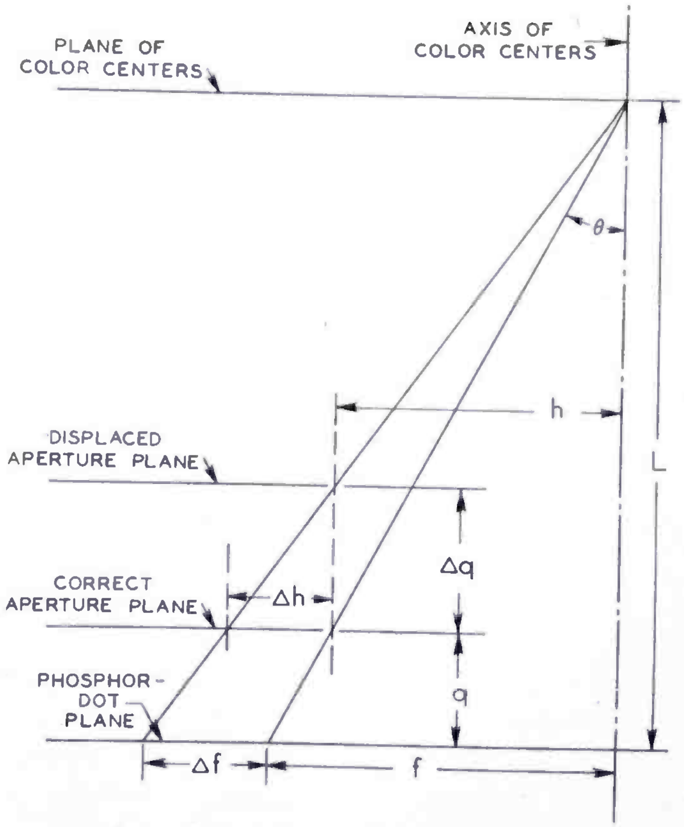

Fig. 2—Plane normal to the screen and passing through the axis of the color centers.

Because $\frac{L}{L-q}$, the magnification of the phosphor array over the aperture array,[2] is, for practical purposes, very nearly unity,

$$\Delta f \approx \Delta q \tan \theta. \tag{8}$$

From Figure 2 and Equation (8), it is apparent that an increase in spacing between the aperture mask and the phosphor-dot plate by an amount Δq produces an effect identical to that produced by an expansion of the aperture array by an amount Δh and is, therefore, equivalent to a manufacturing deviation in dimension a, the hole spacing in the mask. The correction for all of these deviations is the same: placement of the deflecting yoke so that the plane of deflection coincides with the displaced plane of color centers.

It follows that a tilt of the aperture mask with respect to the phosphor plane, so that the two are no longer parallel (i.e., q is no longer a constant but is now a function of θ), causes L to become a function of θ so as to keep $\frac{L}{q}$ constant. The resulting diffusion of color centers makes absolute correction somewhat difficult.

A tilt of the entire screen assembly with respect to the axis of the tube, however, results in a tilt of the color-center plane and displacement of color centers in that plane. Such a tilt can, therefore, be corrected, as are other uniform displacements parallel to the plane of the array, but requires, in addition, tilting of the deflecting yoke.

Conclusions

When the aperture-mask color kinescope is operated, the basic requirement for obtaining pure color fields is that the deflection and color centers be coincident. In order to maintain this condition of coincident deflection and color centers and, therefore, proper tube operation, manufacturing tolerances have been established for the various dimensional deviations which can occur in manufacture. Complete compensation can be made in the finished tube by adjustment of operating conditions for those deviations which affect only the position of the color centers. The limiting values of the manufacturing tolerances for these deviations are imposed chiefly by the envelope and gun dimensions in that beam convergence and freedom from neck shadow must be maintained.

The permissible deviations and resultant tolerances in the dimensions affecting diffusion of the color centers were carefully considered in the design of the screen assembly because they cannot be compensated for by simple means in the finished tube. Allowance for such deviations is made by decreasing the aperture size so that color purity is not affected.

Acknowledgment

The writers wish to express their appreciation for the advice and encouragement given by L. B. Headrick and H. C. Moodey, under whose direction this work was performed. Credit should be given to J. F. Wilhelm, A. M. Morrell, C. W. DeVoll, and R. E. Benway for their helpful assistance.

DEFLECTION AND CONVERGENCE IN COLOR KINESCOPES*†

BY

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Summary—This paper discusses the magnetic deflection of a number of closely spaced, convergent electron beams as used in the three-gun shadow-mask color kinescope, or in the one-gun shadow-mask tube. The entirely different deflection problem of a line-screen color tube, which uses a raster of precisely straight lines, is also considered, but in less detail.

The shadow-mask color kinescope requires that the beams converge to a spot on the raster, regardless of which part of the deflecting-field region is being traversed. A uniform magnetic deflecting field yields only approximately the desired result, since large deflection angles and a plane screen complicate the problem. An experimental arrangement, for yoke-design trimming, utilized a single-beam black-and-white or color kinescope with the electron optics of the one-gun shadow-mask color tube. A rotating magnetic field near the gun produced a conical scan. The rotating beam was next passed through a convergence lens. With adjustable direct currents through the yoke, it was possible to study the convergence at each beam position as a closed pattern on the phosphor screen; a small spot was desired at all deflection positions. Test yokes were built with distributed winding sections, each shunted by a variable resistance to adjust its contributions to the deflecting field. The direct current in the coil of the convergence lens was varied as a function of the radial deflection angle to yield best convergence over the entire raster. Adjustable magnetic compensating tabs at the forward end of the yoke aided in achieving a final best result. After the optimum yoke configuration had been determined, both hand-wound and machine-wound types of yokes were made with the correct windings. They have been used with both one-gun and three-gun shadow-mask color kinescopes. The rotating conical scan method is also especially useful for studying aberrations of other electron-optical systems such as lenses.

The use of a planar screen and the scanning of separated beams requires the convergence lens focus to be adjusted as a function of the deflection angle as mentioned above. This was done by a dynamic convergence system, which applied especially shaped waves of the vertical and horizontal scanning frequencies to either a magnetic or an electrostatic convergence lens.

In the line-screen color kinescope, which used a single beam, the raster lines had to coincide with the ruled phosphor lines, i.e., the yoke was required to produce a raster of essentially straight horizontal scanning lines. A design similar to "antipincushion" yokes of black-and-white kinescopes

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was useful as a first approximation. Again, tapped sectional windings were used for empirical optimization, and a satisfactory design was evolved. On the other hand, a yoke similar to that used with the multibeam tubes could also be used in combination with dynamic focus and "pincushion" correction systems.

Introduction

EACH type of color picture tube requires the practical solution of a particular aspect of the general problem of electron beam deflection. The least complicated color kinescopes may pose very complex problems of deflection. The best over-all result requires that the tube replacement cost should be minimized while maintaining simplicity of apparatus adjustment and a satisfactory degree of excellence of reproduction of both color and black-and-white pictures.

Utilization of the class of color kinescopes described by Baird,[1,2] Geer,[3] and Goldsmith[4] requires a practical solution of the very complex problem of attaining satisfactory separate deflection of each of three electron beams which converge from widely separated sources. The result must allow color registration throughout the picture. It is difficult to combine the three separately scanned color rasters to produce a color image, simply because of the geometry involved.

At the other extreme is another class of color tube, which may be no more difficult to scan than a standard black-and-white kinescope. These tubes may be built with a single electron beam; the color is changed by electrical control of the beam only in the region near the screen, after the scanning action has been impressed on the beam. Such procedures, offering simplification of the deflection problems, are noted by Herold.[5] For color tubes in this class, which require no special deflection means, refer to the accompanying papers by Forgue[6] and by Weimer and Rynn.[7]

A single beam does not, however, assure complete freedom from deflection problems. For example, color tube proposals by Rüdenberg[8]

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[1] J. L. Baird, British Patent 562,168.

[2] "J. L. Baird's Telechrome", *Jour. Tel. Soc.*, Vol. 4, pp. 58-59, September, 1944. See also *Electronic Eng.*, Vol. 17, pp. 140-141, September, 1944; *Electronics*, Vol. 17, p. 190, October, 1949; and *Wireless World*, Vol. 50, pp. 316-317, October, 1944.

[3] C. W. Geer, U. S. Patent 2,480,848.

[4] Alfred N. Goldsmith, U. S. Patent 2,481,839.

[5] E. W. Herold, "Methods Suitable for Television Color Kinescopes", *Proc. I.R.E.*, Vol. 39, pp. 1177-1185, October, 1951.

[6] S. V. Forgue, "A Grid-Controlled Color Kinescope", *Proc. I.R.E.* Vol. 39, pp. 1212-1218, October, 1951.

[7] P. K. Weimer and N. Rynn, "A 45-Degree Reflection-Type Color Kinescope", *Proc. I.R.E.*, Vol. 39, pp. 1201-1211, October, 1951.

[8] R. Rüdenberg, U. S. Patent 1,934,821.

and von Ardenne[9] require a very precise scanning action to cause the single beam to trace accurately a single color line of a group of parallel ruled phosphor lines on a plane screen. Such line-screen tubes and their operation are described by Bond, Nicoll and Moore.[10] Another single-beam color kinescope, developed by R. R. Law,[11] employs the shadow-mask, direction-sensitive screen proposed by Alfred N. Goldsmith and developed by H. B. Law.[12] In this instance, the normal path of a single beam is deviated slightly so as to simulate, at any instant, any one of the beams in a multibeam, tri-color tube.[12] If a beam-deflection system is made to deflect correctly the deviated electron beam in any position which it may occupy within its converging conic locus of rotation, then that system will deflect any similarly restricted, conically converging array of electron beams upon or within that locus. This includes all tubes with one or more beams which converge toward a central axis near the screen. An important example is the shadow-mask (or aperture-mask) tri-color kinescope with three closely spaced guns.[12] The attainment of proper deflection in such tubes is discussed in the major portion of this paper.

Both the three-gun and the one-gun shadow-mask tri-color kinescopes, which are characterized by the use of an aperture mask aligned with color-phosphor dots on a plane screen, appear to offer good performance with sufficient simplicity of apparatus adjustment. The geometry of the shadow-mask is arranged to allow the use of a very small angular separation between the beams to control the emitted colors. This principle is the key to satisfactory deflection of an array of electron beams. It makes possible the passage of the array of beams through a single deflection yoke with a minimum of separation. Thus, the beams may be deflected in unison by approximately the same magnetic field. It is, therefore, possible to avoid the electrical and mechanical registration problems which are encountered in separate deflection of each beam, as when a large angular difference is required between the sources.

Although the problem of separate deflection is eliminated, a considerable number of effects of second order remain. These effects are introduced (1) by the geometry of scanning upon a plane screen, (2) by the geometry of simultaneous deflection of a number of displaced,

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[9] M. von Ardenne, British Patent 388,623.

[10] D. S. Bond, F. H. Nicoll and D. G. Moore, "Development and Operation of a Line-Screen Color Kinescope", *Proc. I.R.E.* Vol. 39, pp. 1218-1230, October, 1951.

[11] R. R. Law, "A One-Gun Shadow-Mask Color Kinescope", *Proc. I.R.E.*, Vol. 39, pp. 1194-1201, October, 1951.

[12] H. B. Law, "A Three-Gun Shadow-Mask Color Kinescope", *Proc. I.R.E.*, Vol. 39, pp. 1186-1194, October, 1951.

converging electron beams, (3) by slight differences between the magnetic deflection fields traversed by each of the different beams, and (4) by manufacturing tolerances.

We are concerned with deflecting yokes and accessories which may be required to deflect electron beam arrays (such as those in the shadow-mask dot-phosphor color kinescope[11-13]) which lie in a conic locus and converge to the central axis at a common point. The development program emphasized yoke design and beam-converging devices to maintain beam convergence at a plane surface throughout the entire raster scanning process. The other circuitry and pieces of apparatus which produce deflection are assumed to be of entirely conventional design.

Multibeam Deflection Concepts

In a conventional black-and-white television kinescope, the outer electrons of the single, focused, electron beam may converge toward the center line of the beam at an angle of perhaps 0.20 degree. For easier understanding of the deflection problems of the shadow-mask dot-screen color kinescope, let us assume that this angle of convergence is enlarged to between 1.0 and 2.0 degrees, and that three, outer-surface, elemental rays of this beam are selected to represent the separately converging electron beams of the shadow-mask color tube (Figure 1). Thus, it becomes apparent that the multibeam deflection problem is the same as that of a single beam, except that many of the effects, commonly termed "defocusing," are magnified by the large effective size of the composite beam. In addition, throughout the deflection process each of the beams must retain not only its separate purity of source, but also its precise relative position within the composite beam. It is desirable as well to maintain a reasonably good approximation of the original shape of the individual beam.

Each electron beam of the three-beam group enters the deflection yoke and traverses about half the length of the yoke before it deviates appreciably from its particular sector of space wherein no other beam passes. In the forward section of the yoke the accumulating deflection of the beams causes each of them to sweep to a considerable extent through the same space. In order to deflect all beams in unison, since their initial proximity and their final broad sweep prevents any completely separate magnetic action upon the individual beams, the turns of the windings of the yoke are distributed to produce an essentially uniform magnetic field across the central transverse section of the space inside the yoke.

[13] H. C. Moodey and D. D. Van Ormer, "Three-Beam Guns for Color Kinescopes", *Proc. I.R.E.*, Vol. 39, pp. 1236-1240, October, 1951.

This creates a slightly pincushioned shape of raster upon the plane screen, but it seems best to concentrate upon producing a satisfactory convergence of the beams, and to consider correction of the slightly pincushioned raster separately. This shape, in which the sides of the raster are concave, may be corrected to reproduce a straight-sided raster by application of an optical correction plate, by a particular modulation of the final anode potential, or by a modulation of the deflection currents, if more simple means are not available. When the shadow-mask tri-color tubes with a 45-degree deflection angle were first publicly demonstrated during 1950, none of these corrections was used, so a small amount of

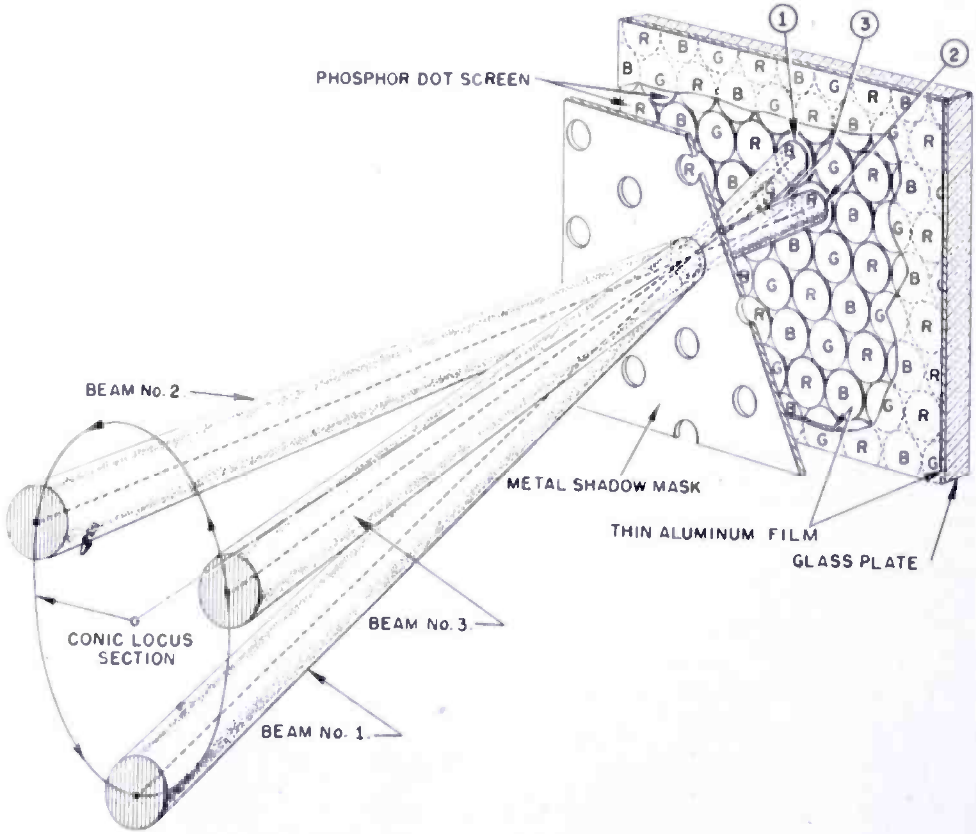


Fig. 1—Electron beams on conic locus.

pincushioning remained (about 4 per cent decrease in central width or height compared with that of the edges). In later demonstrations, however, this was eliminated by circuit modifications not discussed in the present paper.

It was assumed initially that the multibeam deflection yoke was to produce a uniform magnetic field across its central transverse section and to attain high order of uniformity and symmetry of field. Inspections and tests of production yokes for standard black-and-white television indicated that the uniformity and precision of winding distribution, as well as straightness and orientation, would not be adequate for direct adaptation to deflection of the shadow-mask color kinescope.

Consequently, in collaboration with O. H. Schade* and others, it was decided that multisection coils with their windings securely attached to half cylinders of a stiff insulating material, such as phenolic resin, should provide a means for accuately fixing and maintaining the relative positions of the coils. Winding these coils in small sections provided means for repeatedly correcting the various tendencies for progressive deformation of their shapes and the random displacement of turns during the winding process.

It was decided that test samples should be made, with *both* terminals brought out from each of five or six winding sections of each coil. Thus, the ampere turns per section of coil could be adjusted so that, from the data so obtained, the coils might be revised for optimum performance.

Fig. 2—Section-wound coils on half-cylinder mounts.

Preliminary Yoke Structure

A set of the windings used in the original hand-wound yokes for the tri-color kinescope is shown in Figure 2. Each of the winding sections (after the first one) was begun by winding the wire around a set of four pins which were passed through the winding jig and the coil-supporting half cylinder of bakelite. The small openings between the coils were filled with hard-fibre spacers so that each coil was provided with a firm backing and fixed in position by its individual set of four pins. Even the ends of the turns of the coils were sectionalized by covering each coil layer with a piece of rayon adhesive tape. Special care was taken to assure a uniform winding.

When each winding was complete, the coil, with its base and the entire winding jig, was impregnated with wax to fit the windings in

* RCA Victor Division, Harrison, N. J.

position. The waxed coils and their base were separated from the winding form after cooling. The pin holes were then used as openings for a binding of cotton sewing thread (Figures 2 and 3) to retain the coils in position. The larger holes in the winding shells were to admit pins for the precise orientation of each coil-supporting shell.

The horizontal-deflection coils were assembled upon an inner cylinder of bakelite tubing (Figure 3). The insulating strips were placed in the coil-window spaces to support the similarly mounted vertical deflection windings, and the outer vertical deflection coils were arranged at 90 degrees about the central axis with respect to the inner coils. Over these coils a final pair of half cylinders supported the moulded electrolytic iron or ferrite ring cores (Figure 4).

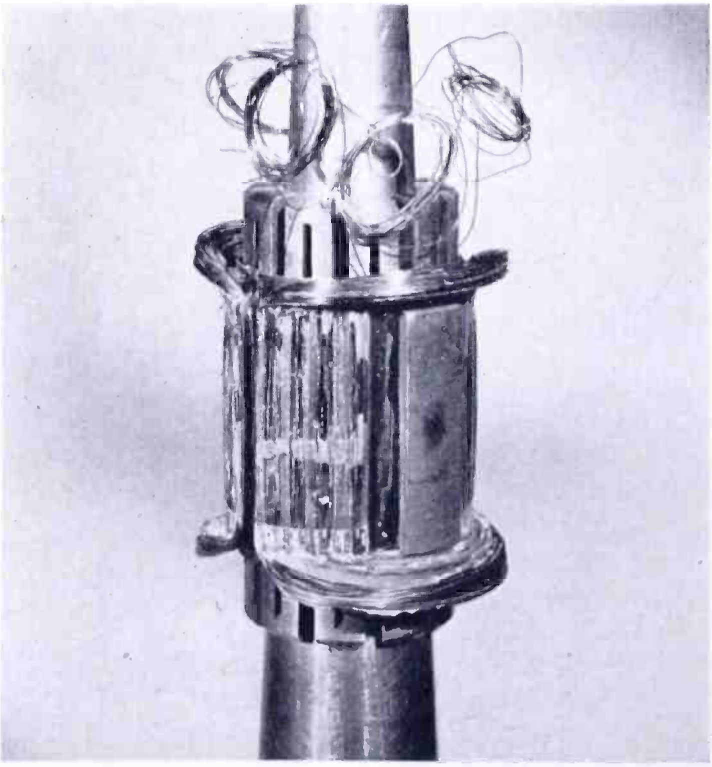


Fig. 3—Horizontal deflection coils and half-cylinder mounts assembled on inner cylinder.

The radial insulating separators and the end covers (Figure 4) were placed during assembly to insulate the separate coils from one another and from the core, to cover the coil ends, and to fix precisely the axial symmetry of the entire structure in relation to the outer cylindrical shell. A complete assembly is shown in Figure 5.

Deflection Testing of Yokes with a Conic-Locus Beam

To test and modify these yokes most effectively, apparatus was set

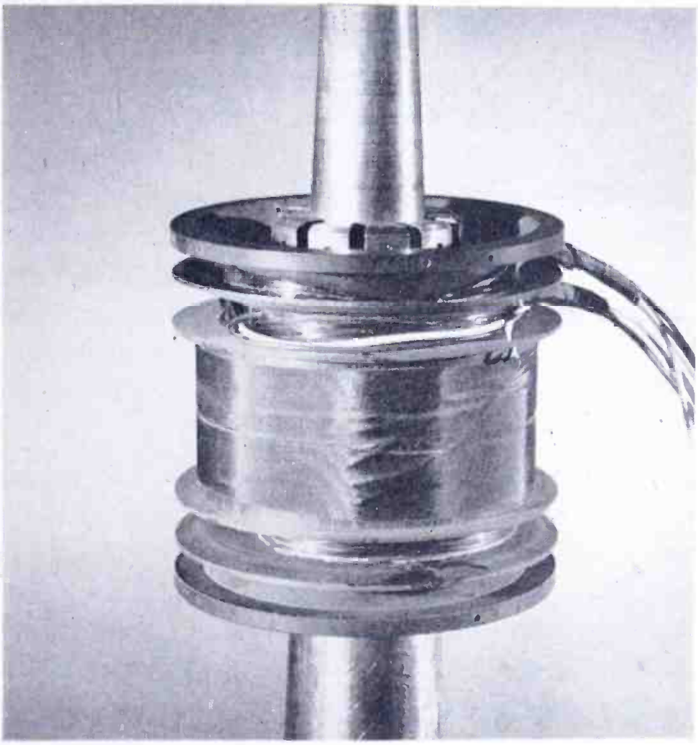


Fig. 4—Coil, core, and spacer assembly of section-wound yoke.

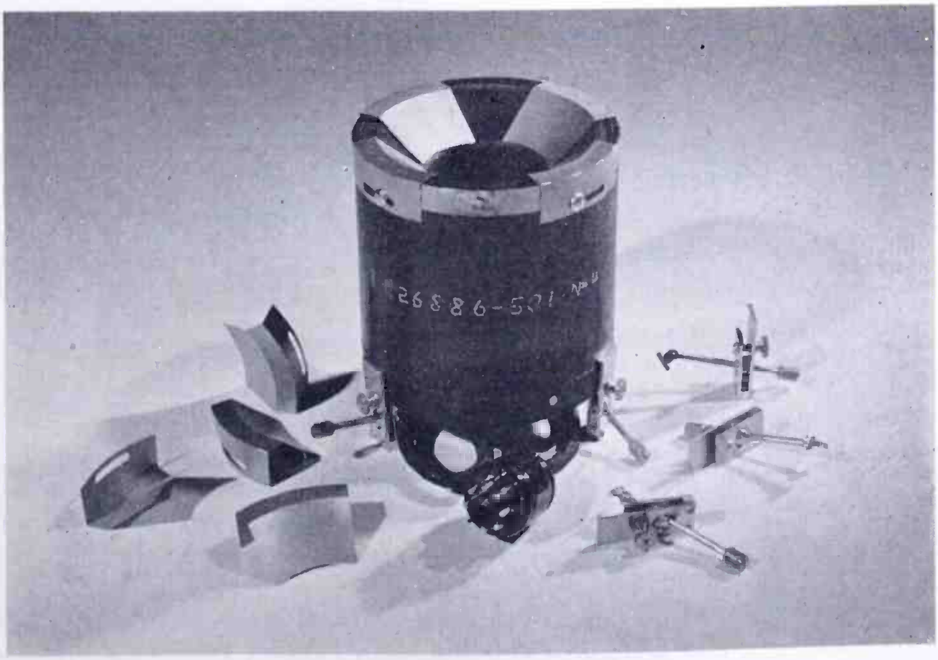


Fig. 5—Section-wound yoke for 45-degree deflection, complete with compensating trimming tabs and beam-alignment magnets.

up to produce an electron beam which could be made to sweep around a conic locus with any desired small convergence angle (Figure 6). Means were provided to produce convergence at any desired point near the planar white screen of a deflection-testing kinescope, or near the shadow mask (or aperture mask) of a single-gun dot-phosphor color tube. To cause the beam to first converge quite near the gun in the conic deflection region, a 5TP4 gun, utilizing an electrostatic focus element, was used with a supplementary external magnetic focus lens coil of standard design (Figure 6). A simpler gun and a stronger external magnetic lens were used in certain instances. A beam-centering coil or magnet was also provided for magnetic centering of the beam as it issued from the gun.

The centered and focused beam was passed through a set of coils which produced a rotating magnetic field, normal to the axis, in the crossover region of the beam. Either a standard deflection yoke or a special set of coils may be used to radially deviate and rotate the electron beam around the central axis. For most of these tests a standard production yoke was driven by two phases of 60-cycle power. When necessary, a special set of resonant coils operating at 3.58 megacycles was used.

A magnetic lens was employed to reconverge the beam toward the axis, as shown. This was simply an electromagnetic focus coil, with a large (2⅝-inch inside diameter) opening to make aberration and astigmatism of the effectively large beam negligible, and to allow space for adequate translation and orientation.

An especially long neck was used in this tube to allow for these various devices and the deflection yoke. This structure was combined with a planar white phosphor screen in an envelope (Figure 6) to simulate the deflection geometry of the shadow-mask color kinescopes. Some of the tests were made with actual single-gun shadow-mask color kinescopes. These arrangements produced an electron beam which could be caused to generate a conic surface. This locus could be adjusted to contain any beam which might be used in a shadow-mask tri-color kinescope.

This system was set in operation by the following procedure:

(a) All component elements were placed upon the neck of the tube in computed positions. Each part was visually centered upon the neck and oriented coaxially therewith.

(b) The electron gun was activated at reduced beam current, or with low-duty-cycle pulse keying, to avoid burning of the screen by the stationary beam.

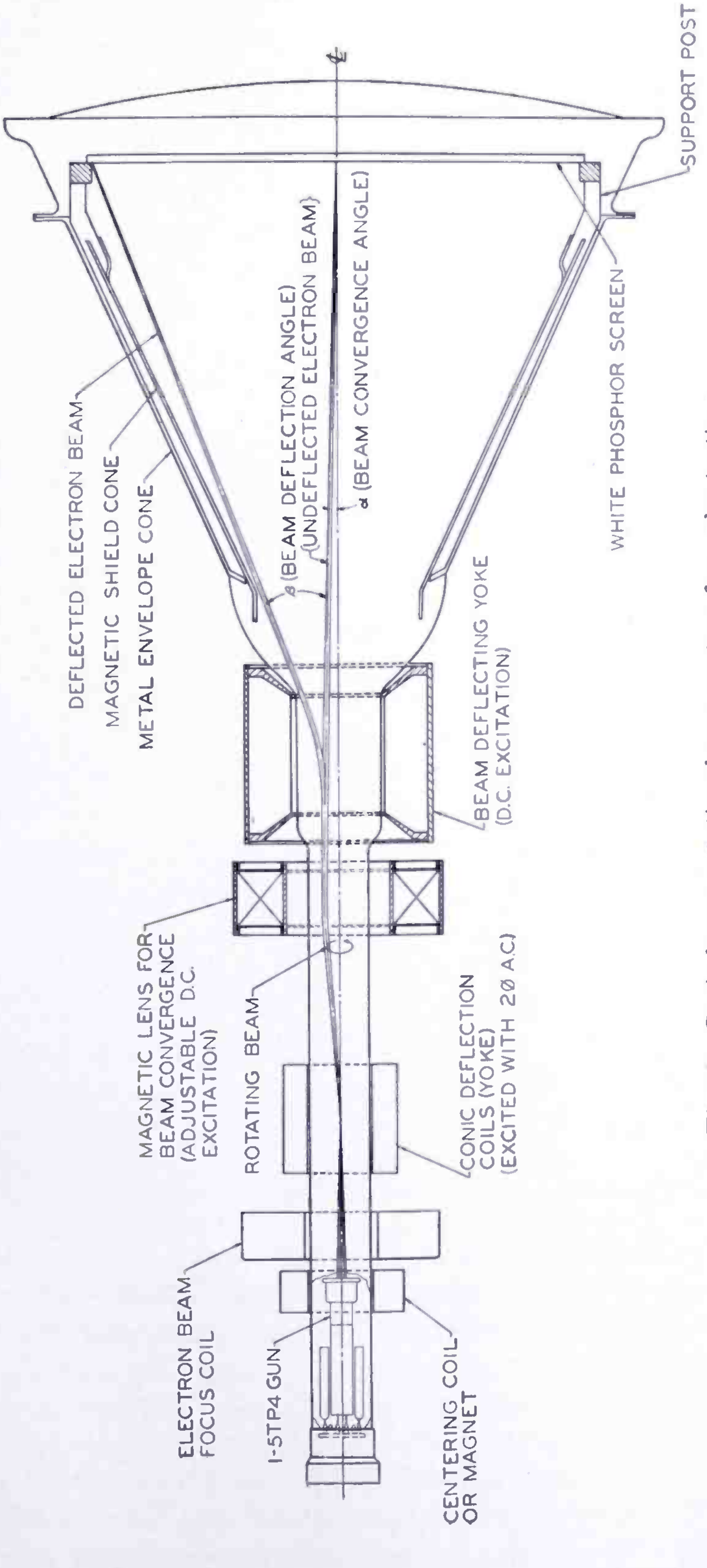


Fig. 6—Conic locus, rotating beam system for yoke testing.

(c) The centering coil or magnet was adjusted to cause the beam to produce a spot at the exact center of the screen.

(d) The focus coil was excited with direct current and oriented to allow the spot to remain at the center of the screen.

(e) The convergence coil was similarly excited and oriented.

(f) The convergence lens was de-energized, and the conic-deflection coils were excited. The excitation currents and their phasing were adjusted to produce a true circular trace of the required diameter (perhaps 2 to 4 inches).

(g) The convergence lens was excited again and adjusted to reduce the diameter of the circular trace to perhaps ¼ to ⅛ inch diameter, with the effective convergence point on the axis in front of the screen (under converged). As the convergence angle increased, and the circle became smaller, any coma or lack of symmetry which existed in the lens system caused distortion of the circular trace. Usually a portion of the circle was bent toward the center. This was progressively eliminated by slight transverse adjustments of the convergence lens, if the lens was free from astigmatism. Symmetrical, well annealed, Mu-metal lens shells were used to achieve this condition. Eventually, by repeated adjustments, a small circular spot was obtained at the center of the screen.

The spot could be made practically as small as that produced when only the gun and the focus coil were in operation, *if the gun structure and its alignment in the neck were sufficiently precise,* and if the focus and convergence lenses were positioned correctly. This process also served as a means for evaluation of the electron lenses. When such a small spot was produced, useful deflection tests were possible to evaluate the characteristics of the yoke.

Deflection Yoke Design Modification Procedure

In the process of determining the desirable empirical modifications of yoke design to obtain best convergence (or focus), the preliminary design-sample yokes were mounted in this test system, with means for passing an adjustable amount of direct current through the deflection windings.

The beam was deflected to one corner of the picture area, for instance, by application of a sufficient amount of direct current to each set of deflection coils. If a sufficiently good yoke could be made and tested in this manner, the spot would simply change to a nearly circular ellipse. The beam convergence would then occur in the space behind the plane screen. Such a pattern could be again converged to a small spot by a simple adjustment of the current through the coil of a non-astigmatic convergence lens. Theoretically, an absolutely uniform deflecting field with abrupt boundaries should produce an egg-shaped trace. The long axis should be in a radial direction, with the narrower end of the trace outward.

Tests show that with the very large equivalent beam diameter used in the shadow-mask dot-screen kinescope, usual production types of deflection yokes for black-and-white television exhibit very distorted beam patterns at the larger angle of deflection (40 to 70 degrees, total angle). These are effectively greatly magnified images of the smaller

(a)

(b)

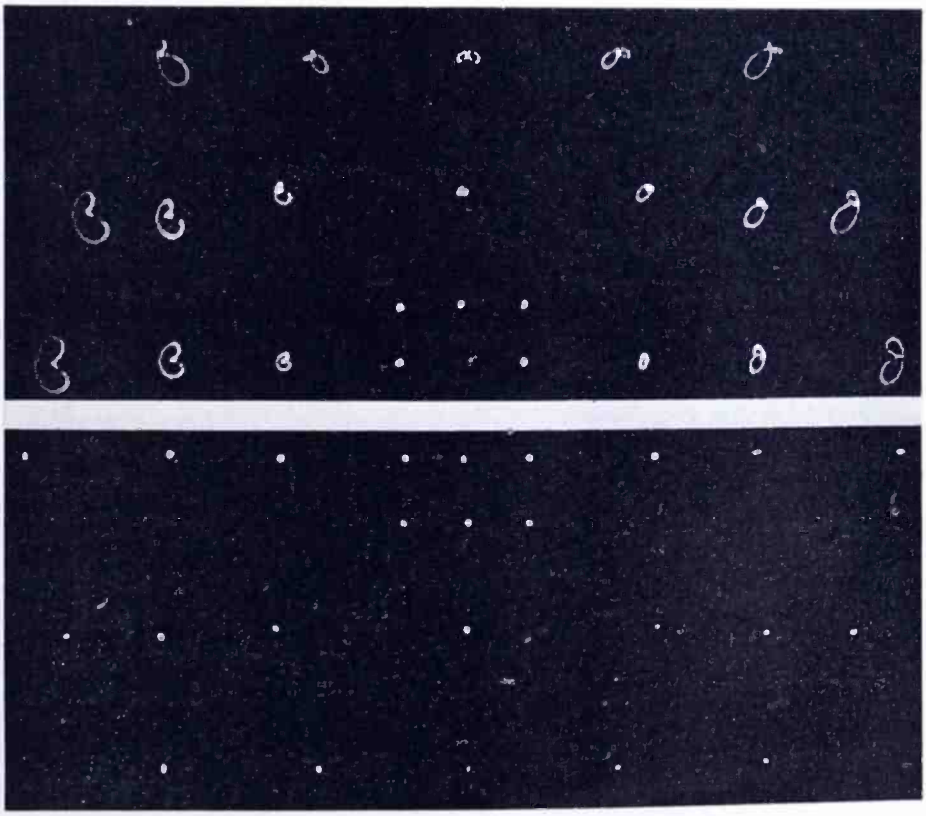
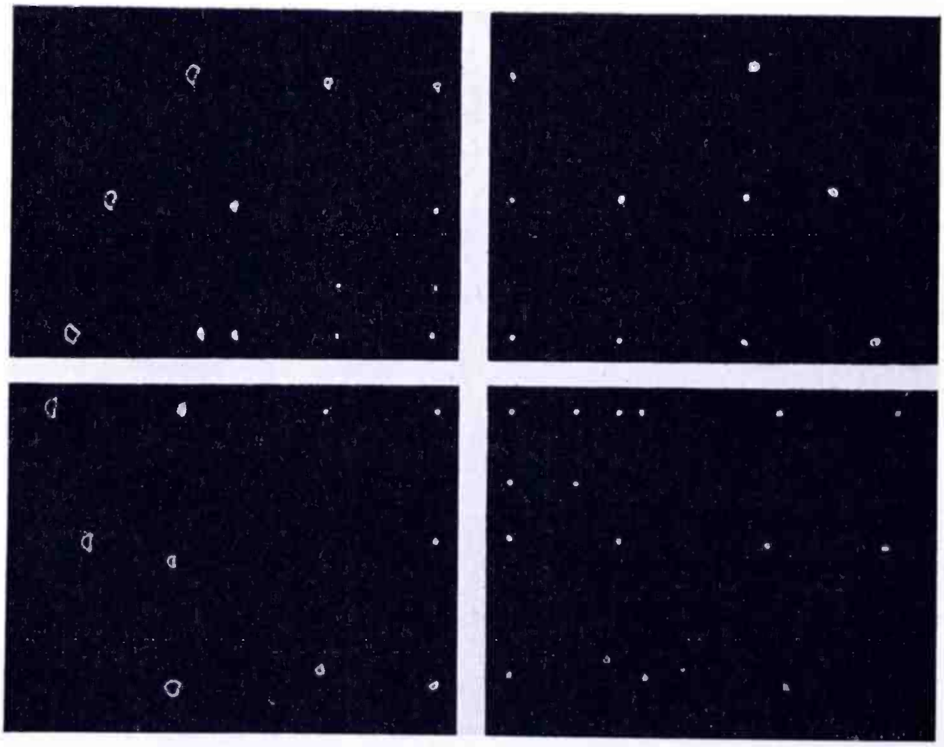


Fig. 7—Spot patterns using an antipincushion yoke, 45-degree maximum deflection angle. (a) Upper half of raster area with large conic beam locus. (b) Lower half of raster area with small electron beam.

defocusing effects observed with a thin beam. They are characterized by the distorted patterns of Figure 7a, which were made with a total angle of 45 degrees and a conic-beam-locus-convergence angle of $\alpha = 1°14'$, while using a yoke designed to produce an accurately rectangular picture raster (antipincushion) for use with the line screen color kinescope. The pattern of focus obtained with a single small electron beam is shown in Figure 7b. In comparison, the yoke of Figure 5, which was designed especially to obtain best convergence in the shadow-mask dot-screen kinescope, produced the simpler and more symmetrical patterns which characterize a yoke with an almost uniform magnetic field throughout its central transverse plane. The raster-quadrant photographs of Figure 8 were taken with this yoke while using the same conic locus of electron beams used in the test of Figure 7a. The center dot of each quadrant pattern is placed nearest the center of the entire figure. For Figure 8a, optimum convergence was produced at the center only. With the same yoke, the convergence patterns of Figure 8b were photographed with simulated dynamic convergence. This was done by adjustment of the beam convergence lens to maintain best convergence as the beams were deflected away from the central axis.

(a) (b)



(c) (d)

Fig. 8—Spot patterns using section-wound improved convergence yoke of Figure 5, 45-degree maximum deflection angle. (a) Upper left quadrant with convergence correction at center only, no tabs. (b) Upper right quadrant with best convergence correction at each spot position, no tabs. (c) Lower left quadrant, convergence correction at center only, 12 compensating tabs adjusted. (d) Lower right quadrant, with best convergence correction at each position, 12 tabs adjusted (final result).

During the empirical modification steps of the yoke design process, a yoke with taps brought out at four or five points on each winding was arranged for independent variation of the currents in the several coil sections. Such variation produced the best possible convergence of the beams throughout the entire area of the raster. Measurements of the coil-section resistances and voltage drops led to computations of ampere-turns products per section which could be used to obtain design modification values.

The turned-up ends of the coils produce oppositely directed axial and other stray fields within the region of the neck-to-funnel junction of the kinescope. The former may be compensated for by the addition to the system of an astigmatic lens excited by especially shaped waves of horizontal and vertical frequency. It is much simpler, however, to use movable compensating tabs of ferromagnetic material, or perhaps of highly conductive nonmagnetic material, to attain the desired trimming of the residual convergence errors. The four tabs of thin ferromagnetic nickel-iron alloy (Figure 5), upon the front cone of the yoke, were added to provide some shielding of the widely-deflected electron beams from the large magnetic field gradients produced by the ends of the windings, and to allow experimental manipulation of the fields in that region.

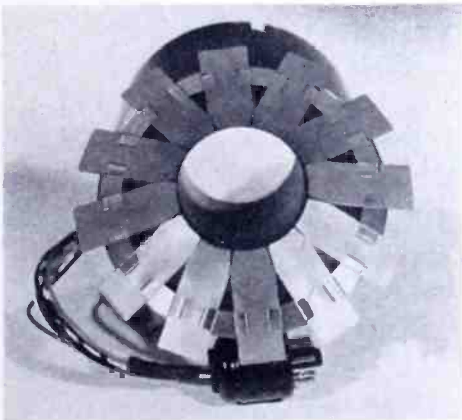


Fig. 9—Array of 12 compensating tabs on section-wound yoke of Figure 5, approximately as used for test of Figures 8c and 8d.

In a more flexible version of the compensating tabs (Figure 9), up to twelve strips of thin metal sheet material may be inserted into the holding clips, which allow freedom of movement by sliding in the radial direction or pivoting about the clip mounting screws. When these ferromagnetic "field-compensating tabs" were added to modify the fields at the front of the yoke, the more nearly circular trace patterns of Figure 8c were obtained with no correction of the convergence angle. The addition of beam-convergence correction as a function of the radial deflection angle improved the convergence to the final result for the yoke of Figure 5, as shown by the spot pattern of Figure 8d. The convergence angle was 1°14′ to correspond with that in use in developmental aperture-mask tri-color kinescopes.[14] In these yokes the trans-

[14] B. E. Barnes and R. D. Faulkner, "Mechanical Design of Aperture-Mask Tri-Color Kinescope", *Proc. I.R.E.*, Vol. 39, pp. 1241-1245, October, 1951.

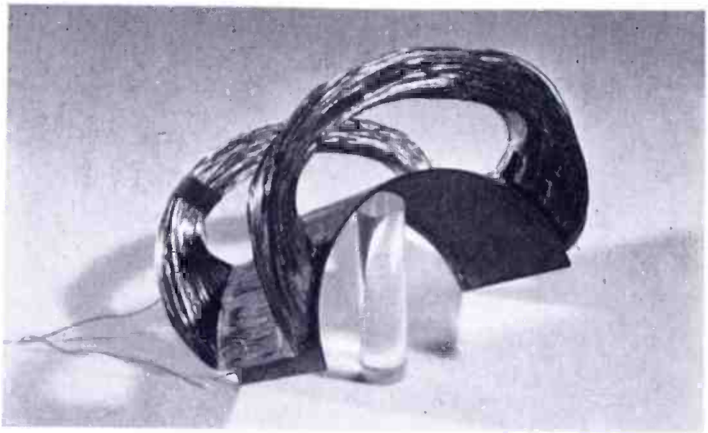


Fig. 10—Sectional-wound yoke coil with elevated turn-ends.

verse magnetic fields were found to be quite uniform when they were measured by means of a very small exploring coil placed within the yoke. The maximum deviation from the assumed state of uniform direction flux across the central transverse plane of the yoke was less than three degrees at the outer boundary of the deflecting space.

Originally, when these tabs were installed on the early model yokes, the use and adjustment of the entire complement of twelve tabs was required in order to produce acceptable convergence of the beams near the edges of the picture. It was decided to lift the ends of the turns radially, however, away from the deflected beams (Figure 10). This reduced from twelve to only four the number of tabs required to obtain best convergence of the beams at the picture edges. The remaining tabs required only partial insertion when they were correctly oriented. This very desirable change not only reduced the number of adjustments, but reduced the loss of deflection power as well and also allowed the

Fig. 11—At left is the unmounted 45-degree multibeam deflection yoke, adapted for machine winding and die forming. The completed yoke, in its case, is shown with four compensating tabs in their approximate operating arrangement, at right.

approximate plane of deflection to occur somewhat farther forward, thus minimizing "neck-shadow" trouble.

The windings of the yoke of Figure 11, were produced through the cooperation of M. J. Obert* and J. K. Kratz.* The object was to provide a design adaptable to machine winding while retaining the desirable features of the previous yokes. In this yoke, the effect of the lifted coil ends was simulated in the horizontal deflection coils by elevating the major portion of the turns of the windings and allowing only the very thin inside edges of the windings to fill the ends of the coil windows. The vertical deflection coils were made with all the turn ends elevated. The horizontal and vertical coils were interlocked so that the magnetic core diameter was reduced and the inside diameter of the yoke increased simultaneously. The decreased core diameter increased the deflection sensitivity, and, at the same time, the decreased radial thickness of the coils produced a larger inside diameter which allowed greater tolerance of movement of the yoke about the neck of the tube. The complete yoke in its bakelite case is also shown in Figure 11. Four of the convergence tabs are attached to the case by the clips, as shown, in approximately their normal operating position.

Even without the compensating tabs, this improved yoke produced a much superior convergence pattern (Figure 12b). When the *four* tabs were added, the final convergence pattern of Figure 12d was achieved. These patterns may be compared with those of Figures 12a and 12b, which were photographed without an equivalent dynamic convergence signal, without and with tabs, respectively. Again, in each case, the nominal convergence angle $\alpha = 1^\circ 14'$ corresponded with that in use in developmental aperture-mask tri-color kinescopes.[14]

A simpler compensating-tab mount and coil cover (Figure 13) was mounted upon a deflection yoke for a 65-degree deflection model of the shadow-mask dot-phosphor color kinescope. This mounting unit was moulded of polyethylene with a thin inner portion to allow the yoke windings to be moved to within 0.020 inch of the tube funnel, when necessary. This light, injection-moulded part provides simple, low-cost, mechanical and electrical separation between the coils and the tabs, and its smooth surface permits easy adjustment of the tabs. The slots which are visible in Figure 14 allow ventilation and provide flexible fingers to tuck under the combination clamp and terminal board to hold the tab mount in place. The four tabs shown in Figure 13 are in approximately their normal positions as they might appear on the left and right sides of the kinescope. Rotation after adjustment is prevented by tightening the nuts with a socket wrench. The raster-

* RCA Victor Division, Harrison, N. J.
[14] Barnes and Faulkner, *loc. cit.*

(a) (b) (c) (d)

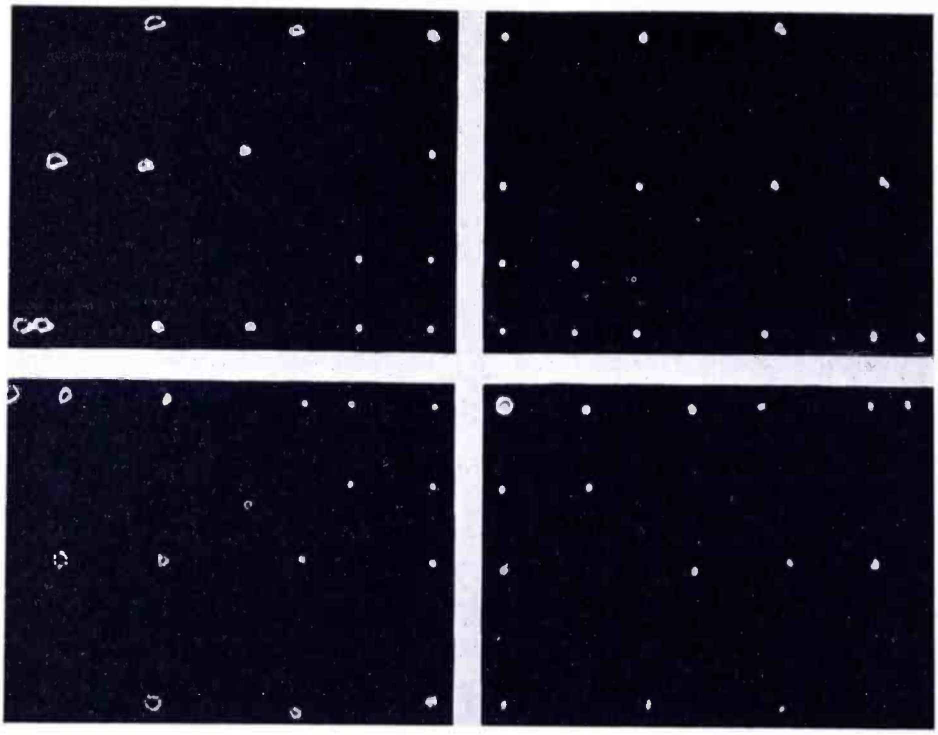


Fig. 12—Spot patterns using formed-winding yoke of Figure 11, with 45-degree maximum deflection angle. (The circle around the axial dot in 12d indicates the required dynamic convergence amplitude.) (a) Upper left quadrant, convergence correction at center only, no tabs. (b) Upper right quadrant, best convergence correction at each spot position, no tabs. (c) Lower left quadrant, convergence correction at center only, 4 compensating tabs adjusted. (d) Lower right quadrant, best convergence correction at each position, 4 tabs adjusted (final result).

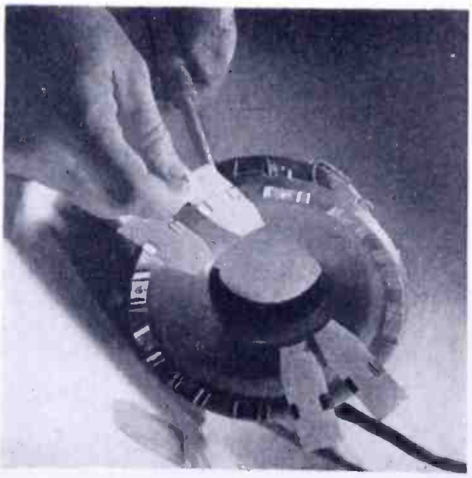


Fig. 13—Front view of 65-degree multibeam deflection yoke adapted for machine winding and die forming. Four compensating tabs are shown in place on moulded polyethylene mounting cover.

quadrant convergence patterns for this yoke with 65-degree deflection are shown in Figure 15. The final results in Figure 15d are as good or better than those of the earlier yokes, in spite of the increased deflection angle.

It was possible to eliminate the compensating tabs by modifying the ferrite or powdered iron ring-core structure of the deflection yoke so that it was segmented and adjustable, but the tabs are preferable for simplicity and better performance. The best experimental models of yokes previously described for application to the triple-gun shadow-mask color kinescope have been found to produce an essentially uniform magnetic field in the deflection space, but with a slightly higher flux density near the periphery. When these yokes are used with adjustable-segment cores, best adjustment is attained with the core segments pulled radially outward in the region near the four corners of the raster. The final result is a somewhat pincushioned raster, but this effect can be corrected by other means.

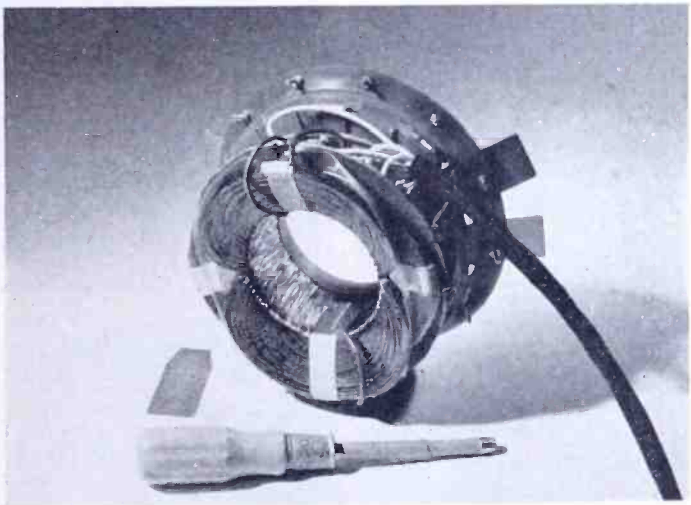


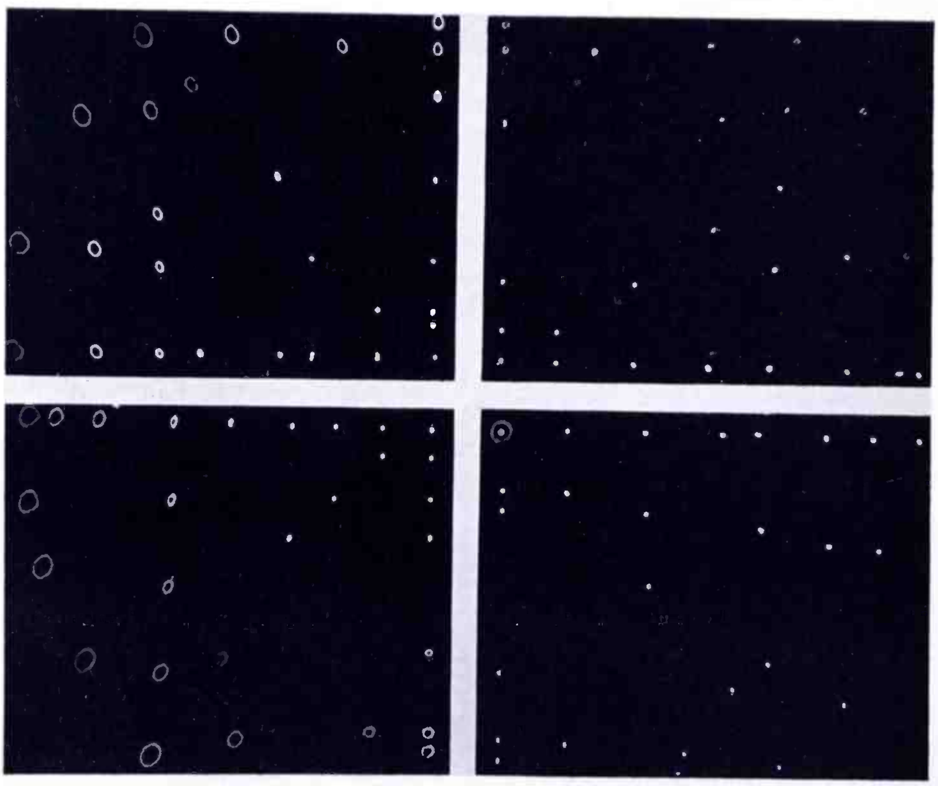
Fig. 14—Rear view of 65-degree deflection yoke of Figure 13, showing tab-clip tightening nuts and mounting of front cover fingers under core clamps.

The present results have been achieved by a practical combination of theory and experiment. The number of variables is sufficient so that perhaps a number of similar solutions may be available. However, the requirement that a number of somewhat separated electron beams behave in a very similar manner makes it expedient to begin the analysis with the uniform field theory and to begin the experimental work under essentially the same conditions. Well chosen minor adjustments and, *above all*, precise construction and assembly of the kinescope and the associated adjustment and deflection components, are the factors which lead to a useful final result.

Simplified Geometry of Deflection of Multiple Convergence Electron Beams

The convergent electron beams of the conic locus (Figure 1) must be bent in unison to scan the surface of a plane phosphor screen in a television raster. A simple deflection field, e.g., a uniform magnetic field, causes a serious geometric distortion of the locus, producing an elongated and complex convergence region rather than a simple convergence point. A portion of this geometric effect is the movement of the convergence region backward from the plane screen so that its

(a) (b)



(c) (d)

Fig. 15—Spot patterns using formed-winding yoke of Figures 13 and 14, with 65-degree maximum deflection angle. (The circle around the axial dot in 12d indicates the required dynamic convergence amplitude.) (a) Upper left quadrant, best convergence correction at center only, no tabs. (b) Upper right quadrant, best convergence correction at each spot position, no tabs. (c) Lower left quadrant, best convergence correction at center only, 12 compensating tabs adjusted. (d) Lower right quadrant, best convergence correction at each position, 12 tabs adjusted (final result).

distance from the approximate deflection plane is proportional to the cosine of the deflection angle (Figure 16). A simple planar surface, at which all beams are deflected through an angle β_0, is to be assumed normal to the central axis for the preliminary considerations. In this instance, two opposite beams in the conic locus have been assumed, for convenience of illustration, by taking an axial section through the locus and deflecting it normal to the plane of the section. The deflected central axis is also shown for reference. The convergence point Q_B traces a simple circular arc so that the axial distance X_{QB}, from the plane of deflection to the beam convergence point, Q, varies in proportion to the cosine of the angle of deflection, β_0, as measured from the central axis. The ratio of X_{QB} to the axial convergence distance X_P, between the plane of deflection and the aperture mask, is

$$\frac{X_{QB}}{X_P} = \cos\beta_0. \tag{1}$$

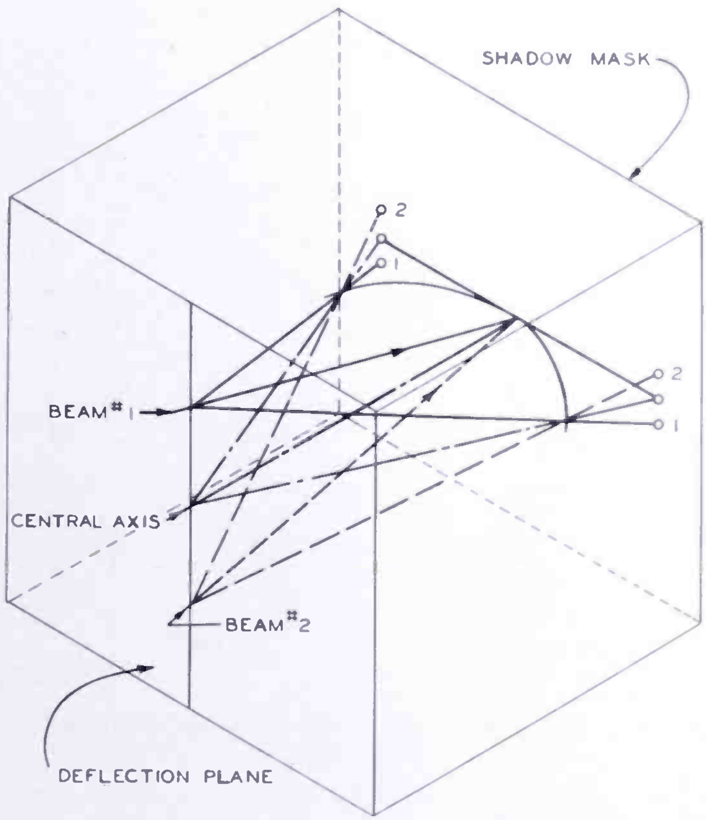


Fig. 16—Deflection normal to plane of beam convergence.

This phase of the problem treats deflection normal to a plane B in which these beams lie. The deflected central axis lies in a plane A which passes through the central axis normal to plane B. The assumed opposing electron beams of the conic locus always converge at the same point on the deflected axis, in plane A. This point is deflected in a circular arc.

Figure 17 is introduced to initiate a study of the problem of convergence of a second pair of assumed oppositely converging beams which lie in plane A. Again, the figure is greatly simplified by the assumption of the equal, abrupt bending through an angle β_0 of each beam which passes through the assumed plane of deflection. Each beam crosses the deflected central axis at a different point, Q_{A01} and Q_{A02}, and they converge at a third point Q_{A12}, further from the undeflected axis. The ratio of X_{QA} (the axial distance from the plane of deflection to the intersection of each beam with the deflection axis) to X_p (the axial distance from the plane of deflection to the center of the aperture mask) is

$$\frac{X_{QA}}{X_p} = \frac{1}{2} [1 + \cos(\alpha + 2\beta_0)], \quad (2)$$

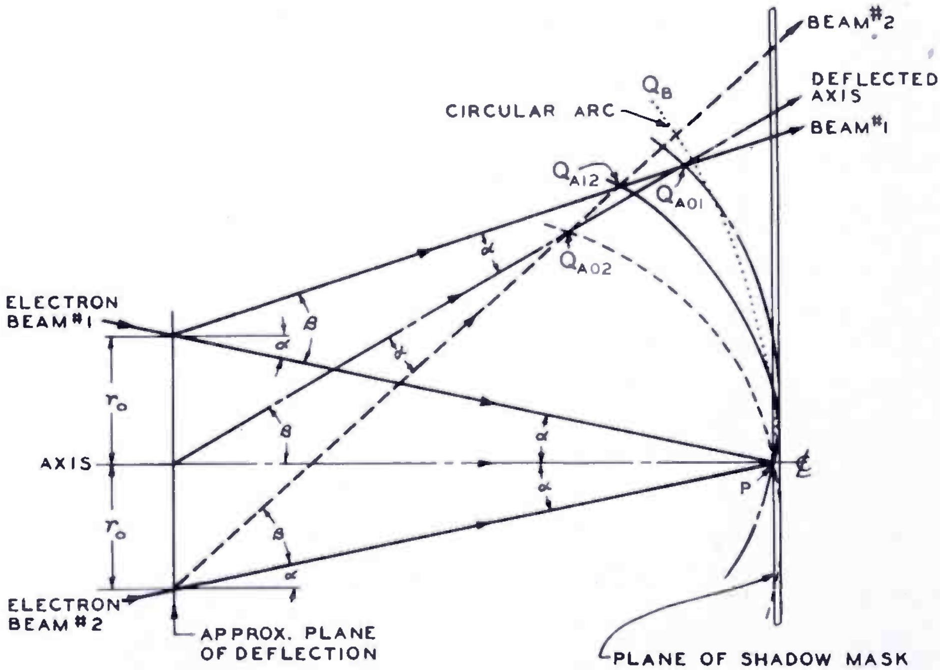


Fig. 17—Simplified geometry of multibeam deflection system.

where α is the angle of convergence of the beams of the conic locus toward the central axis.

Plots of X_{QB}/X_p and X_{QA}/X_p from Equations (1) and (2) are shown in Figure 18. In this case, $\alpha = 1°00'$, and the angle of off-axis deflection β_0 is the variable. The axial distance X_{QA}, from the deflection plane to the point of convergence of each beam with the deflected axis, decreases at a much more rapid rates with increase of β_0 than does X_{QB}. When $\beta_0 < 10°$, the difference is relatively small. It is obvious, however, that for practical maximum values of β_0, such as 20 to 35 degrees, a correction must be made to produce a useful convergence of the beams.

Plane A, in which deflection of the axis always occurs, was chosen as a radial plane through the central axis. Plane B was assumed to be also through the central axis of the locus of beams, but normal to plane A. If a full conic locus of electron beams which converge at an angle $\alpha = 1°14'$, was deflected at an angle of $\beta_0 = 32.5°$ from the axis to a point six inches from the center of a plane screen, the magnified trace which would occur due to the overconverged beams, is shown in Figure 19. The major axis of the egg-shaped trace lies along the radial line from the center of the screen, extending outward farthest from the deflected axis position (0, 0) in the radial direction. This pattern

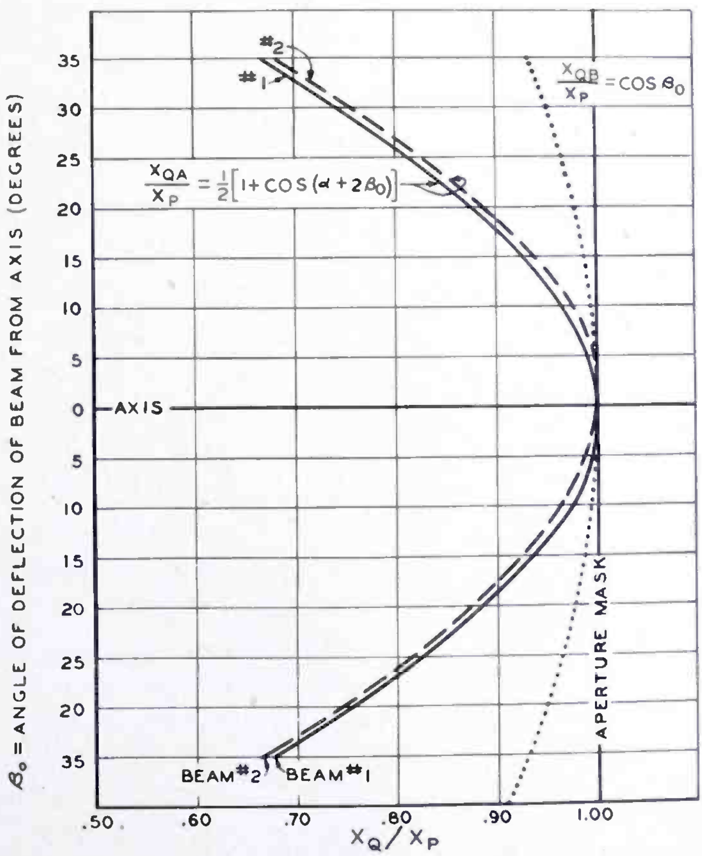


Fig. 18—Fractional distance to convergence point (Q) as a function of deflection angle (β_0), $\alpha = \pm 1°$.

was computed under the assumption of a uniform magnetic field, which yields a constant finite radius of beam curvature within an equivalent deflecting space bounded by two infinite planes normal to the axis, with a separate distance Y, the equivalent yoke length. The patterns obtained with the experimental yokes were somewhat flattened on the side nearest the axis and distorted as shown in Figure 8a, due to the edge effects in the actual field.

This analysis indicates that the axial distance between the geometrical center plane of the deflection yoke, normal to the axis, and the instantaneous apparent center of beam deflection is very closely approximated by relation

$$g_0 = \frac{Y}{2} \tan^2 \frac{\beta_0}{2}, \tag{3}$$

where Y is the effective length of the yoke, and β_0 is the angle of deflection from the undeflected position of the beam. It is found, for instance, that for a 70-degree deflection angle ($\beta_0 = 35°$), $g_0 = .049$ inch. Thus it is evident that the "plane" of deflection is actually a *curved* surface of deflection, which is the locus of the apparent center

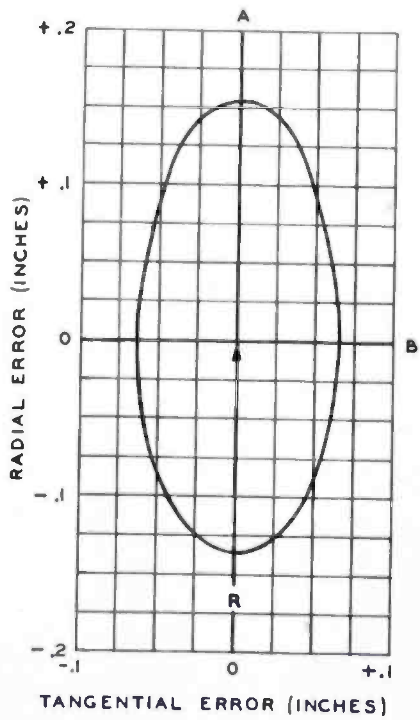


Fig. 19—Computed beam-convergence error pattern plot (32.5 degrees off axis on 12-inch screen).

of deflection. This and numerous other higher-order effects contribute to the microgeometry of deflection and convergence of multiple electron beams.

Dynamic Convergence Procedures

An improved state of convergence at the plane aperture mask can be attained by dynamic modulation of the convergence angle α of the conic locus of the electron beams by alternating-current excitation of the beam convergence lens, by modulation of the single-beam rotation amplitude, or by dynamic modification of each of the angles of convergence α of the individual beams with respect to the central axis, in accordance with functions of the angle of beam deflection β_0 from the axis.

As a first approximation it is possible to produce a symmetrical decrease of the convergence angle of the converging beam locus which enters the deflection yoke as an function of the angle β_0. For best results, this function must be such that the values of X_Q/X_P are intermediate between those of Equations (1) and (2).

A symmetrical lens of either the magnetic or electrostatic type may be used to produce the desired variation in beam convergence. During the deflection yoke tests, with adjustable direct-current deflection, the change in convergence was readily produced by a simple change in the current which passed through the coil in the beam convergence lens (Figure 6).

During actual scanning of a television raster, the convergence angle α must be modulated at a rapid rate by a combination of signal components synchronized and correctly phased with the saw-tooth waves of horizontal and vertical deflection current. A separate dynamic convergence lens coil was added to accommodate the signals of scanning frequency and their first several harmonics, when dynamic convergence was used with the single-gun shadow-mask dot-screen color kinescope.[11] For optimum results this lens should be made with two separate elements of opposite sense. This avoids the rotational effect introduced by a single magnetic lens, which causes a slight twist in the beam orientation.

The same magnetic lens system may be used with a three-gun dot-screen color kinescope. The tubes of this type demonstrated in 1950 were made with an internal, electrostatic, beam-convergence lens, so that the electron beams issuing from their parallel-axis guns could be bent toward the central axis to converge at the aperture mask. This afforded a simple means for applying the required dynamic convergence as a voltage signal added to the 9 to 10 kilovolt direct-current potential of the convergence anode.

It was found that a parabolic voltage wave applied across the elements of the convergence lens produced an acceptable approximation of the desired compromise dynamic convergence signal. Such a wave may be produced quite readily by integrating a saw-tooth wave from the deflecting circuits. Unbalance conditions, which may arise from manufacturing tolerances in the tube and its accessories, may be corrected by simply adding to the parabolic waves appropriate amounts of the original saw-tooth wave or its inverted counterpart. These

[11] R. R. Law, *loc. cit.*

parabolic and saw-tooth signals are required at both the horizontal and vertical scanning frequencies.

The schematic diagram of Figure 20 indicates one arrangement which has been used for deriving these signals from common types of horizontal and vertical deflection circuits. The saw-tooth input signals to the horizontal and vertical deflection output tubes are of the correct relative phase and shape for adaptation to produce the required dynamic convergence. In both the horizontal and vertical dynamic convergence channels an inverter stage is used in combination with an attenuator to provide saw-tooth signals of variable amplitude and of *either* relative polarity.

In the channel which operates at the horizontal deflection frequency (15,750 cycles) a portion of the saw-tooth input signal is passed through a single integrating RC circuit and then amplified after combination with the modified saw-tooth signal of similar frequency. The output of these signals from the amplifier is coupled, via a suitable voltage-increasing transformer, to the convergence anode of the kinescope. Approximately 1200 volts peak-to-peak signal is provided from this circuit, of which perhaps 900 to 1100 volts may be required for present tubes.

Since a voltage step-up output transformer, correctly designed to minimize distortion of the low-frequency vertical deflection dynamic convergence signals is much too heavy and expensive, a considerably smaller differentiating transformer is used. In order to counteract this differentiation, the signal of the vertical saw-tooth channel is integrated once and the vertical parabola signal is integrated twice. Later, each is amplified by an additional amount to compensate for the considerable loss of amplitude in the integrating circuits. The same effect may be attained by an integrating feed-back amplifier. The output from this vertical convergence transformer should be approximately 1000 volts, maximum peak to peak, of which about 700 to 900 volts is generally adequate. Similar performance has been obtained by use of a high-voltage resistance-coupled output amplifier, with no output transformer. The output of both the vertical and the horizontal dynamic convergence signals are added together and to the necessary direct-current component required by the second (convergence) anode of the shadow-mask color kinescope.

When dynamic convergence is produced by magnetic lenses, the output transformers may be modified or eliminated, and the output signal currents simply passed through one or more magnetic lens coils. This system has been used in tests of tri-color kinescopes with both the three-gun three-beam array and with the single-gun rotating beam.

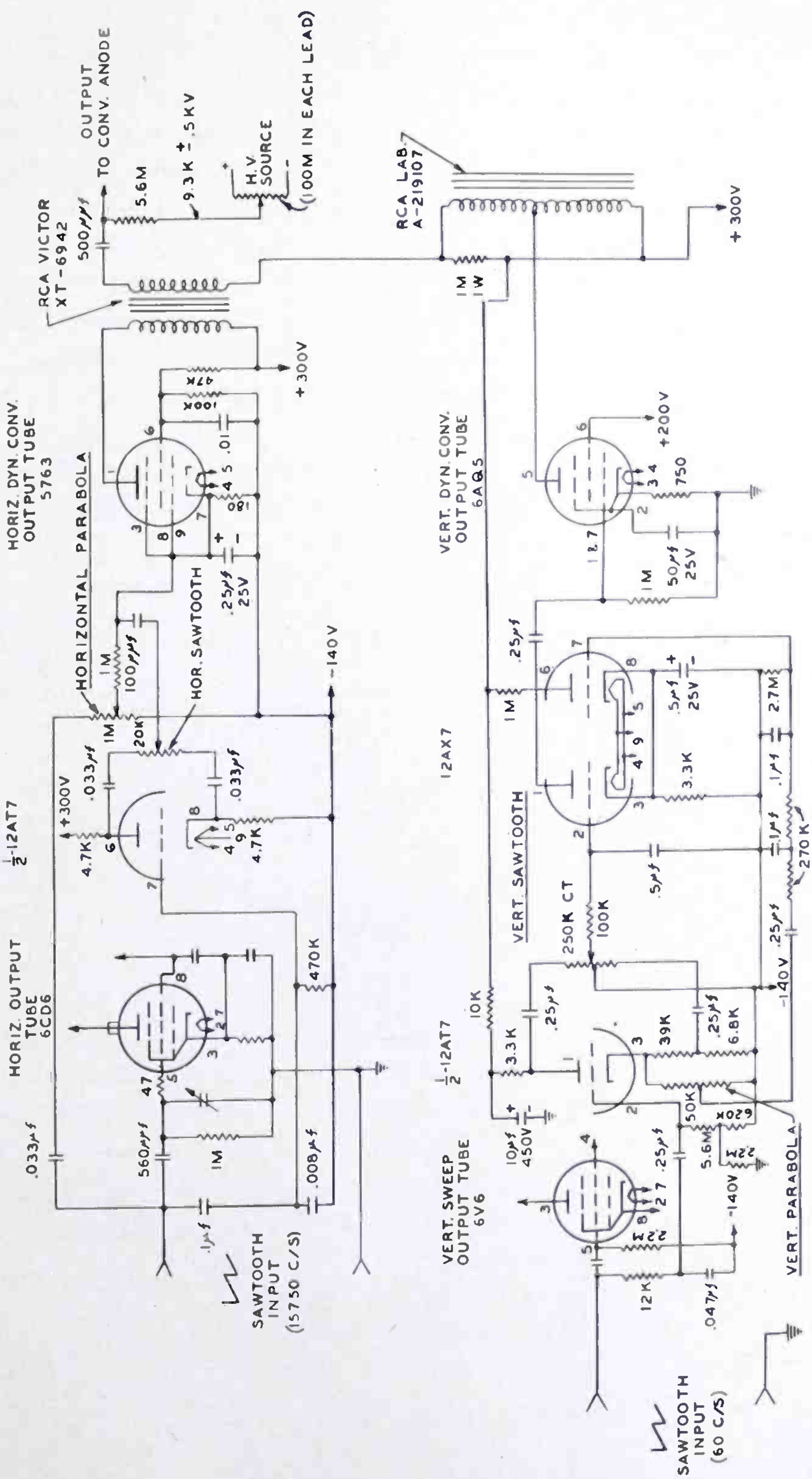


Fig. 20—Dynamic convergence system for three-gun shadow-mask color kinescope.

In the three-gun kinescope the magnetic lenses are most useful when each of the guns is aimed mechanically in a manner which does not quite converge the undeflected electron beams at the center of the aperture mask, so that convergence is produced at the maximum deflection angle. Both the convergence anode and its required high (10 kilovolts) direct-current potential supply may thus be eliminated. A similar gun arrangement was used in the original tubes built by H. B. Law.[12]

It is noteworthy that, at the expense of additional complication, it is possible to apply crossed horizontal and vertical astigmatic convergence lenses to produce a somewhat more accurate dynamic convergence. This is done by taking into account the differences between the convergence error effects illustrated by Equations (1) and (2) and the plots of Figure 17. For instance, if a locus of beams is deflected solely in a horizontal direction, as the vertical deflection passes through zero, the radial deflection vector is horizontal. Figure 17 shows that the degree of overconvergence in the radial deflection direction is greater than in the tangential (vertical) direction, but a symmetrical lens produces the same correction in both directions. An astigmatic lens may be used to compensate for this difference by producing less correction in the vertical direction. Thus an equivalent spherical and cylindrical lens combination is required to be excited at only the horizontal scanning frequency. Similarly, a like lens oriented about the axis at right angles is needed to produce the correction for vertical deflection of the beams. The two combine their actions as required for their respective components when both horizontal and vertical deflection are simultaneously present.

In a possible *magnetic* lens system for this purpose (Figure 21), the two elongated coils are made to approximate the desired relative corrections in the two directions. Two of these dual-coil units may be used to attain the most precise results. They may be connected in opposing sense to cancel their beam-rotation effects. If desired, such coils may be provided with a housing which acts as an external ferromagnetic return path. Materials such as ferrite or moulded powdered iron may be used to reduce the required driving power. Alternatively, the coils may remain circular and ferromagnetic adjustment elements may be provided to modify the lens to introduce the desired astigmatism.

It is apparent from Figure 19, that even the double-astigmatic dynamic convergence correction (magnetic or electrostatic) is not complete because of the small residual differences of deflection which occur between oppositely converging electron beams or their components in plane *A*. Absolute convergence upon the deflected central axis in this

[12] H. B. Law, *loc. cit.*

plane requires a differential modulation of the deflection of the opposing beams or components, in addition to the more simple dynamic corrections. Among the simpler procedures for accomplishing both this and the required adjustments for the stray fields from the ends of the deflection yoke windings are various methods of modifying the magnetic paths within and about the yoke. It is also possible to apply individual beam controlling means and their associated circuits.

The voltage waves generated for application to the electrostatic convergence lens may be modified in amplitude and applied to the beam focussing elements of the electron lenses to maintain essentially optimum focus throughout the entire area of the raster. Likewise, similar waves, of greater amplitude, may be applied to the final anode to eliminate pincushion effect caused by scanning upon a plane shadow mask or screen. Similar effects may be produced with magnetic lenses.

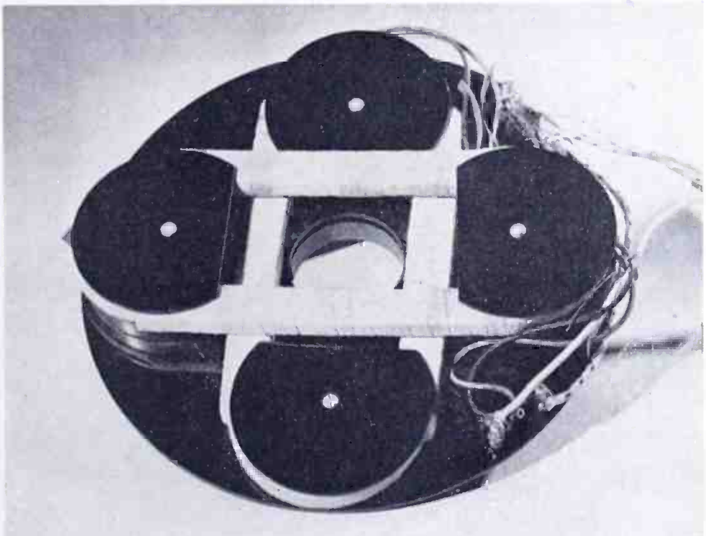


Fig. 21—Double astigmatic magnetic lens assembly for dynamic convergence of electron beams.

Auxiliary Components and Adjustments for Operation of the Three-Gun Shadow-Mask Dot-Phosphor Color Kinescope

A three-gun shadow-mask dot-phosphor color kinescope may contain a triangular array of three parallel electron guns which should project their beams symmetrically into a "convergence anode" cylinder.[13] From this anode space they pass through a convergence lens formed by the opening of the end of the convergence anode cylinder and into the final (accelerating) anode portion of the tube neck, which is provided with a conductive coating on the inside. A direct-current potential of about 10 kilovolts is applied across these convergence lens elements to cause

[13] H. C. Moodey, D. D. Van Ormer, *loc. cit.*

the three beams to converge at the center of the screen. Manufacturing tolerances make it difficult to produce triple-gun assemblies in which the guns are precisely parallel to each other and to the central axis of the tube. A uniform transverse magnetic field produced by a "color purity" coil, may be applied to all the electron beams to orient the *system* of beams as desired. This coil uses either a rotatable yoke-like single pair of coils, or two fixed pairs of coils at right angles, energized by an adjustable direct current. The *individual* beams can also be adjusted separately by use of small permanent beam-alignment magnets. The arrangement is shown on the neck of the three-gun shadow-mask dot-phosphor color kinescope in Figure 22. Another arrangement for

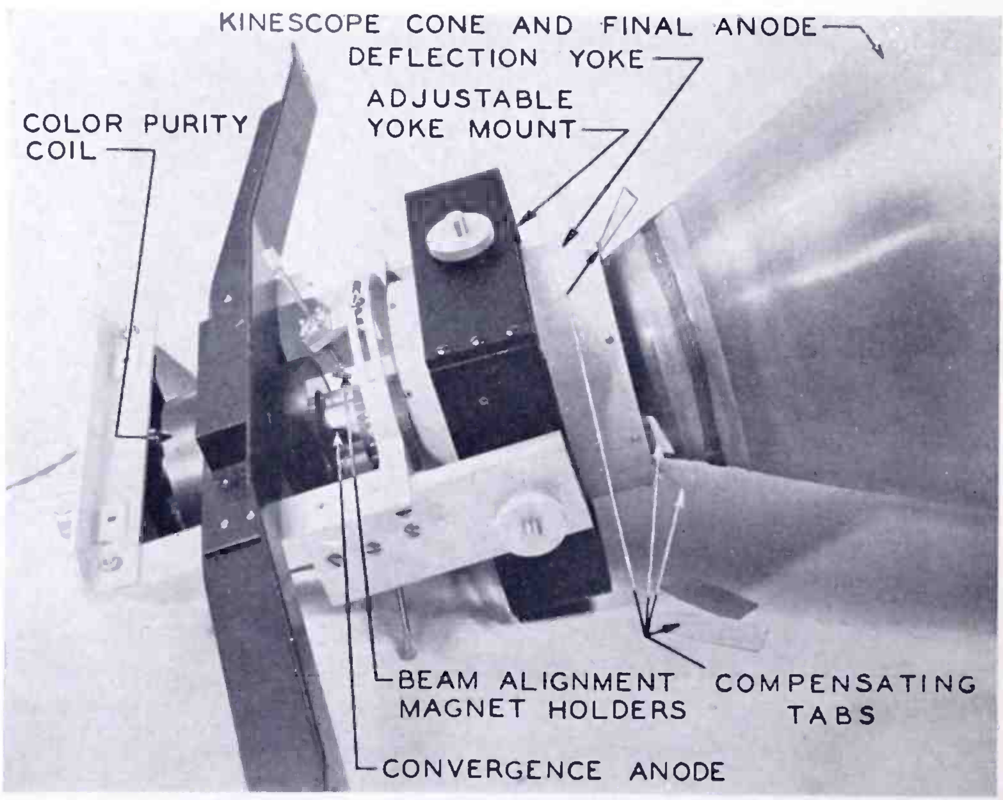


Fig. 22—Assembly of deflection and convergence components on neck of three-gun shadow-mask color kinescope.

mounting the beam alignment magnets at the rear of the deflection yoke is shown in Figure 5. The structure of the swivel-type adjustable mounts is apparent in both photographs.

It may not be sufficient to use the color-purity coil simply to cause the axis of the beam locus to coincide with the central axis of the kinescope. The tolerances of manufacture of the aperture mask and dot-screen assembly may make it desirable that the undeflected axis of the beam system approach them at an angle which differs slightly from ninety degrees, to compensate for very slight relative transverse shifts of these elements. To adjust the approach angle of the beam system for color purity, the direct-current in the transverse magnetic field of the color purity coil, which is in the vicinity of the electron-gun structure, is adjusted to deflect the beams very slightly. The beam axis can then be recentered by the application of a transverse direct-current centering field in the deflection yoke to achieve a slight angle of incidence of the central axis of the beams with the plane of the aperture mask. Rotation of the field and adjustment of the excitation current in the color-purity coil, in combination with adjustments of the centering currents of the deflection yoke, and the axial positioning of the yoke, makes it possible to simulate satisfactorily any required movement of the equivalent array of electron guns.

The correctly oriented array of beams is caused to pass symmetrically through the deflection yoke by adjustment of the transverse position and orientation of the yoke to bring into coincidence the central axes of the yoke and the undeflected system of beams. The final adjustment is made after a test pattern of horizontal and vertical bars has been applied to the shadow-mask color kinescope and after the dynamic convergence signals have been adjusted to produce straight, parallel lines in the red, green, and blue patterns. The yoke orientation adjustments are made to improve further the parallel adjustment of the sets of color bars of the test pattern. Additional adjustments of the small beam-alignment magnets may be made next to produce equally spaced spots of the three colors at the intersections of similarly colored lines so that they fall at the corners of equilateral triangles. When this process is completed, the direct-current convergence control provides means for completing the color-raster convergence to produce essentially white lines, except for possible residual convergence errors, which sometimes occur very near the edges of the raster and which are eliminated by adjustment of the field-compensating tabs.

The compensating tabs of ferromagnetic material are provided at the end of the yoke to assure good convergence, even near the edges of the raster. They are inserted between the uplifted conductors at the forward end of the deflection yoke and the cone (or "funnel") section of the kinescope envelope. The important regions are those nearest the beams as they pass out of the yoke to scan the four corners of the picture, and to a lesser extent those near the regions where they pass to scan the entire left and right edges of the raster. The convergence tabs should be adjusted in both radial insertion depth and orientation about the pivot points of the tab holders.

To prevent effects due to surrounding magnetic fields, such as small residual magnetism of the chrome-steel cone of the kinescope, a cone of Mu-metal, or possibly of 50 per cent nickel-iron alloy, shaped as in Figure 23, is installed *within* the metal cone of each shadow-mask color kinescope. The small end of the shield cone is made to extend backward beyond that of the outer metal envelope cone to attenuate the fields across the small opening, where they might otherwise produce their maximum effect.

YOKE WINDING DESIGN FOR SINGLE-BEAM LINE-SCREEN TUBES

Deflection means for the electron beam of a line-screen color tube, such as that described by Bond, Nicoll and Moore,[10] introduce an entirely different set of requirements. A single, very narrow, electron beam must be deflected quite accurately along a straight line. It is desirable to provide a dynamic focus means, similar to the dynamic convergence apparatus, to assure the smallest possible spot size throughout the raster. In addition, the horizontal scanning lines must

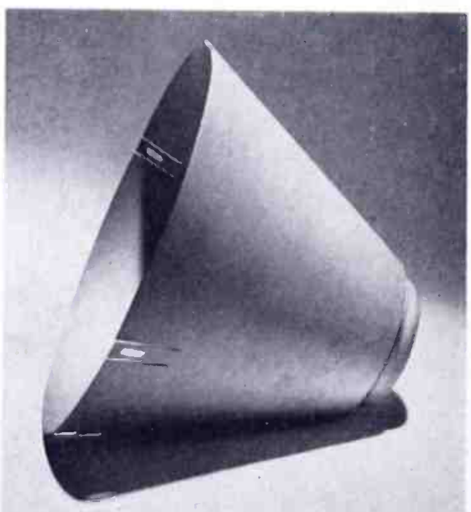


Fig. 23—Internal magnetic shield cone for shadow-mask color kinescope.

be essentially straight. Satisfactory results have been achieved by very precise sectional winding and by experimental modification of the magnetic field distributions of previously developed black-and-white television yokes which have been designed to eliminate pin-cushion effects.[15] O. H. Schade provided valuable assistance in making a number of these tests and in recommendations for modification of the windings. The final turns distribution was adjusted by taps, while the yoke was in operation, in order to provide the straightest possible

[10] Bond, Nicoll and Moore, *loc. cit.*

[15] K. Schlesinger, "Anastigmatic Yoke for Picture Tubes", *Electronics*, Vol. 22, pp. 102-107, October, 1949.

scan lines. The result was a much more concentrated sort of winding than that used for deflection of the shadow-mask dot-screen color kinescope. Electrostatic lenses and external circuit arrangements were used by Bond, Nicoll, and Moore[10] to produce the final corrections. The system of associated circuitry which is required to maintain a precisely uniform deflection rate across the phosphor-line structure is described in detail in the same paper.

A yoke similar to that developed for the shadow-mask tri-color tube might be used with advantage in the future to allow maintenance of optimum focus. The pincushioning of the raster could then be eliminated by means separate from the deflection yoke. This may be done by the appropriate cross modulation and mixing of horizontal and vertically synchronized corrective signals in the deflection yoke, by similarly modulating the potentials of various anode elements of the kinescope, or by extending the application of post-deflection electrostatic lens techniques within the kinescope.

CONCLUSIONS

A group of three closely-spaced, converging, electron beams may be deflected satisfactorily in unison by a single magnetic deflection yoke to excite a dot-phosphor color screen through an aperture mask, as in the tri-color kinescope. In the reproduced color or black-and-white image it is found that the accuracy of beam convergence at the maximum radius of deflection may be readily held to within less than one half of one per cent of the raster height. Closer tolerances are attainable, but with more difficulty. Very careful design and precise construction of the deflection yoke are required to produce equivalent deflections of the different beams. There should also be means for producing slight adjustments of the magnetic fields near the front of the yoke to produce minor corrections of convergence near the edges of the picture and to compensate for tolerance errors. Dynamic modulation of the beam convergence angles, or an equivalent process, is essential to compensate for geometrical effects involved in the scanning process. Rather simple means are available for the production of satisfactory wave shapes for the dynamic convergence process from signals already available in the deflecting circuits. The application of similar waves in a dynamic focus system is found also to be applicable for maintenance of the best possible focus over the entire picture raster. Similar waves may be applied to the final anode to counteract any pincushion effect.

The mathematics of the simplified deflection geometry is useful in predicting the design of the required dynamic convergence, focus, and

[10] Bond, Nicoll and Moore, loc. cit.

pincushion control apparatus and their essential operating conditions. It is also applicable to more precise iterative solutions of deflection problems.

A single-gun kinescope with a conically-deflected and reconverged electron beam has proved to be an extremely valuable tool for the adjustment and evaluation of electron lens and beam deflection systems. Since the original draft of this manuscript was prepared, essentially the same experimental methods have been discussed by others.[16]

The line-screen tube poses the problem of the precise scanning of a straight line. In the first approximation, the deflection problem seems less difficult of solution than that for the dot-screen shadow-mask tube. Somewhat more complicated circuitry is required, however, in addition to the yoke, to produce and to maintain the required linearity of deflection. The multibeam deflection yoke may also be used for this purpose to obtain best focus. Pincushioning of the raster must then be corrected by other means.

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In addition to those mentioned in this and the accompanying papers, it is a pleasure to acknowledge the assistance of J. B. Zirker of the RCA Laboratories Division in some of the early work in the mechanical design of test apparatus. T. R. Bashkow, also of the RCA Laboratories Division, has participated actively in the more recent work in the improvement of the dynamic convergence circuits, deflection coils and adjustment procedures.

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[16] D. E. George, R. G. E. Hutter and M. Cooperstein, "The Rotating Beam Method for Investigating Electron Lenses," I. R. E. National Convention, Paper No. 69, March 20, 1951, New York, N. Y., also *Sylvania Technologist*, Vol. 4, No. 2, pp. 41-43, April, 1951.

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