TOTH

VOLUME 25 AUGUST, 1937 NUMBER 8

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PROCEEDINGS

of

The Institute of Radio Engineers

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Institute of Radio Engineers Forthcoming Meetings

PACIFIC COAST MEETING
Spokane, Washington
September 1 and 2, 1937

SEATTLE SECTION
September 24, 1937

WASHINGTON SECTION
September 13, 1937

TOTH

PROCEEDINGS OF

The Institute of Radio Engineers

Volume 25 | August, 1937 | Number 8

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The Institute of Radio Engineers

GENERAL INFORMATION

Institute. The Institute of Radio Engineers was formed in 1912 through the amalgamation of the Society of Wireless Telegraph Engineers and the Wireless Institute. Its headquarters were established in New York City and the membership has grown from less than fifty members at the start to several thousand.

Aims and Objects. The Institute functions solely to advance the theory and practice of radio and allied branches of engineering and of the related arts and sciences, their application to human needs, and the maintenance of a high professional standing among its members. Among the methods of accomplishing this is the publication of papers, discussions, and communications of interest to the membership.

Proceedings. The Proceedings is the official publication of the Institute and in it are published all of the papers, discussions, and communications received from the membership which are accepted for publication by the Board of Editors. Copies are sent without additional charge to all members of the Institute. The subscription price to nonmembers is $10.00 per year, with an additional charge for postage where such is necessary.

Responsibility. It is understood that the statements and opinions given in the Proceedings are views of the individual members to whom they are credited, and are not binding on the membership of the Institute as a whole. Papers submitted to the Institute for publication shall be regarded as no longer confidential.

Manuscripts. All manuscripts should be addressed to the Institute of Radio Engineers, 330 West 42nd Street, New York City. They will be examined by the Papers Committee and the Board of Editors to determine their suitability for publication in the Proceedings. Authors are advised as promptly as possible of the action taken, usually within two or three months. Manuscripts and illustrations will be destroyed immediately after publication of the paper unless the author requests their return. Information on the mechanical form in which manuscripts should be prepared may be obtained by addressing the secretary.

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Proceedings of the Institute of Radio Engineers
Volume 25, Number 8 *August, 1937*

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Applications for transfer or election to the various grades of membership have been received from the persons listed below and have been approved by the Admissions Committee. Members objecting to transfer or election of any of these applicants should communicate with the Secretary on or before August 31, 1937. Final action will be taken on these applications on September 1, 1937.

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	Chicago, 2705 S. Drake Ave.	Hajek, A. F.
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	Maywood, 1619 Washington Blvd.	Taylor, W. P.

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	New York, 4006 Pratt Ave.	Orback, M.
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Wisconsin	Kenosha, 4617–19th Ave.	Kiertscher, H.

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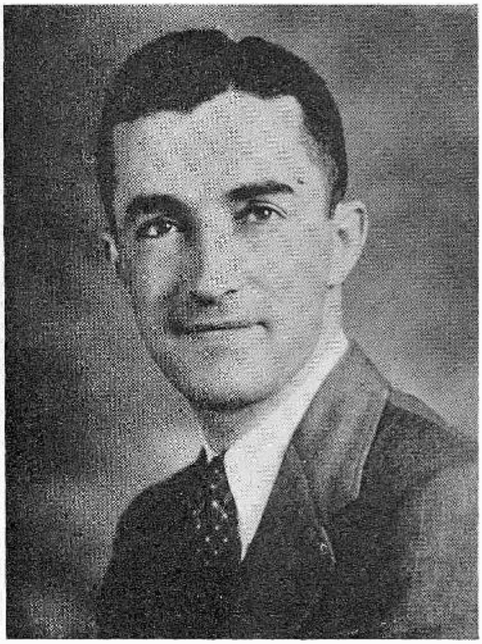

WILLIAM H. DOHERTY

Recipient, Morris Liebmann Memorial Prize, 1937

William H. Doherty was born in Cambridge, Massachusetts, on August 21, 1907. He received a B.S. degree in electrical communication engineering from Harvard in 1927 and a M.S. degree in engineering in 1928. After a few months in 1928 in the Long Lines Department of the American Telephone and Telegraph Company in Boston, he became a research associate of the radio section of the National Bureau of Standards and was assigned to the study of radio wave phenomena. In June, 1929, he joined the radio development department of the Bell Telephone Laboratories where he has since been engaged in the development of high power transmitters in transoceanic radiotelephony and broadcasting. He joined the Institute as an Associate in 1929 and transferred to the Member grade in 1936.

The Morris Liebmann Memorial Prize was voted to him for his improvement in the efficiency of radio-frequency power amplifiers. It was presented to him during the Silver Anniversary banquet of the Institute which was held in the Hotel Pennsylvania on May 12, 1937.

INSTITUTE NEWS AND RADIO NOTES

Pacific Coast Meeting

Through the co-operation of the American Institute of Electrical Engineers, arrangements have been made for a two-day technical session on radio which is being sponsored by our three Pacific Coast sections. The meetings will be held in Spokane, Washington, on September 1 and 2. Institute members have been invited to participate in an all-day trip to the Grand Coulee Dam which the American Institute of Electrical Engineers has arranged for September 3. They are also invited to attend their banquet which will be on the evening of September 1. The summaries of the papers to be presented during the two-day radio meeting are given below. This program is tentative but it is expected that relatively few changes will be made in it.

HIGH-FREQUENCY TRANSMISSION LINE NETWORKS

Andrew Alford
(Mackay Radio and Telegraph Company)

It is sometimes economical to operate a directional transmitting antenna on two frequencies simultaneously. This paper deals with transmission line networks which enable such operation. Both theory and practice are discussed.

ULTRA-SHORT-WAVE PROPAGATION

H. H. Beverage
(RCA Communications, Inc.)

The theoretical laws for ultra-short-wave propagation over unobstructed optical paths are simple and check fairly well with observations. Beyond the horizon, other factors such as diffraction and atmospheric refraction become of importance, but sufficient information for calculating these effects requires further experimental data. Measured values of signal intensity versus distance are shown for several different frequencies which indicate that the attenuation beyond the horizon increases rapidly as the frequency is increased. Sky-wave transmission over long distances sometimes takes place on frequencies up to 45 megacycles or above. The sky-wave transmissions on 41.5 megacycles and 45 megacycles from the London television transmitter have been observed at Riverhead, L.I., N.Y. and the periods of good transmission are found to correlate fairly well with the periods of high critical frequencies of the f_2 layer as measured in Washington by the National Bureau of Standards.

EXPERIENCE WITH THE SHUNT-EXCITED ANTENNA AT KWSC

H. V. Carpenter
(Washington State College)

This paper is a review of the problems experienced with a shunt-excited broadcast antenna and a review of practical results obtained with an actual installation.

NEWLY DEVELOPED LOUD-SPEAKER SYSTEM FOR USE IN SMALL ROOMS

George Downs
(Lansing Manufacturing Company)

This loud-speaker is patterned after the well-known Shearer horn system. It is designed for use in monitor rooms, audition rooms, and for use in the better grade of residential radio or phonograph installations. This loud-speaker is of the "two-way type." It uses a 15-inch cone to cover the audio system up to 800 cycles. Above this point, a new metal diaphragm unit is used. Provision is made for giving uniform frequency response over a large solid angle.

THE USE OF COMPRESSED GAS CONDENSERS IN HIGH POWER TRANSMITTER DESIGN

Noel Eldred
(Heintz and Kaufman)

The requirements for the tank circuit of a high power transmitter are considered. It is shown that the tank circuit capacitance must not be too low if the radiation of spurious harmonics is to be prevented, and that the size depends upon the load on the oscillating circuit and the voltage across it.

The importance of the tank circuit Q as a design factor is considered. Investigation indicates that this Q should be at least fifteen, with values of twenty-five probably more appropriate. Higher values of Q are to be desired, but the upper limit is imposed by the factor of side-band cutting which is a serious consideration in high fidelity broadcasting. Curves are derived to show the amount of this reduction of high-frequency response for various values of Q. Study of the curves of these diametrically opposed conditions readily indicates the point of proper compromise.

Practical tank circuit calculations indicate rather high values of capacitance are required. Methods of obtaining this capacitance are reviewed and their relative merits cited. The compressed nitrogen condenser is found to be ideal from the standpoint of cost, small size, stability, and efficiency.

Two practical physical circuit designs are suggested which combine the tank and neutralization condensers in a simple and effective arrangement. A circuit design is stressed which gives convenience of wiring and conservation of space in high power push-pull broadcast amplifiers.

Use of the compressed gas condenser as an antenna tuning unit is illustrated.

AMPLIFICATION PROBLEMS OF TELEVISION

F. Alton Everest
(Oregon State College)

This paper deals with television amplifier design requirements as they are influenced by the severe wide-band characteristics of television signals. As a background for this discussion of amplifiers and their frequency response, a brief analysis of transient pulses resulting from the scanning of a single line is made. By treating this transient pulse as an aperiodic wave, a Fourier analysis may be made and the frequency components determined. The frequency distribution of a single line scan is not continuous and the possibility of utilization of empty spaces is touched upon.

Methods of attaining the necessary high- and low-frequency amplitude and phase characteristics of both intermediate- and television-frequency amplifiers are shown. Various compensating circuits and calculated curves showing their effect are given.

GRID-CURRENT FLOW AS A FACTOR IN THE DESIGN OF VACUUM TUBE POWER AMPLIFIERS

W. L. Everitt and Karl Spangenberg
(Ohio State University)

In the design of class C amplifiers analytical methods have been proposed which give good results from the standpoint of plate circuit operating conditions. Similar methods have not been available for the determination of grid circuit conditions. It is the purpose of this paper to describe a method by which this result can be obtained.

An analytical determination of grid circuit operating conditions requires a knowledge of grid current as a function of grid and plate voltage. Since good approximations for the space current in a triode are available, an expression for grid current can be had if the ratio of plate-to-grid current as a function of plate and grid voltage can be determined. Theoretical considerations show that the ratio of plate current to grid current should be a function of the ratio of plate voltage to grid voltage. The nature of this functional relation was determined experimentally and a comparatively simple and accurate expression for grid current in cases in which there is only a small amount of secondary emission is thus obtained.

The design procedure for class C amplifiers is based upon the allowable grid and plate dissipation. The method of determining optimum operating conditions on the basis of plate-circuit analysis alone is modified to include the analytical determination of the corresponding grid driving power and grid loss. This procedure results in the determination of the operating conditions which will give the highest output which can be obtained without exceeding the allowable grid or plate dissipation. The design procedure is facilitated by the use of universally applicable functions presented in graphical form. Experimental results are in good agreement with the theory developed.

ELECTRONIC MUSIC FROM ELECTROSTATIC TONE GENERATORS

Raymond C. Fisher
(Tacoma, Washington)

Electronic instruments employing vibrating parts, with electrostatic pickup therefrom, are briefly reviewed. At least one such instrument has attained commercial importance. The discussion proceeds to a second class of instruments, wherein the musical tones originate in variable condensers, whose parts move in rotation or translation. Several inventors have secured patents in this field. Discussion is given of the auxiliary circuits and switching arrangements necessary in conjunction with them for the production of music. The description includes details of an experimental musical instrument now under development by the author, which employs rotary condenser generators and is playable from a console having two manual keyboards, a pedal keyboard, and thirty-four stops.

BALANCED FEED-BACK AMPLIFIERS

Edward L. Ginzton
(University of California)

An amplifier is described in which two controlling voltages, balanced against each other, are used at the input of the amplifier for the purpose of controlling its performance. One of these voltages is the conventional negative feedback which regulates the performance of the amplifier, and is called the negative feed-back voltage. The other voltage, in opposite polarity to the negative feed-back and hence called the positive feed-back voltage, is obtained in such a way that it is independent of frequency over the range of frequencies it is desired to amplify linearly. Hence, when the performance of the amplifier is perfect, the positive and negative feedbacks cancel each other and have no effect on the performance of the amplifier. But if the output should for some reason differ from the input, the feed-back circuits introduce voltages at the input of the amplifier in such a direction and of such magnitude that the output is changed back to normal.

Circuit diagrams and performance equations are given for the balanced feed-back amplifier and experimental results are presented showing a reduction of distortion and improvement in the frequency response for an amplifier of this type.

AIRCRAFT RADIO EQUIPMENT TRENDS

Ralph M. Heintz
(Heintz and Kaufman)

This is a discussion of telephone and telegraph transmitters, receivers, and inter-communication systems for aircraft purposes. The use of alternating-current sources of power for aircraft radio purposes is considered, and the effect that this has upon radio design is treated in detail.

MAGNETIC GENERATION OF A GROUP OF HARMONICS

E. Peterson, J. M. Manley, and L. R. Wrathall
(Bell Telephone Laboratories, Inc.)

This paper describes a method of producing a number of harmonics which may be used, for example, as carriers for high-frequency multiplex transmission.

TRANSMISSION LINES AT ULTRA-HIGH RADIO FREQUENCIES

L. E. Reukema
(University of California)

Accurate equations are developed for thera diation resistance of parallel-wire and concentric lines of any length, any ratio of outer to inner diameter which might be used in practice, and any termination. These equations are expressed in a form that will give an accurate answer with not more than a few minutes computation. The equations for the radiation resistance of the shorting bar for parallel wire lines are given. It is proved that the radiation resistance of the shorting disk for a concentric line is zero.

TRANSMISSION LINES AT ULTRA-HIGH RADIO FREQUENCIES

L. E. Reukema
(University of California)

Radiation resistance, although ordinarily neglected, is actually of dominant importance in determining the selectivity factor Q and the input impedance Z_s of both parallel wire and concentric transmission lines at high radio frequencies, and therefore materially changes the optimum design of the line, whether used as a low-loss inductive or capacitive reactance or to give high selectivity or high impedance as a resonant line. Accurate design equations for either maximum selectivity or maximum impedance are developed in this paper for both parallel wire and concentric lines, and curves are included showing radiation resistance, selectivity, input impedance, optimum values of spacing, conductor radius, etc., for any length of correctly designed line and any frequency, whether the line is open- or short-circuited or is terminated in its characteristic impedance. It is shown that for maximum Q the optimum ratio of spacing to wire radius for parallel wire lines is $D/r = 6.186$, and the ratio of outer conductor radius to inner conductor radius for concentric lines is $b/a = 4.22$, as compared with values of about 3.6 for both ratios when radiation resistance is neglected. For maximum impedance corresponding values are $D/r = 20.96$ and $b/a = 14.3$, as compared with values of 8 and 9.2, respectively, predicted neglecting radiation resistance. Moreover, Q and Z_s are not proportional to D and b, respectively, as indicated in previous analyses; instead definite values of D and b give maximum Q and slightly larger values give maximum Z_s, and even a small departure from the best value produces a large decrease in Q or in Z_s. Q and Z_s for optimum design are both *inversely* proportional to the cube root of the frequency for parallel-wire lines and *inversely* proportional to the 0.4 power of the frequency for concentric lines, whereas previous analyses showed both *increasing* as the square root of the frequency.

KGW SECTIONALIZED ANTENNA TOWER

Harold C. Singleton
(The Portland *Oregonian*)

The new antenna is a uniform cross-section vertical steel radiator. Its height is 625 feet above the ground and it is sectionalized for the dual purpose of giving optimum electrical length when so adjusted for 620 kilocycles (KGW) and at the same time using the portion of the radiator below the sectionalizing point for 1180 kilocycles (KEX). In this case the sectionalizing network is so designed to offer a high impedance to 1180 kilocycles while producing the proper reactance at 620 kilocycles for the over-all antenna.

The ground system will consist of 120 half-wave length radial conductors.

The antenna is so located that a second element can be erected at a later time to form a two-element array with augmented signal strengths north and south and suppression toward Phoenix, Arizona, where KTAR operates on the same frequency with KGW.

RADIOTELEPHONE NOISE REDUCER

C. C. Taylor
(Bell Telephone Laboratories, Inc.)

This describes a device which lessens the effect of noise by reducing the noises which occur between syllables of speech and also by reducing weak speech sounds which are obscured by noise.

HIGH EFFICIENCY GRID-MODULATED AMPLIFIERS

Frederick Emmons Terman and John R. Woodyard
(Stanford University)

A grid-modulated amplifier is described that has an average efficiency exceeding seventy per cent, and that requires negligible modulating power. In this modulator the radio-frequency amplifier is divided into two sections that are interconnected by a quarter-wave length line. By taking advantage of the impedance inverting action of this line, high efficiency is obtained during unmodulated as well as heavily modulated intervals. Theoretical possible efficiencies are calculated for this high efficiency grid-modulated amplifier as well as for high efficiency linear amplifiers. Means of improving these theoretical maximum efficiencies are discussed and the practical possibilities and limitations considered.

THE DEVELOPMENTAL PROBLEMS AND OPERATING CHARACTERISTICS OF TWO NEW ULTRA-HIGH-FREQUENCY TRIODES

Winfield G. Wagener
(RCA Manufacturing Company, Inc., RCA Radiotron Division)

To introduce the problem of high power at ultra-high frequencies a curve of maximum power obtainable at various wave lengths in the limiting region is presented for various types of tube generators. The factors of the electrical circuit and power as they influence size, and the problem of the transit time of electrons as it affects performance are discussed.

The design principles that result from these conditions have been used in the development of two new ultra-high frequency triodes which are described. The water- and air-cooled triode is capable of delivering above 700 watts per tube at 100 megacycles. It is capable of operation as a neutralized power amplifier up to frequencies of the order of 200 to 250 megacycles with an output of about 500 watts. A second triode is described which is a radiation-cooled glass tube with a 300-watt plate dissipation rating. Normal efficiency is obtained up to 40 and 50 megacycles and operation as a neutralized power amplifier is possible up to about 100 megacycles. The efficiency at 100 megacycles is about sixty per cent.

GROUND CONDUCTIVITY IN WESTERN UNITED STATES

James W. Wallace and Martin V. Kiebert
(Puget Sound Broadcasting Company)

This is a report on the effect of various soil conditions on radio transmission. Important factors in efficient broadcast station coverage are discussed. Experimental data taken by the authors in the state of Washington, where all types of soil and ground conductivity are present, show striking sample conditions. Some contours of iso-potential run almost directly on a radial from the transmitter. Equipment and methods of measurement and calculation are explained.

Western States conditions are compared with those throughout the United States. It is found that regions such as Lake Washington, noted for its water purity, are low conductivity regions. Of interest to transmission and telephone men is the correlation with the problem of obtaining pole grounds in various regions.

THE VODAS

S. B. Wright
(Bell Telephone Laboratories, Inc.)

This describes and gives the characteristics of the voice-operated device used to prevent singing between a radio transmitter and receiver. Although the device has been mentioned in two earlier papers it has not previously been described in so much detail nor were performance curves previously included.

Committee Work

Constitution and Laws

Further consideration on the revision of the Institute's constitution was made at a meeting of the Constitution and Laws Committee which was held in the Institute office on June 11 and attended by H. M. Turner, chairman; B. J. Thompson, J. D. Crawford, assistant secretary; and H. P. Westman, secretary.

Standards Committee

On June 22 a meeting of the Standards Committee was held in the Institute office and attended by L. C. F. Horle, chairman; J. F. Farrington, representing H. A. Wheeler, F. T. McNamara, representing H. M. Turner; H. F. Olson, J. C. Schelleng, B. J. Thompson, L. P. Wheeler, William Wilson, J. D. Crawford, assistant secretary; and H. P. Westman, secretary.

Final approval was given to the reports of the Technical Committee on Electroacoustics and the Technical Committee on Electronics. These two reports are now to be considered by the Board of Directors and after approval of that body will be published.

Institute Meetings

Atlanta Section

The Atlanta Section met on May 20 at the Atlanta Athletic Club with N. B. Fowler, chairman, presiding. There were sixty persons present.

"Advances in Transmitter Antenna Design" was the subject of a paper presented by George H. Brown of the Research Division of the RCA Manufacturing Company, RCA Victor Division. Dr. Brown first spoke of experiences which he had in the study of antennas. He outlined the various problems encountered and how solutions were obtained through mathematical analysis, supplemented by actual measurements in the field of a special model antenna erected for the purpose. It was demonstrated that antennas of limited height were entirely feasible if effectively excited and operated against an efficient ground system. Considerable information was given on the subject of ground systems and an effective one was indicated as being a pattern of 120 buried radial wires, each one-half wave long.

Almost everyone in the audience participated in the discussion of the paper.

A meeting of the Atlanta Section was held on June 17 at the Postal Telegraph and Cable Company plant and there were nine present. N. B. Fowler, chairman, presided.

A tour of the plant was made under the direction of H. P. Thornton, division equipment engineer. The inspection tour started with the incoming cables at the testboard and continued through the various bays of equipment including the half duplex, full duplex, and multiplex machines with their associated apparatus. Much of the equipment was demonstrated as well as its functions outlined.

Boston Section

Harvard University was the place for the June 4 meeting of the Boston Section which was attended by fifty and presided over by E. L. Bowles, chairman.

A paper on "A Method of Obtaining Static Characteristics of Power Tubes and the Calculation of their Operating Characteristics" was presented by E. L. Chaffee, professor of physics at Harvard University. It disclosed a method of obtaining static characteristics of power tubes in the regions of extreme positive bias over a wide range of plate voltages. Using these characteristics and with the aid of a simplified harmonic analysis a means of calculating the operating characteristics of the tube is available. The paper was discussed by Messrs. Dallin, Karplus, and Krahl.

The Nominating Committee submitted its report and it was agreed by a written ballot that the section would affiliate with the Engineering Societies of New England. This will result in the inclusion of notices of the Boston Section in the Journal of that organization which is mailed weekly to all affiliated groups.

Chicago Section

The Chicago Section met on June 11 at the Stevens Hotel. J. K. Johnson, chairman, presided and there were 250 present.

"Recent Developments in Receiver Test and Service Equipment" was presented by Kendall Clough of the Clough-Brengle Company. In it he presented new developments in receiver test and service equipment during last year. A new frequency modulator was described with emphasis on new features for the suppression of spurious responses. The paper was discussed by W. C. Dunn.

A second paper on "What Standardization of Radio Receiving Tubes Means to the Radio Industry" was presented by R. M. Wise, chief radio engineer of the Hygrade Sylvania Corporation. He discussed the present complex tube type situation in detail and presented arguments favoring greater standardization than now exists. The benefits to be realized were enumerated and suggestions for appropriate action were made. The paper was discussed by Messrs. Kohler and Kranz. A third paper on "Chicago's Contribution to the Radio Receiver Art in 1937" was presented by J. K. Johnson, chief engineer of Wells Gardner and Company. In it he reviewed some of the outstanding developments offered to the public by Chicago radio manufacturers. Several of the recent and novel developments were covered in detail.

Detroit Section

On June 19 a meeting of the Detroit Section was held in the Detroit News Conference Room and presided over by R. L. Davis, chairman. There were forty present.

A paper on "Bringing the Ionosphere Down to Earth" was presented by S. L. Bailey of Jansky and Bailey. The density of the atmosphere decreases with altitude while the intensity of ultraviolet radiation from the sun increases. At about one hundred kilometers above the earth, there is sufficient ultraviolet radiation to ionize the remaining molecules of gas to an extent that permits refraction of radio waves used for communication purposes. The velocity of propagation of radio waves is different in the ionosphere than in the atmosphere, and this results in refraction. If the angle of refraction is sufficiently large, the wave is bent back toward the earth's surface, where it may be useful. Changes in solar radiation during the day and season affect substantially the amount of ionization and how near to the earth's surface it penetrates. The Dellinger effect which is a sudden cessation of radio reception has been identified as being caused by sudden eruptions on the surface of the sun. The paper was closed with a description of a continuously variable frequency transmitter used to obtain ionosphere height recordings. The paper was discussed by Messrs. Brewington, Byerlay, and Davis.

Indianapolis Section

The March meeting of the Indianapolis Section was held on the 25th at the Indianapolis Athletic Club. Due to adverse weather conditions, the attendance was only thirty-two and it was agreed to hold an election of officers to serve until the January meeting. V. C. MacNabb of Fairbanks Morse and Company was named chairman; C. F. Wolcott of Noblitt Sparks Industries was elected vice chairman; and the temporary secretory, I. M. Slater of P. R. Mallory and Company was named secretary.

A paper on "Recent Tube Developments—Their Design and Application" was presented by W. R. Jones of Hygrade Sylvania Corporation. In it he traced the evolution of the screen-grid, pentode, and multigrid tubes. Particular emphasis was placed on the new beam power tubes. Various tube problems were discussed in detail.

The April meeting was held at the Indianapolis Municipal Airport on the 29th with Chairman MacNabb presiding.

E. Kramer of the Lorenz Radio Company, Berlin, presented a paper on "Ultra-Short-Wave Radio Landing Beam for Aircraft." In it Dr. Kramer discussed the various advantages and disadvantages of the Lorenz blind landing system. The difficulties due to hangar reflection and other interferences were outlined and methods to overcome these problems presented. An acoustical demonstration of the tones and signals heard when the plane is landing using this system was reproduced from a phonograph record. After the paper, members and guests were invited to inspect both the transmitting and receiving equipment. There were approximately ninety-five present.

The May meeting was held on the 14th at the Indianapolis Athletic Club and a paper on "Direct Reading Instruments" was presented by R. F. Field of the General Radio Company. It covered various types of instruments and the evolution of direct reading equipment. The advantages of logarithmic type scales were presented. A number of the thirty-eight members and guests participated in the discussion of the paper.

Los Angeles Section

Thirty-six members and guests were present at the Los Angeles Section meeting which was held on May 18 and presided over by Douglas Kennedy, chairman.

Robert Moore, engineer of the Southern California Telephone Company, presented a paper on "Marine Radiotelephone Service in Southern California." He described the transmitting and receiving equipment installed at Palos Verdes. The location was chosen after field measurements indicated reliable communication with boats could be maintained within a two-hundred-mile radius. In a number of instances, satisfactory communication has been maintained over a distance of 1500 miles. A five-hundred-watt transmitter is employed and is remote controlled from Los Angeles, there being no operator on duty at the station. To demonstrate the operation, a call was placed from a telephone in the lecture room. A monitor amplifier and loud-speaker attached to the circuit allowed the audience to hear both sides of the conversation. The station called was the yacht *Gypsy* anchored in Balboa Harbor which is about thirty miles from the transmitter station.

Montreal Section

On April 14 the Montreal Section held a meeting in the Engineering Institute Building which was attended by sixty. A. M. Patience, chairman, presided.

A paper on "Current Developments in Radio Tubes in the United States" was presented by R. M. Wise, chief engineer of the Hygrade Sylvania Corporation. This review included a discussion of the higher tensile strength filaments for battery tubes, higher sensitivity battery pentodes such as the 1G5G, the beam power types, and converters. Graphs were shown depicting the effect of plate current, mutual conductance, amplification factor and other characteristics resulting from variations in the spacing between grids and changes in the size of grid wires. The paper was closed with a plea for more co-operation between set manufacturers and tube manufacturers in order to avoid further increases in the already too large number of tube types on the market. The paper was discussed by Messrs. Farley, Fisher, Hackbusch, Moore, Oxley, Parker, Patience, and Vennes.

The May 26 meeting was also held in the Engineering Institute Building and attended by forty, with Chairman Patience, presiding.

A. B. Oxley, quality control engineer of the RCA Victor Company, Ltd., presented a paper on "Vibrational Analysis of Radio Tubes." It dealt with a new method of analyzing tube structures by mechanical modulation of various elements and interpretation of the results as illustrated on the cathode-ray oscillograph. The exact measurements of microphonic susceptibility at critical frequencies was demonstrated and a method of classification outlined together with a proper method of attack for the elimination of these undesirable characteristics. The usefulness of the method was demonstrated for both tube design and production test purposes. Fundamental equations of natural resonance and common modes of complex mechanical shapes were reviewed together with short-cut methods of diagnosing troubles. The detection of loose welds, faulty suspension, and improper clearance in standard tubes was discussed and demonstrated and the relation of quantitative mechanical tests to electrical tests in production examined. A lively discussion of the paper followed its presentation.

New Orleans Section

The June 16 meeting of the New Orleans Section was attended by forty-three and was held at the Shushan Airport. L. J. N. Du Treil, chairman, presided.

A paper on "Radio Equipment Used by the Department of Commerce Aeronautics Division" was presented by F. C. Mashburn, operator-in-charge of the Department of Commerce station which is also used by the Weather Bureau. H. L. Bannon, chief radio operator of Eastern Airlines station presented a paper on "Radio Equipment Used by Modern Air Lines." After the meeting, an inspection trip was made to the radio facilities at the airport and equipment used on the modern transport planes was examined.

Pittsburgh Section

Carnegie Institute of Technology was the place in which the May 17 meeting of the Pittsburgh Section was held. There were twenty-three present and B. Lazich, chairman, presided.

A paper on "The Port-A-Phone" was presented by R. E. Stark of the Federated Metal Products Corporation and P. N. Wettlaufer of the LaSalle Lamp Company. After reviewing the general theory of carrier current communication, a description was given of the Port-A-Phone which comprises a pair of transmitter-receivers for communication over existing electric lighting circuits. A switch permits transmission of a calling signal to other receivers on the line, conversion of the device into a transmitter employing the loud-speaker as a microphone, or its operation as a receiver for reception from similar devices. A modulated tone is used as a call signal. The paper was discussed by Messrs. Adams, Backer, Baudino, Bossart, Phillips, Pickels, and Sutherlin.

Rochester Section

L. A. DuBridge, chairman, presided at the May 20 meeting of the Rochester Section which was held in the Sagamore Hotel and attended by sixty-five.

D. E. Foster, an engineer of the RCA License Laboratory, presented a paper on "Principles of Automatic Frequency Control in Radio Receivers." The author presented a brief statement as to the objective of the developments which he discussed and outlined the problems and the various solutions which have resulted in the work done in the field.

As this was the annual meeting, the election of officers took place. Dr. DuBridge was continued as chairman. W. F. Cotter of the Stromberg-Carlson Telephone Manufacturing Company was elected vice chairman, and H. A. Brown was re-elected secretary-treasurer.

Seattle Section

On June 18 the Seattle Section met at the University of Washington with J. W. Wallace, chairman, presiding. There were thirty-two in attendance.

"A Review of the Theory of the Stabilized Feed-Back Amplifier" was presented by R. O. Bach, exchange transmission engineer of the Pacific Telephone and Telegraph Company. The subject was introduced by a review of feed-back theory outlining the voltage and phase relationships and how they may be utilized to reduce noise and harmonic distortion which arise in the output stages of the tube amplifiers. The use of a feed-back amplifier as an equalizer was described. Performance data were also presented to show the improvement obtained from a particular amplifier through the use of feedback. Following the discussion of the paper which was participated in by Messrs. Eastman and Wallace, a Western Electric portable line amplifier was exhibited to show the design advantages obtained by the use of feedback.

Washington Section

The Washington Section met in the auditorium of the Potomac Electric Power Company building on June 14. W. F. Burgess, chairman, presided and there were eighty present.

W. E. Jackson, chief of the radio development section of the Bureau of Air Commerce, presented a paper on "Improvement in Air Navigation Radio Facilities." He included a brief discussion of loop radio ranges, and the reasons for changing to tower ranges, problems involved in the use of these and solutions of the problems, simultaneous radio range and broadcast operation, Z and fan markers, ultra-high-frequency communication between planes and ground, remote receiving antennas, and tuning houses.

The executive committee was given authority to take any necessary steps in regard to the pending bill for the registration of engineers.

Proceedings of the Institute of Radio Engineers
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TECHNICAL PAPERS

DEVELOPMENT OF THE PROJECTION KINESCOPE*[1]

By
V. K. Zworykin and W. H. Painter
(RCA Manufacturing Company, Inc)

Summary—*This paper discusses the general requirements and design of Kinescope tubes for projecting television images. A picture 18×24 inches in size having a brightness in the high lights of 0.9 candle per square foot appears to be an acceptable minimum for home television reception. Several years of developmental work were required before the problems of designing a suitable projection system were clarified. This clarification led to a developmental Kinescope which closely approaches the minimum brightness requirements. The possibilities of further improvements in electron guns, fluorescent screen materials, and optical systems are discussed.*

THOSE who have had the opportunity of viewing a modern cathode-ray television receiver under typical conditions in the home are agreed that the brightness and resolution of the picture are quite satisfactory. Some observers, however, have expressed a desire for a somewhat larger picture in order to eliminate the necessity of crowding around the viewing screen. The actual size of the picture in one of the console television receivers used in recent tests is $7\frac{1}{2}\times10$ inches.

The size of image required will be influenced by the number of observers to be accommodated and the desired viewing distance, this latter factor varying with the perfection of the image.[2] When viewing an image of low detail, the observer tends to step back to such a distance that the visible imperfections blend into a more harmonious whole. As the detail is increased the picture will bear closer inspection and the optimum viewing distance is hence decreased. As we approach the high detail represented by the proposed RMA standard of 441 lines, Engstrom[3] has shown that the optimum viewing distance is about four times the picture height. To avoid crowding of observers, it would seem that a height of at least eighteen inches is necessary, making the optimum viewing distance some six to eight feet. If the

* Decimal classification: R583. Original manuscript received by the Institute, June 9, 1937. Presented before Silver Anniversary Convention, New York City, May 12, 1937.
[1] Registered trade-mark RCA Manufacturing Company, Inc.
[2] V. K. Zworykin, "Television with cathode-ray tube for receiver," *Radio Eng.*, vol. 9, p. 38; December, (1929).
[3] E. W. Engstrom, "A study of television image characteristics," Proc I.R.E., vol. 21, pp. 1631–1651; December, (1933).

present picture could be increased to about six times its area, or, in other words, to about 18×24 inches, it would probably be an acceptable size for home television reception.

In brief, the Kinescope consists of an electron gun and a fluorescent screen assembled within an evacuated vessel in such a way that the cathode-ray beam can be made to scan across the screen, where the electrical energy of the electron beam is converted into light reproducing the picture. Fig. 1 is a photograph of such a tube.

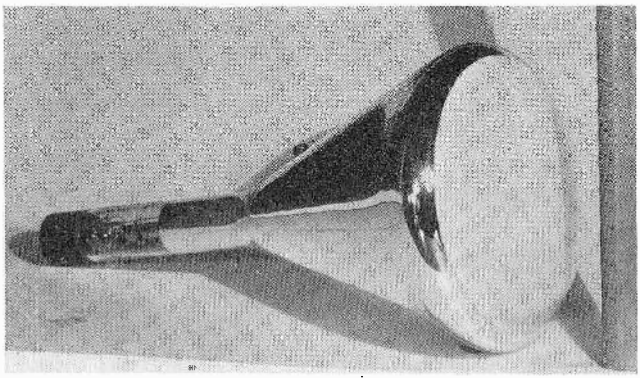

Fig. 1—Conventional 9 inch-diameter Kinescope. The television image is viewed directly on the large end of the tube.

In order to increase the size of image on a directly viewed tube it is necessary merely to increase the physical dimensions of the tube. Within reasonable limits this can be done without serious sacrifice of brilliance. However, if we wish to make the picture size 18×24 inches, the physical bulk of the tube becomes enormous. For example, the diameter would be nearly thirty inches, the length more than three feet, and the glass face would have to withstand a pressure of over five tons. This is obviously a rather difficult solution of the problem.

An alternative method of obtaining an enlarged picture is through the use of a projection Kinescope. The projection tube is similar to the directly viewed Kinescope in principle, but produces a small, very bright image. By the use of a suitable lens the picture on the Kinescope may be projected to any desired size on a screen. The principal problem involved in this method is that of obtaining sufficient illumination on the screen so that the picture may be viewed without fatigue.

Let us consider for a moment the 12-inch Kinescope, widely used in test console receivers at present. The electron gun supplies a beam current of about 250 microamperes to the high lights of the picture and the tube operates at an over-all potential of 6000 volts. Thus, about 1.5 watts of electrical energy are available for conversion into light in the high lights. This energy is supplied to a tiny spot about 0.5 millimeter in diameter which, by means of a magnetic deflecting system, is made to scan the fluorescent screen in a 441–line pattern at the rate of thirty times a second. The luminous output of the fluorescent material, a form of zinc orthosilicate, is a function of both current and voltage, as can be seen from Fig. 2. Under the conditions specified the fluorescent

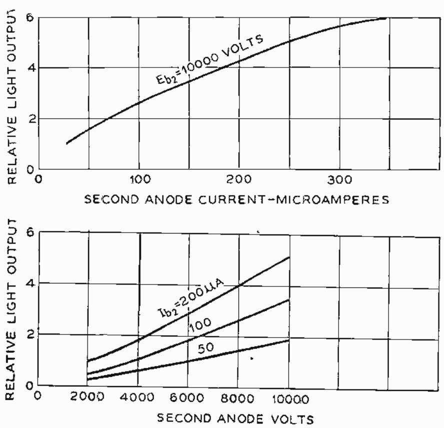

Fig. 2—Top curve shows variation of light output of fluorescent material with beam current. Bottom curve shows light output vs. second anode potential. Both curves are for RCA phosphor No. 1.

material has a luminous output of about two candles per watt. The brightness of the screen, therefore, will be $\dfrac{1.5\times 2}{75\times\dfrac{1}{144}}=5.8$ candles per square foot, or 18.2 foot-lamberts.

The Society of Motion Picture Engineers has devoted considerable attention to the subject of brightness in relation to moving picture projection.[4] The May and August, 1936, issues of the Journal of the SMPE contain much interesting information on the subject. It is at once apparent that the subject is full of controversy and that present information is not by any means final. Evidence was presented to show that the high lights of a 35-millimeter moving picture should have a brightness of about 11 foot-lamberts if eye fatigue is to be completely avoided. It was estimated that in theaters throughout the country the actual level attained probably ranged from 1 to 9

[4] *Jour. SMPE*, vol. 26, May, (1936), and vol. 27, August, (1936).

foot-lamberts. As a temporary measure it was recommended that 3.7 foot-lamberts be adopted as a standard, with limits of from 2.7 to 5.2 foot-lamberts. These recommendations were actually made in terms of light from a projector running with no film in the gate, but we have converted them to terms of highlight brilliance for convenience in this discussion. The suggestion has also been made that a high-light brilliance of 2.7 foot-lamberts be considered standard for 16-millimeter projection. In this case the recommendation was couched in terms of intensity of light falling on the screen; in converting, we assumed a diffuse screen with a reflection factor of 75 per cent.

For the sake of direct comparison, the brightness of these and other familiar objects is shown in the following table:

Lighted page (minimum recommended brightness for reading fine print)	10 foot-lamberts
High-light brilliance on screen of moving picture theater	2.7 to 5.2 foot-lamberts
High-light brilliance in 16-millimeter movie	2.7 foot-lamberts
Outdoor scene—bright day	300 to 600 foot-lamberts
High-light brilliance of picture on 12-inch console television receiver	18.2 foot-lamberts

These figures, particularly those referring to the 16-millimeter movie and the 12-inch Kinescope, should be kept in mind as we investigate the elements constituting a means of projecting television images.

The most efficient viewing screen to use for our purpose is a highly directional transmission screen. The transmission characteristics of two such screens are shown in Fig. 3. The solid line represents a commercial type of screen made from a rubberized material, while the dotted curve was obtained from a piece of ordinary tracing paper. Screens of this type will transmit in a direction normal to their surface several times as much light as would a perfect diffusing screen. For the commercial screen the ratio is 480 per cent while for the tracing paper it is 360 per cent. In the former case the picture can be viewed without too serious loss of light within an angle of twenty degrees on either side of the normal, while the tracing paper allows an angle of about fifteen degrees. In both cases, the light is distributed with sufficient uniformity to avoid the bright area due to direct transparency of the screen known as "hot spot."

For the purpose of computation, let us consider the projection arrangement shown in Fig. 4. Before we can arrive at any conclusions as to the light output required from the Kinescope it is necessary to make certain restrictions on the lens that is to be used. These are determined chiefly by the commercial aspects of the problem. The lens must be one that can be manufactured in quantities and must be relatively inexpensive. Since the resolution of the picture is to be 441 lines, the correction of the lens does not have to be as perfect as in the case of

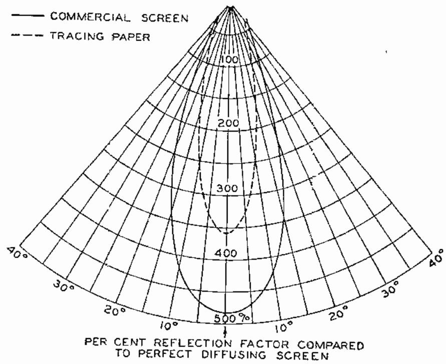

Fig. 3—Brilliance distribution of two types of transmission screens.

a photographic objection. This will be an important consideration in large scale production. Because lens makers have never before faced the problem of making high quality lenses in the quantities foreseen for television, cost estimates are at best a guess. However, from our present understanding of costs, it seems that the lens diameter should

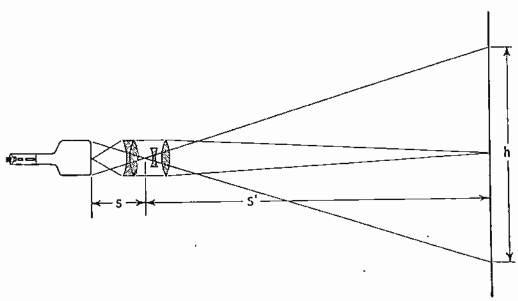

Fig. 4—Schematic diagram of optical system for projection Kinescope.

not be much greater than three inches nor the *f* value much smaller than *f* 1.5. A lens of this type in use at present has an angle of field of approximately 35 degrees, and the focal length is 120 millimeters.

From these lens specifications, and using our 18-×24-inch standard, it can be shown that the distance from lens to viewing screen is about 4.6 feet. The lens of Kinescope distance will then be 130 millimeters and the image on the projection tube screen should measure 1.66 by 2.22 inches.

The brightness of the projection tube screen can be calculated from the brightness of the image on the viewing screen, the lens aperture, the magnification and the losses in the system. Assuming fifty per cent transmission through the lens and applying the distribution of our transmitting screen to the result, we find that the image on the projection Kinescope must be 480 times as bright as that on the viewing screen. To attain a brilliance equal to that on our 12-inch Kinescope we must have a brightness of about 2800 candles per square foot.

At first glance this brightness seems very large indeed, but when it is remembered that we are using a small area and that we are referring only to the picture highlights it will be seen that the light output is not excessive. The equivalent light output will be $\frac{2800 \times 1.66 \times 2.22}{144} = 71.4$ candle power.

There are, unfortunately, practically no data available on the efficiency of fluorescent materials at high input levels. However, if we assume that it may some day be possible to produce a fluorescent material having an efficiency of 1.5 candles per watt at such levels, then we find that the peak input required to produce this light in the high lights would be 47.6 watts. At 10,000 volts this would require a peak beam current of 4.76 milliamperes; if the voltages were raised to twenty kilovolts, the required peak current would be only 2.4 milliamperes. It should be remembered that the required brilliance has been figured on the basis of equalling the brilliance of present Kinescope tubes. If, however, we are satisfied with the brilliance attained with a reasonably priced home movie projector, the brightness of the high lights need be only 427 candles per square foot, or the light output only 11 candle power. At 10,000 volts the current needed to produce this light, even with present screen materials, is only 0.73 milliampere. Thus, while the type of tube described in this paper will not yet compete with the directly viewed tube in brilliance, it does not fall so very far below the minimum requirements.

Although such a set of clear-cut requirements as previously described seems an almost essential part of any co-ordinated development program, it must be admitted that projection tube work was not started with any such definite goal in view. The successful reception of cathode-ray television pictures of any sort has been accomplished within the last decade. Since the early work on projection tubes was carried out at a time when a good imagination was an essential aid to viewing a picture, it can readily be recognized that a certain amount of inspiration went hand in hand with science.

While some of the initial ideas were tested by one of the authors in the laboratories of the Westinghouse Electric and Manufacturing Company at East Pittsburgh, more active development of the projection Kinescope was undertaken at the RCA Victor Company plant in Camden. For several years work has progressed steadily in the RCA laboratories both in Camden and later in Harrison.

The original projection Kinescope involved simply a scaling down of dimensions of a standard 9-inch Kinescope. The electron gun and screen were assembled in a common Ehrlenmeyer chemical flask. The usual vacuum technique did not permit of very high voltage operation, yet a picture of reasonable detail, though lacking in brilliance, was obtained. The tendency of the soft glass blanks to crack under the heat generated by the beam spelled the doom of a majority of these tubes.

One of the first major steps forward was the realization that the projection tube deserved recognition as a separate problem rather than as merely an offshoot of larger tubes. With this recognition came the design of a special glass blank having an optically clear window suitable for use with a highly corrected lens system. Vacuum technique was improved to allow the consistent use of ten kilovolts on the anode. A realization of the need for far higher beam currents concentrated in much smaller areas than had hitherto been considered feasible guided further experiments on the electron gun.

While the principles of electron optics had not yet been widely espoused at that time, the gun development proceeded along quite logical lines. Attention first centered on the focusing field between first and second anodes, now known as the final lens, until the optimum conditions, within the restrictions of the bulb, were determined. So well was this foundation established, in fact, that even today some of the oscillograph tubes obtainable commercially utilize the exact dimensions of first and second anodes which these early tubes employed. It was soon realized however, that a major source of trouble was the field adjacent to the cathode and effort was concentrated on improvements there. The necessity of decreasing the area of the beam near the crossover was recognized; a wide range of means for accomplishing this was tried, including a study of preconcentrating cylinders attached to the grid and the shaping of fields by the introduction of various sizes and shapes of electrodes.

Two circuit considerations served to handicap the work. The first was the need of maintaining a fairly restricted modulating range, since a high signal voltage covering the necessary range of frequencies was impractical. The other was the need of maintaining a small constriction in the tube neck, in order that magnetic poles might be placed close enough together to allow full deflection of the beam. This in turn set such a limit upon the size of electrodes which would be used that considerable aberration was always present. The first of these difficulties is being overcome by refinements in tube design; the latter has been greatly modified by improvements in deflecting circuits.

The advent of electron optics allowed a theoretical analysis of the remaining faults to be made and pointed the way to refinements which are so necessary to give the projection Kinescope a place in the field of high definition television.

While the major effort was spent on tubes of the type described, several investigations of interest were made along somewhat different

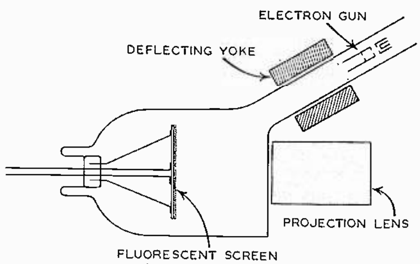

Fig. 5—"Front surface" type of projection Kinescope. Use is made of the greater amount of light emanating from the side of the screen which is scanned.

lines. One of these particularly worthy of mention is the so-called "front surface" type of projection tube. It has been determined that the light on the surface of the screen adjacent to the scanning beam may be double that appearing on the outer surface. To utilize this fact seemed an easy way of improving the brilliance of the image.

Attempts to accomplish this were made by depositing the fluorescent material upon a metal plate within the tube. To enable the lens to be placed directly in front of the screen, it was necessary to seal the neck containing the electron gun onto the bulb at an angle, as shown in Fig. 5. This imposes several difficulties upon the problem of focusing. First of all, because of interference with the optical lens there is little clearance of the magnetic deflecting yoke. The electron gun must therefore be placed well back in the neck and the distance between gun and screen is greater than in the direct type. This, of course, limits the focus obtainable. Since the beam strikes the screen at an angle the fluorescent spot is no longer round but is elliptical. To make the long axis of the ellipse equal to the diameter of the corresponding round spot requires better focusing than in the direct viewing type of tube if the same resolution is to be maintained. The keystone shape of the scanned pattern can be corrected by suitable changes in the scanning circuits. From a manufacturing standpoint, backing plates of metal or conventional insulators are extremely difficult to degas, and the heat generated by the high power input required tends to develop gas in the tube during operation. Glass plates can be used but they tend to increase the fragility of the tube and complicate the assembly.

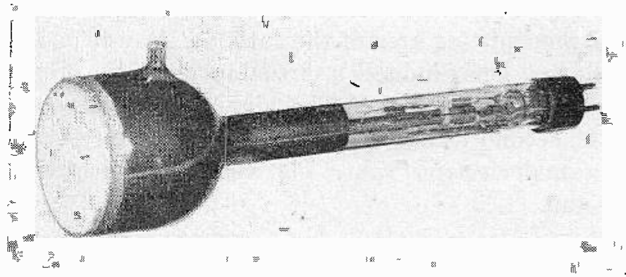

Fig. 6—Developmental model of a projection Kinescope. The face of the tube is carefully ground and polished.

While some fairly good pictures with low definition have been obtained, this design has not yet worked successfully in a 441-line system.

Fig. 6 shows a developmental model of one of the projection tubes developed in our laboratories. The picture size for this type of tube is 2.25×3 inches. The high-light brightness under operating conditions is about 280 candles per square foot. Since the image is larger than in

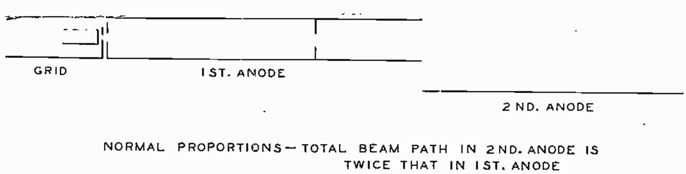

Fig. 7—Sectional diagram of the electron gun used in a projection Kinescope. The second anode is formed by a conductive coating on the bulb wall.

our example the lens suitable for use with it must have a slightly longer focal length (assuming the field is limited to 35 degrees). If this lens has the same diameter as the one considered in the previous example, the brightness of the picture on a viewing screen 1.5×2 feet in size is about 0.6 candle per square foot, or about 1.9 foot-lamberts. This illumination is not quite great enough to allow comfortable viewing for any length of time.

The electron gun used in this tube is shown in Fig. 7. It operates at an over-all voltage of 15,000 volts and delivers a beam current of about 400 microamperes, thus generating six watts in the high lights at the fluorescent screen. The spot size for this condition is about 0.005 inch. In principle this gun is similar to the gun used in the directly viewed Kinescope. It consists in essence of a cathode, a control grid, and a two-lens electron optical system. The first lens in this system causes the electrons from the cathode to converge into a narrow bundle known as the crossover. This crossover has a diameter much smaller than that of the emitting area of the cathode. As well as forming the crossover, the first lens produces a virtual image of the crossover lying slightly behind the cathode itself. This virtual image serves as a virtual object for the second lens and is imaged on the fluorescent screen in the form of a small electron "spot." Fig. 8 shows the electron trajectory through the gun.

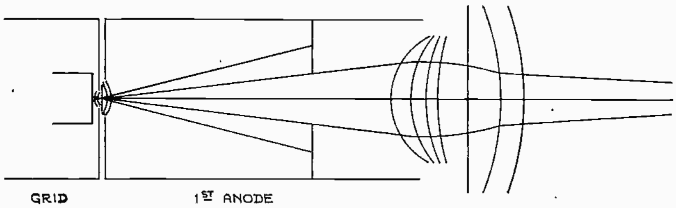

Fig. 8—Diagram of electron trajectories through the electron gun of Fig. 7. The electron lenses are represented by the lines of equal potential.

The control grid, as shown, consists of an apertured disk near the cathode, whose potential is controlled by the television signal. The potential of this element controls the size of the area on the cathode over which there is a positive field allowing the escape of electrons. Fig. 9 shows the control characteristics of this type of grid and the variation of spot size with bias.

The cathode is of the indirectly heated oxide-coated type. The emissive coating consists of a mixture of barium and strontium oxides and covers an area of about 6×10^{-3} square inches. This material is operated at a brightness temperature of 1050 degrees Kelvin. Although the entire coated surface is capable of emission, only an area slightly smaller than the grid aperture is utilized. From this portion a current to 1.0 to 1.5 milliamperes is drawn, about 0.4 milliampere being delivered to the beam and the remainder being collected in the first anode.

The fluorescent materials commonly used in the projection Kinescope are zinc or zinc-beryllium orthosilicates. These give a green or greenish-yellow fluorescence. Another class of fluorescent materials are the zinc sulphides, some of which produce a nearly white light. In general, the sulphides have higher initial efficiencies than the silicate materials; however, they are characterized by instability, and their use to date has therefore been restricted.

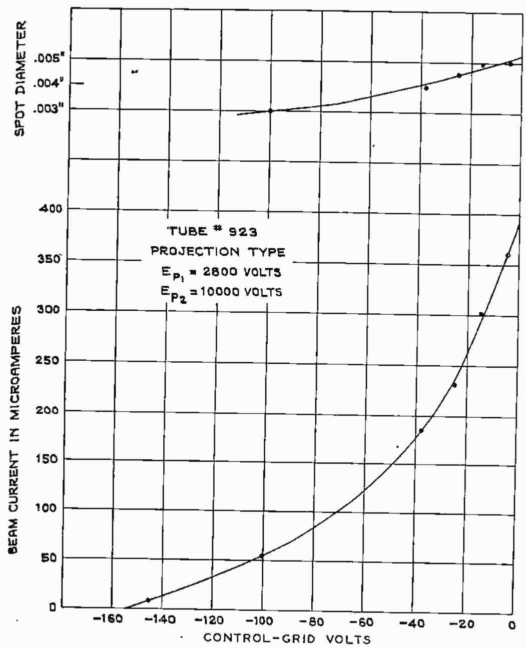

Fig. 9—Control characteristic of a projection Kinescope. The upper curve represents the variation of focused spot size with control grid bias.

It is interesting to note, however, that use of a material giving white light under normal conditions does not seem as important in the case of the projection tube as it does with larger tubes. When viewing the image projected from tubes having green fluorescent screens, several observers have commented on the apparent black and white appearance of the picture. This might possibly be due to a broadening of the spectral characteristic of the fluorescent material at high intensities, although further study is necessary before reliable conclusions can be drawn.

Turning now to the question of bringing the performance of this tube up to the standard set by our earlier considerations, the most important requirement is found to be that of increasing the brightness.

In addition, it would be desirable to increase the contrast of the picture and to improve the resolution.

An increase in brightness of the projected picture involves (1) increasing the power output from the gun while maintaining the present spot size, or, if possible, reducing its dimensions; (2) improving the fluorescent material and screen design; and (3) designing a more efficient optical system. These points will be taken up in the order mentioned.

The improvement of the electron gun can take place along one or more of the following lines: (1) Construction of the gun so that it can be operated at a higher potential; (2) improvement in the electron optical system so that less current is lost to the first anode; (3) increase of specific emissivity of the cathode; and (4) increase of the usable area of the cathode by altering the electron optical system.

The problem of constructing a tube which will withstand voltages of twenty kilovolts does not seem particularly difficult. Commercial oscillograph tubes are on the market today which operate consistently and satisfactorily at 15,000 volts, and tests at 20,000 volts are a rather common occurrence in the laboratory. The experience gained in the construction of these tubes shows that the problem is concerned chiefly with the elimination of sharp points or edges where exceptionally high gradients might build up and with proper shielding to insure that the electrons are confined within their designated path. One outstanding difficulty is the problem of applying a black conductive coating to the inside of the bulb. This coating is used to reduce reflection from the walls of the bulb. Conventional coatings consist chiefly of carbon. We have experienced some difficulty in preventing minute particles from shaking off and causing arcs. In the oscillograph tubes mentioned, we substituted a coating of platinum which adheres tightly to the glass bulb.

The matter of improving the performance of the electron optical system is much more difficult. In order to approach the question in a systematic manner, it will be necessary to examine in greater detail the way in which this system works. As was described above, the system consists of two focusing fields or lenses. The first of these lenses produces a small virtual object which is imaged by the second lens on the fluorescent screen. This second lens, like the lens which is used in ordinary optics, produces an image which is subject to the same aberrations which are met in the Seidel theory. Assuming good alignment of the gun parts, we are concerned only with axial aberration; that is to say, chromatic and spherical aberration. As far as this lens is concerned, chromatic aberration, that is, the aberration produced by the fact that the electrons do not all have the same velocity, may be assumed to be negligible. This is because the electrons entering this lens have attained a velocity, due to the accelerating field of the first lens, which is a different order of magnitude from the initial velocity of the electrons.

Spherical aberration, however, is by no means negligible. In order to reduce this aberration, it is necessary (1) to shape the electrodes in such a way that the fields they produce give a minimum of aberration, or (2) to limit by means of apertures the portion of the lens used, or conversely, (3) to increase the diameter of the electron lens, which involves necessary improvements in the deflecting system.

The spherical aberration of such a lens has been the subject of considerable investigation.[5] It is possible to show mathematically that spherical aberration cannot be entirely eliminated in any electron lens. However, the aberration can be reduced and guns which are used today are superior in this respect to earlier guns. As our knowledge of the properties of specific lens fields increases, it will undoubtedly be possible to make better electron lenses.

With the type of lens available at present about fifteen per cent of the lens aperture (i.e., fifteen per cent of the diameter of the first anode) can be used. The course of electron rays coming from the crossover, if extended to the second lens, would occupy slightly more than twenty-five per cent of its diameter. The aperture therefore limits the beam current to about thirty per cent of the current from the crossover. This not only reduces the beam current, but also represents considerable power loss and causes undesirable heating at the first anode. As the spherical aberration inherent in the lens is reduced by better lens design, it will permit the use of larger stopping apertures and, therefore, a greater beam current.

The configuration of the first lens and the cathode diameter determine the current in the crossover and also the angle subtended by the electron rays as they enter the second lens system. From a theoretical standpoint the first focusing lens is very complicated. The current density is very high in this region and cannot be neglected. Furthermore, the electrons enter the lens system at a low velocity so that the initial velocities produce considerable chromatic aberration. Finally, the analysis is further complicated by the varying action of the control grid as modulation is applied. In spite of its complicated nature, considerable progress has been made in analyzing this region. As this study has progressed, it has been possible to decrease the angle of the beam leaving the crossover and to increase the ratio of the area of cathode

[5] D. W. Epstein, "Electron optical system of two cylinders as applied to cathode-ray tubes," Proc. I.R.E., vol. 24, pp. 1095–1139; August, (1936).

used to the area of the crossover. A more complete discussion of the results of this investigation and the parameters which determine the performance of the region is beyond the scope of this paper.

Analysis of the electron optical properties of the cathode-ray gun has now made it possible to design a gun in which there is very little change in spot size with control-grid voltage, which utilizes an area of the cathode several times greater than that of the crossover, and in which thirty to fifty per cent of the current leaving the cathode is delivered into the beam. Furthermore, we feel that still better performance can be expected in the future.

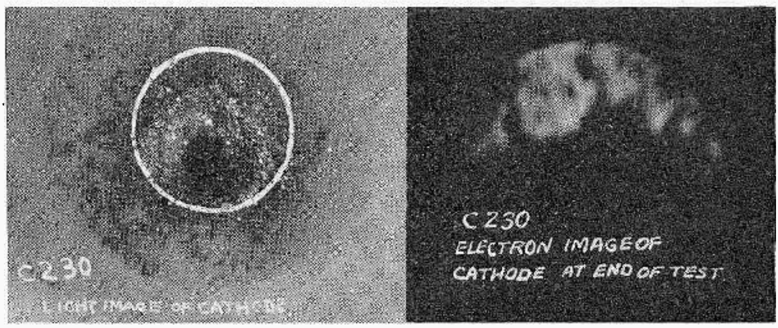

Fig. 10—Effect of positive ion bombardment on oxide-coated cathode. The dark central area is a hole through the cap. The pebbled area is bare nickel. The uniformly gray part is oxide coating. The useful area of the cathode is contained within the inner circle. The photograph to the right is the electron image of this cathode.

The cathode materials used at present give fairly satisfactory performance but it is quite possible that a material may be developed which will give even higher emission and have greater stability. One of the more serious problems is the destruction of the emitting surface due to bombardment by positive ions originating in the residual gas always present even in a high vacuum. The cathode, of course, lies directly at one end of the beam path and, except for the control grid, is the most negative element in the tube. The ions generated by the passage of the beam through the residual gas strike the surface with tremendous impact. Numerous cathodes have been examined from which the emitting material opposite the grid aperture has been knocked off completely. Fig. 10 is a photograph of a cathode which not only shows this action but which also shows a hole eaten entirely through the 0.002-inch nickel cap on which the coating was originally deposited. The solution of this difficulty is not yet at hand; still, it is believed that a rigorous processing will yield good enough vacuum to at least minimize the effect. This hope is borne out by life tests in which tubes have run at an anode potential of 10,000 volts for well over 500 hours with little trace of the bombardment effect.

Also connected with the general problem of cathodes is the characteristic dark spot which appears on the fluorescent screen directly opposite the apertures of the electron gun. The exact nature and cause of this discoloration is still the subject of considerable study, but many indications point to the fact that it may be due to bombardment of the screen by negative ions originating at the cathode upon bombardment by the positive ions mentioned above. The size and shape of the spot indicates that very little deflection of these ions takes place in ordinary magnetic deflecting fields. If a single pair of deflecting plates is introduced into the tube, the ions and electrons are deflected equally by the electrostatic field, and the result is a dark line. If deflection is accomplished entirely by electrostatic means, the entire screen is bombarded and the effect is diminished to a point where it is not noticeable in the course of the ordinary life of the tube.

The type of gun just described, though quite practical, is not the only one possible. Work is being done on different types which make use of a higher ratio of working area of cathode to crossover in order to increase the beam current. Some phases of this work are reported in a companion paper by R. R. Law.[6]

While most of our attention has been devoted to questions concerning the electron gun, the problems involved in the fluorescent material can in no wise be neglected. At the current densities and voltages used in the directly viewed Kinescope, present fluorescent materials yield fairly satisfactory light output and have demonstrated their ability to withstand bombardment for extended periods of time without undue deterioration. However, as the beam current and operating voltages are increased, a saturation effect becomes evident. The exact point at which the effect becomes objectionable varies with different materials, and not very much information concerning the behavior of fluorescent materials at high input levels is yet available for discussion.

Extension of the point where voltage saturation sets in seems to depend upon a better understanding of the secondary emissive properties of the screen material, which place a limit upon the effective bombarding voltage as distinguished from the final accelerating potential.

[6] R. R. Law, "High current electron gun for projection Kinescopes," Proc. I.R.E., this issue, pp. 954–976.

Physical chemists are engaged in an intensive study of means of extending the point where current saturation begins, and the results to be expected are as yet a matter of conjecture.

The question of the useful life of the material immediately comes to mind when voltages and currents of the order contemplated are mentioned. The picture is more encouraging than might be imagined; life tests run with a steady beam current of 200 microamperes at a potential of 10,000 volts have shown an efficiency drop of only twenty-seven per cent in 1200 hours. This, indeed, is more satisfactory than were the results at 50 microamperes and 6000 volts a brief three years ago. There is every reason to believe that work in progress will yield comparable improvements.

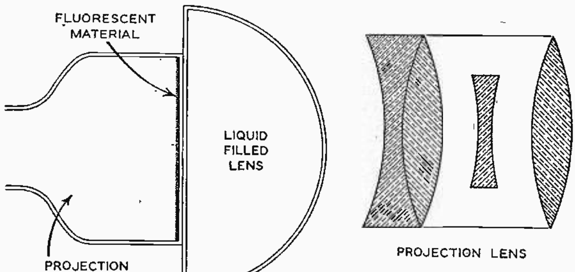

Fig. 11—A hollow shell filled with liquid and sealed to the face of a projection Kinescope will increase the amount of light entering the projection lens. Aberration is a serious defect in this system.

There is some possibility of improving the performance of the projection system by improving the optical system. An obvious way of doing this is by increasing the diameter of the projection lens; however, here we are restricted by the increasing cost of such lenses. There is, however, the possibility of increasing the light-gathering power of the system by a factor of two or three times by the use of a liquid lens in contact with the face of the projection tube. Such a lens is shown in Fig. 11. The arrangement consists of a hollow shell sealed to the front of the projection tube. This shell is filled with a liquid whose index of refraction is about equal to that of the glass of the projection tube. Aberration is a serious problem, but proper design of the shell can minimize this defect. Such an arrangement increases the effective aperture by a factor equal approximately to the square of the index of refraction of the liquid in the shell. With water as the liquid, output is increased by a factor of about seventy per cent, while if a liquid such as paraffine oil or cedar oil is used the gain in light is in the neighborhood of two and one-fourth times.

In addition to improving the optical system, the liquid of this lens can be used to aid the dissipation of heat generated at the fluorescent screen. It will also serve to reduce the loss of contrast due to halation in the glass face of the tube, so that if the aberration can be sufficiently reduced, the scheme may prove advantageous.

This paper has touched upon many of the technical aspects of the projection tube television system and has outlined some of the lines along which improvement may be expected. It must be obvious that a considerable amount of developmental work remains to be done before the projection type receiver can be added to our practical television system. Nevertheless, the results attained thus far give us reason to believe that in the projection Kinescope may lie the eventual solution to the problem of obtaining large television pictures.

Acknowledgment

The development of this type of projection Kinescope to its present state has been the result of the concerted efforts of many minds. Certain men, however, are worthy of special mention: J. C. Batchelor, whose enthusiasm and vision nurtured the idea through the early stages; G. N. Ogloblinsky, whose interest in the optical system proved so helpful; A. W. Vance, whose work most of the later refinements have been. To them and to a host of others we gratefully acknowledge our indebtedness.

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HIGH CURRENT ELECTRON GUN FOR PROJECTION KINESCOPES*

By
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Summary—*One of the problems in the art of reproducing a scene by television is to obtain an image of adequate size. Because of this there has been considerable interest in projection systems where a small, high intensity image reproduced on the face of a projection Kinescope[1] is thrown onto a viewing screen of the desired size by a suitable optical system. The light output and the definition of these systems has been limited by the inability of the electron gun to provide a sufficiently large beam current in a small spot.*

This paper describes an electron gun giving large beam current in a small spot. The design of this electron gun is based on the results of the present investigation which shows that the ratio of the current in the first crossover inside the radius r to the total space current is $I/I_s = 1 - \epsilon^{-ar^2E}$ *where E is the voltage applied to the first crossover forming system and a is a constant for any given cathode temperature, potential distribution, and geometry. Inasmuch as the total space current varies approximately as* $E^{3/2}$, *the concentration of current in the first crossover increases very rapidly with voltage.*

A description is given of an electron gun based on this theory. All available voltage is used to form a small intense first crossover whose edges are sharply defined by a first crossover defining aperture. A magnetic final focusing lens reimages this first crossover on the fluorescent screen. This electron gun gives beam currents of 1.5 to 2 milliamperes at an operating potential of ten kilovolts. This beam current may be readily concentrated into a 300-micron spot on the screen when the electron gun is spaced at such a distance from the screen as to give a 2.4- ×1.8-inch image. In conjunction with an f 1.4 lens having a focal length of 12 centimeters, this projection Kinescope has a light output sufficient to give an 18- ×24-inch picture having high lights with an apparent brightness of about 2.5 foot-lamberts when viewed on a 480 per cent directional screen.

Introduction

One of the problems in the art of reproducing a scene by television is to obtain an image of adequate size. The size of image required will be influenced by the number of observers to be accommodated and the perfection of the image. In viewing a low definition image, an observer tends to select a viewing position such that the psychological benefit to be derived from moving closer is just balanced out by the psychological loss due to visible imperfections in the picture structure. Engstrom[2] has shown how this optimum viewing

* Decimal classification: R583. Original manuscript received by the Institute, June 29, 1937. Presented before Silver Anniversary Convention, New York, City, May 12, 1937.

[1] Registered trade-mark, RCA Manufacturing Company, Inc.

[2] E. W. Engstrom, "A study of television image characteristics," Proc. I.R.E., vol. 21, pp. 1631–1651; December, (1933).

distance depends upon detail and size of image. He finds that as the definition of the image is improved, the observer tends to move closer and closer until the viewing distance is about four times the picture height, at which time the image occupies the optimum field of view. This tendency for an observer to select an optimum viewing position is well illustrated by the preference for a centrally located seat in modern motion-picture theaters.

In older experimental television systems providing 120- to 180-line definition, image sizes of about 5×7 inches were entirely adequate for home entertainment purposes where only a relatively few observers were to be accommodated. However, in more recent experimental systems giving up to 300-line definition, the need for images of 8×10 inches or larger is already being expressed. As the resolution is pushed up to the proposed RMA standard of 441 lines,[3] the definition becomes substantially equivalent to a projection print, for which the optimum viewing distance is about four times the picture height. The viewing distance will depend upon the number of observers. To avoid crowding, it is probable that a viewing distance of six to eight feet would be desirable for home entertainment. In this event the picture should be at least 18 inches high. By this reasoning it would seem that an image size of about 18×24 inches will be required to furnish the optimum home entertainment value.

In anticipation of this need, many workers are investigating means for the production of large images. Different systems for accomplishing this result have been proposed. Although the final solution to this problem is not in sight, much can be said in favor of the inertialess electron beam method of tracing out the picture. Inasmuch as it may be impractical to reproduce a picture of large size directly, a very attractive method appears to be one in which an electron beam is used to produce a relatively small primary image which, in turn, may be projected onto a viewing screen of the desired size by a suitable optical system. This idea is not new. Many tests of projection systems have been carried out in the laboratories of the various organizations engaged in television research. Those familiar with these tests have long recognized certain fundamental problems.

Because of the low light-gathering power of the optical system, the original image must be very bright. With conventional optical systems not more than five or ten per cent of the light flux from the original image can be collected and projected to the final image on the viewing screen. The original image must therefore have a light output of some

[3] Latest television standards as proposed by RMA, *RMA Eng.*, vol. 1, pp. 9–13, 18; November, (1936).

ten to twenty times that required to illuminate satisfactorily the large viewing screen.

So long as the light in the primary image is derived directly from the energy in the electron beam, as by fluorescence, this system will require an electron beam of high power. Such an electron beam is not particularly difficult to obtain provided no restrictions are placed upon the spot size or voltage. The real problem arises when one attempts to concentrate a high current beam into a small spot at a moderate voltage so that the required detail can be reproduced in a relatively small image.

Conventional electron guns of the type commonly used in present-day oscilloscopes and Kinescopes may be adapted to projection work

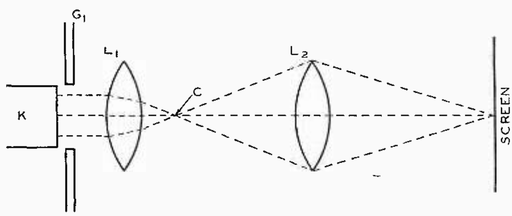


Fig. 1—Schematic optical analogy of an electron gun.

by minor modifications. However, systems utilizing such electron guns have been only moderately successful due to the inability of the electron gun to give a sufficiently large beam current in a small spot. Although improved performance of the electron gun may be obtained by operating it at increased potentials,[4] the electron gun has usually been the limiting factor in projection systems of this type.

Brief Theory of Electron Gun

Before entering upon a detailed analysis of specific problems in connection with electron beam formation, it seems desirable to recall certain fundamental principles underlying the operation of an electron gun.

An electron gun is that device which serves to generate, control, and concentrate the electron beam in a cathode-ray tube. Experience in the design of electron guns[5] has indicated that these functions are advantageously accomplished as indicated in the schematic drawing of Fig. 1. In Fig. 1, a cathode K, generally as an indirectly heated, oxide-coated, unipotential surface, serves as a source of electrons. A control

[4] Kette, "Television receivers for 1936," *Zeit. für Tech. und Kultur des Fernsehwesens und des Tonfilms*, vol. 7, p. 74; October, (1936).

[5] V. K. Zworykin, "Description of an experimental television system and Kinescope," Proc. I.R.E., vol. 21, pp. 1655–1673; December, (1933).

electrode G_1 regulates the number of electrons drawn out and thereby permits modulation of the intensity of the electron beam. A cathode region or first crossover forming lens L_1 concentrates the electron beam into a small diameter at a first crossover C. The electrons emerging from this first crossover are collected and refocused to a small spot on the fluorescent screen by the final focusing lens L_2.

Bush[6] has shown that a sufficiently narrow electron beam will be focused by any nonuniform electrostatic or magnetic field provided these fields have axial symmetry with the beam. Such a field constitutes an electron lens. Because of the large number of geometrical structures that will satisfy this requirement, electron lenses and electron guns assume a variety of forms in the hands of different designers. Picht[7] considers electron trajectories in a continuously varying electrostatic field and treats the focusing system as a thick electron lens. Maloff and Epstein[8] show that certain types of thick electron lenses may be described by a set of constants analogous to those used in ordinary optics. These constants include the location of the focal points and the principal planes. This analogy partly justifies the schematic drawing of Fig. 1 wherein the lenses L_1 and L_2 are to be interpreted as thick electron lenses formed by nonuniform electrostatic or magnetic fields or combinations of the two. By assigning appropriate optical constants to these thick electron lenses, we may approximately represent the system in this schematic manner. Such a representation is entirely satisfactory insofar as the final focusing lens L_2 is concerned. This lens simply reimages some cross section of the beam into a spot on the screen. To produce the smallest spot, the Lens L_2 is adjusted to image the apparent minimum section—usually the first crossover—on the screen. If the size of the first crossover, or electron object, and the optical constants of the lens are known, the magnification of the system for any given set of object and image distances is immediately given by the laws of ordinary geometric optics. Thus, in Fig. 2, if the location of the principal planes H_1 and H_2, the focal distances f_1 and f_2 and the object and image distances U and V are known, the magnification m, is given by

$$m = \frac{a}{b} = V/f_2 = f_1/U$$

and

$$f_1 f_2 = UV.$$

[6] H. Bush, "The calculation of the electron path in an axially symmetric electromagnetic field, *Ann. der Phys.*, vol. 81, p. 974; December, (1926).

[7] J. Picht, "Theory of geometric optics for electrons," *Ann. der Phys.*, vol. 15, p. 926; December, (1932).

[8] I. G. Maloff and D. W. Epstein, "Theory of electron gun," Proc. I.R.E., vol. 22, pp. 1386–1411; December, (1934).

The behavior of the cathode region lens L_1 is not fully described in this simple manner. Although a suitable set of optical constants for this lens might enable one to describe the image it produces, the function of this lens is not to produce an image but to concentrate the beam into a small crossover. The size of this crossover is not uniquely determined by the optical constants of this lens. To describe the crossover,

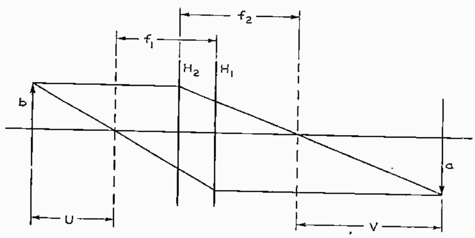


Fig. 2—Optical constants of a thick lens.

we must have additional information about the trajectories of particular electrons in the beam. Although Ruska[9] has carried out an excellent analysis of electron trajectories in a central force field, and although it has been generally recognized that initial velocity of emission plays an important part in determining the size of the first crossover, there has been no available theory describing the characteristics of a first crossover in the general case where the initial velocities are considered to have a Maxwellian distribution and the potential function is not analytic.

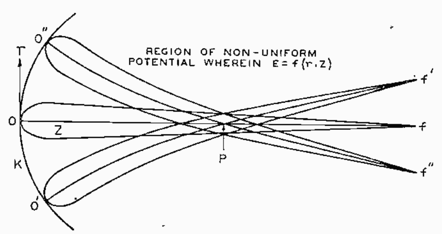


Fig. 3—Generalized representation of a first crossover forming system.

Generalized Analysis of First Crossover

For a generalized analysis of first crossover formation, we may consider any nonuniform potential field having axial symmetry wherein $E=f(r, z)$. Let the cathode K, Fig. 3, conform to one of the equipotential surfaces defined by $E=f(r, z)$. In the absence of space charge we may so choose this potential function that all electrons leaving the cathode with zero velocity of emission will unite in a common point p

[9] E. Ruska, "Focusing of cathode-ray beams of large cross section," *Zeit. für Physik.*, vol. 83, p. 684; July, (1933).

at the crossover. Let us designate the paths of these electrons as principal trajectories. Other electrons leaving the cathode surface with initial velocities of emission will deviate from these principal trajectories by amounts depending upon the magnitude and direction of their initial velocities.

Inasmuch as the nonuniform potential function $E=f(r, z)$ is symmetrical about the axis, it constitutes an electron lens. The action of this electron lens is best illustrated by observing its effect upon a few representative electrons. For example, electrons originating at point o which do not deviate greatly from the principal trajectory will be brought to a common focus at point f. Similarly, electrons originating at adjacent points o' and o'' will be focused at points f' and f'', respectively. For small deviations from the principal trajectory, the force tending to restore an electron to its particular principal trajectory is everywhere proportional to its displacement. Furthermore, the displacement is in turn proportional to the initial radial velocity. Neglecting the effects of initial longitudinal velocity, the deviation of the kth electron from its principal trajectory may be expressed by

$$\delta_k = \sqrt{\frac{E_{\dot{r}_{0_k}}}{E}}\, f(Z)_k \tag{1}$$

where,

δ_k = deviation of kth electron from its principal trajectory
$E\dot{r}_{0_k}$ = initial radial velocity of the kth electron in equivalent volts
E = voltage applied to crossover forming system
$f(Z)_k$ = function of Z describing the deviation of the kth electron from its principal trajectory.

Since all the principal trajectories intersect at a common point p which is on the axis of symmetry at the center of the crossover, the radial position r_k of the kth electron at the crossover is

$$r_k = \sqrt{\frac{E_{\dot{r}_{0_k}}}{E}}\, f(Z)_k \frac{1}{\cos\theta_k} \tag{2}$$

where θ_k is the angle between the kth principal trajectory and the axis of symmetry. In practice θ_k is small so that $\cos\theta_k$ is substantially unity. Furthermore $f(Z)_k$ is substantially the same for all electrons, consequently the radial position of any electron at the crossover is very nearly

$$r = \sqrt{\frac{E_{\dot{r}_0}}{E}}\, f(Z). \tag{3}$$

With reference to any particular potential configuration which forms a crossover at a specified distance Z from the cathode, the function $f(Z)$ must have the dimensions of Z and is dependent upon some proportionality factor F which defines how the potential E is applied to the system. Equation (3) therefore may be written

$$r = \sqrt{\frac{E_{\dot{r}_0}}{E}}\, Z \times \frac{1}{F}. \tag{4}$$

Solving (4) for E_{r_0}

$$E_{\dot{r}_0} = \frac{r^2 E}{Z^2} F^2. \tag{5}$$

If the thermally emitted electrons leaving the cathode surface have a Maxwellian velocity distribution, the current contributed by electrons with initial radial velocity components lying being $\dot{r}_0$ and $\dot{r}_0 + \Delta\dot{r}_0$ is

$$dI(\dot{r}_0) = A\,\epsilon^{-m\dot{r}_0^2/2KT}\,\dot{r}_0 d\dot{r}_0. \tag{6}$$

The ratio of the current due to electrons with initial radial velocities lying between $\dot{r}_0 = 0$ and $\dot{r}_0 = \dot{r}_0$ to the total space current is

$$\frac{I}{I_s} = \frac{A\int_0^{\dot{r}} \epsilon^{-m\dot{r}_0^2/2KT}\dot{r}_0 d\dot{r}_0}{A\int_0^{\infty} \epsilon^{-m\dot{r}_0^2/2KT}\dot{r}_0 d\dot{r}_0} \tag{7}$$

which yields

$$\frac{I}{I_s} = 1 - \epsilon^{-m\dot{r}_0\ /2KT}. \tag{8}$$

If $\dot{r}_0$ be expressed in equivalent volts

$$\frac{I}{I_s} = 1 - \epsilon^{-(e/kT)E\dot{r}_0}. \tag{9}$$

Substituting (5) in (9), the current in the crossover inside the radius r is

$$I = I_s\left[1 - \epsilon^{-(e/kT)(r^2/Z^2)F^2E}\right] \tag{10}$$

where,

e = charge on the particle
k = Boltzmann's constant
T = cathode temperature in degrees Kelvin
Z = cathode-to-crossover distance
r = radius at crossover
E = voltage applied to crossover forming system
F = a proportionality factor depending on the way in which the potential is applied to the system.

For purposes of subsequent analysis it is convenient to abbreviate (10) as

$$I = I_s[1 - \epsilon^{-ar^2E}] \tag{11}$$

where,

$$a = \frac{e}{kT}\frac{F^2}{Z^2}.$$

The current density is also of interest because it gives a physical picture of conditions at the crossover. By differentiating (11) with

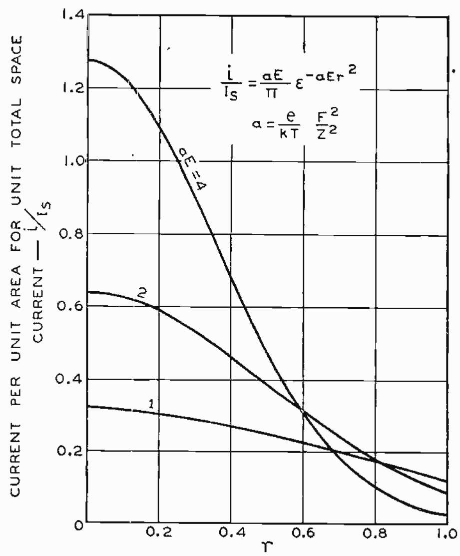


Fig. 4—Computed variation of current density in a crossover.

respect to r and dividing both sides by $2\pi r$, we see that the current density i is

$$i = \frac{I_s}{\pi} aE\epsilon^{-ar^2E}. \tag{12}$$

These last two equations are sufficient to describe many features of the crossover. For purposes of illustration let us suppose that a cathode temperature T, a cathode-to-crossover distance Z, and a potential distribution F are selected such that the coefficient $a = (e/kT)(F^2/Z^2) = 0.001$. In addition, let the voltage across the first crossover forming system assume the values 1, 2, and 4 kilovolts. The parameter aE then assumes the values 1, 2, and 4, respectively. Let us now see what happens at the crossover under these conditions. Fig. 4 shows the variation of current density per unit total space current with radius for these three values of applied voltage computed from (12). The current density is seen to be greatest in the center and has the maximum value $i_m = (I_s/\pi)aE$ amperes per square centimeter. At the lower value of the parameter aE for the case when the applied potential is one kilovolt, the maximum current density is seen to be only 0.32 I_s ampere per square centimeter, and it is observed to drop off very slowly with radial distance. At the higher value of the parameter aE for the case when the applied potential is four kilovolts, the maximum current density is 1.27 I_s amperes per square centimeter, or four times as great, and drops off very rapidly with radial distance away from the

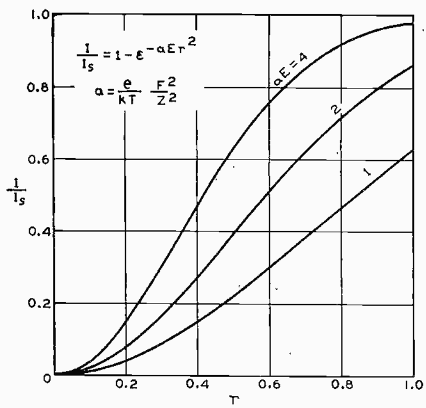


Fig. 5—Computed variation of current through a crossover defining aperture.

center. Thus at the higher voltage the current density at the center of the crossover per unit space current is increased because the beam is concentrated into a smaller crossover. No matter how high the voltage or how large the parameter aE, the edge of the crossover is never sharply defined. Inasmuch as the final spot on the screen will be an image of this crossover, the final spot would not be homogeneous and sharply defined. Instead it would be a spot of high intensity at the center fading off to a poorly defined edge of indefinite size.

This lack of definition has been described by Zworykin.[5] He has inspected photographically the spot on the fluorescent screen of a Kinescope and finds a distribution very closely approximating the curves shown in Fig. 4.

To define sharply the edge of the first crossover and prevent radical changes in its size due to defocusing by modulation, it would be desirable to use a small defining aperture located at the crossover. In contemplation of this we become interested in determining how the current through a first crossover defining aperture depends on the size of the aperture and the parameter aE. Fig. 5 illustrates how the current through a crossover defining aperture varies with the radius of the defining aperture. These plots are computed from (11) for the same values of the parameter aE.

In Fig. 5 it will be observed that larger and larger fractional parts of the total space current may be concentrated into a crossover of given size as the parameter aE is increased. For example, if as before $a = 0.001$, fifty per cent of the total space current may be concentrated into a crossover defining aperture 1.68 millimeters in diameter with a potential of one kilovolt. At two kilovolts, fifty per cent of the total space current may be concentrated into a 1.18-millimeter aperture, while at four kilovolts the same fraction may be concentrated into a 0.84-millimeter aperture. Thus, at higher and higher values of voltage, a given fractional part of the total space current can be concentrated into a smaller and smaller crossover defining aperture.

In addition to the effects of different voltages applied to the crossover forming system, it is evident that any alteration in cathode temperature, crossover forming system geometry, or potential distribution factor which may alter the coefficient a, will have an effect analogous to a change in voltage insofar as concentration of the beam at the crossover is concerned. For example, the curves of Figs. 4 and 5 might be taken to represent a case wherein the applied voltage was constant at one kilovolt and the coefficient a assumed the values 0.001, 0.002, and 0.004, respectively. In the light of these observations we would conclude that the cathode temperature T should be kept as low as possible consistent with satisfactory emission, the voltage E applied to the first crossover forming system should be as high as possible, and the potential distribution should be adjusted to give a large value of F. The proper choice of these factors requires a consideration of other problems and will be discussed in more detail later on.

Experimental Verification of Crossover Theory

The foregoing relationships describing the general characteristics of a crossover have been studied experimentally by structures of the type illustrated in Fig. 6. In these studies the several electrodes were connected to a common potential source through potentiometers of such low resistance that the potential of any electrode was substantially independent of the current drawn by the electrode. The way in which the potential was applied to the system; i.e., the potential function $E = f(Z)$, was adjusted by the positions of the several potentiometers. A variation of the supply voltage was then utilized to change the over-all potential supplied to the system without altering the assigned distribution.

Various potential distributions in different structures have been studied. In each case the distribution was adjusted to satisfy the three conditions:

1. E increasing with Z
2. No current to intermediate electrodes
3. Maximum current through final aperture

To avoid collecting the group of low velocity secondary electrons originating on the edges of the final aperture, the collector electrode was operated at a somewhat lower potential than the final aperture. To provide proper alignment, particularly at low voltages where stray

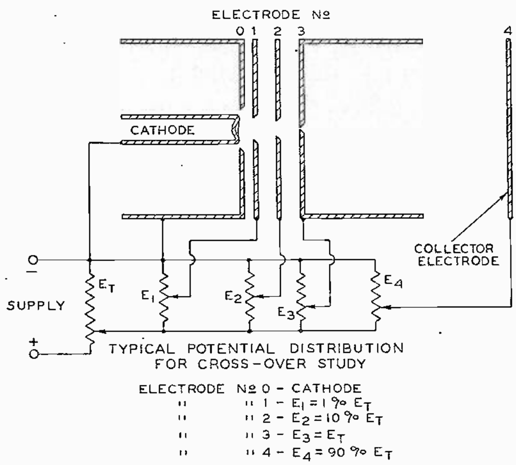


Fig. 6—Beam forming structure and circuit for studying crossover characteristics.

magnetic fields produce large displacements, the crossover was centered on the final aperture by adjusting the position of an external magnet to give maximum current through the aperture.

The results of these studies are illustrated by the following representative data. For purposes of analysis I is the current through the final aperture, I_s is the total cathode current, E is the potential applied to the first crossover forming system, and r is the radius of the final aperture.

The curves of Fig. 7 show log-log plots of the experimentally determined space current and current through the final aperture of the structure shown in Fig. 6 with the indicated potential distribution. In this structure, the 0.1-millimeter diameter final aperture is spaced approximately six millimeters away from a one-millimeter diameter cathode. It will be observed that the total space current varies as somewhat less than the three-halves power of the voltage. Inasmuch as the electrodes adjacent to the cathode are at relatively low potentials, these electrodes substantially shield the cathode from the higher potentials applied to the electrodes adjacent to the crossover. The equivalent diode potential is therefore relatively low and it is not improbable that the deviation of the total space current from the three-halves-power law is due to the effects of initial velocity. This argument is

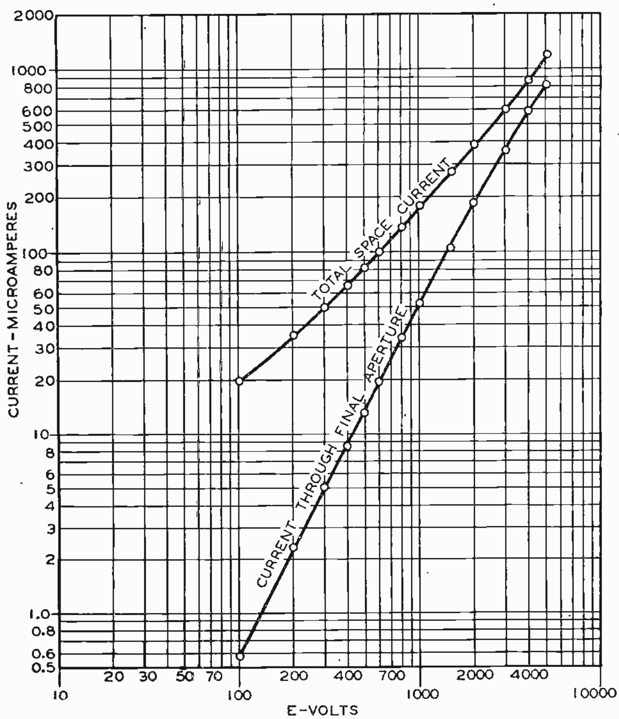


Fig. 7—Typical curves of space current and current through final aperture as a function of voltage applied to first crossover forming system.

strengthened by the fact that the deviation from the three-halves power becomes greater as the applied voltage is less.

Fig. 8 shows a plot of the ratio of I/I_s for the low voltage range of the data portrayed in Fig. 7. The value of the factor ar^2 in (11) may be evaluated from

$$\lim_{E\to 0} \frac{\partial}{\partial E} \frac{I}{I_s} = ar^2. \tag{13}$$

The straight line through the origin tangent to the experimental curve has a slope which yields the value $ar^2 = 3.5 \times 10^{-4}$ reciprocal volts.

The solid line, Fig. 9, shows a log-log plot of the ratio of I/I_s for the full range of the data portrayed in Fig. 7. The dashed line, Fig. 9, shows the calculated ratio of I/I_s using $ar^2 = 3.5 \times 10^{-4}$ in (11).

For the case of an idealized focusing system in the absence of space charge, the coefficient a involves only one unknown factor, the factor F which describes the potential distribution. D. B. Langmuir[10] has described certain theoretical limitations in cathode-ray tubes. From his work, this factor F, and likewise the coefficient a, may be evaluated

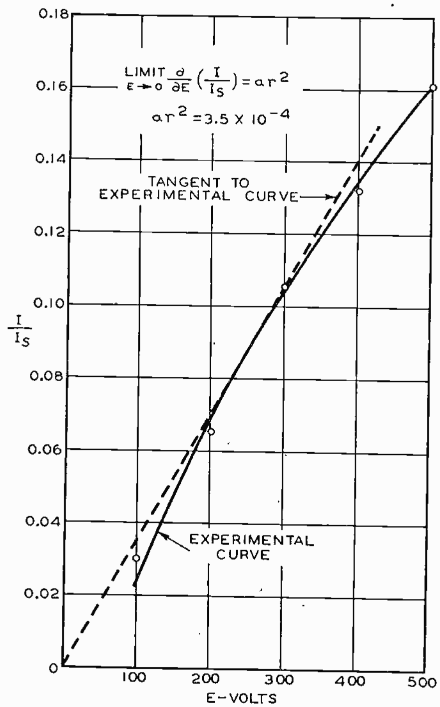


Fig. 8—Evaluation of ar^2 from experimental data.

directly in terms of the spread of the emergent beam. However, because of complications introduced by space charge and imperfections in the focusing system, the value of a so obtained does not agree with the experimentally determined value here presented. The correlation of these results requires a special study which is at present being undertaken.

Fig. 10 shows a log-log plot of the factor ar^2 versus final aperture size. Each value of ar^2 in this plot is obtained from a particular tube

[10] D. B. Langmuir, "Theoretical limitations of cathode-ray tubes," Proc. I.R.E., this issue, pp. 977–991.

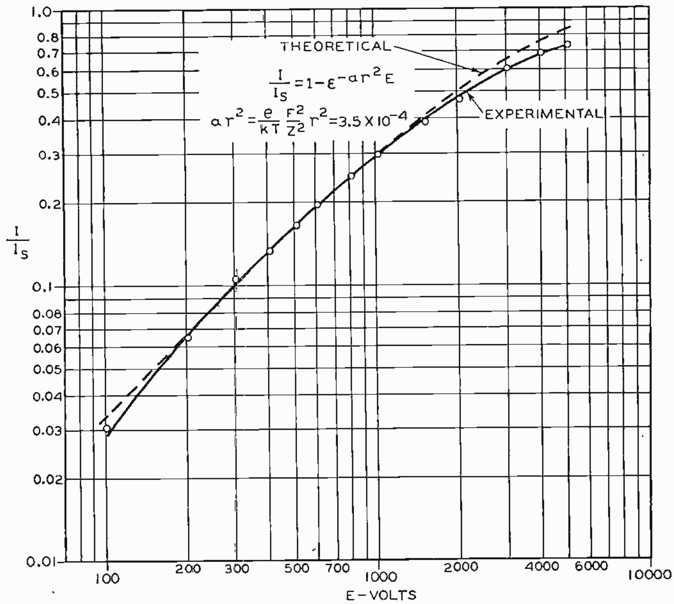


Fig. 9—Ratio of current through final aperture to total space current as a function of voltage applied to first crossover forming system.

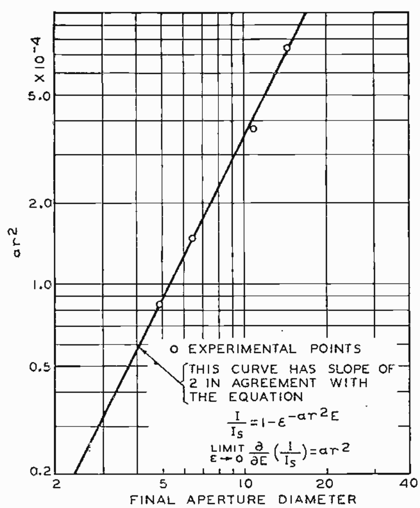


Fig. 10—Variation of ar^2 with final aperture diameter.

in a series of similar tubes with different final aperture sizes. The solid line drawn through the experimental points has a slope of two and indicates the theoretical square-law variation of ar^2 with aperture size.

Although these tests do not inquire into the validity of the complete theory underlying (10), the agreement between the theoretical and experimental curves of Figs. 9 and 10 shows that (11) gives a good account of the variables E and r. These two variables have particular significance in electron gun design.

Application of First Crossover Theory to Electron Gun Design

The design of a complete electron gun requires a consideration of certain other factors in addition to the theory of first crossover formation. First, we must recall that the electrons issuing from the first crossover are to be reimaged on the distant screen by a final focusing lens. The usable aperture of the final focusing lens is limited by its aberrations.[11] As a consequence, the spread of the beam emerging from the first crossover must be kept within the limits imposed by the available aperture of the final focusing lens. Second, the available voltage may be apportioned to the two functions of first crossover formation and final focusing in any desired manner. That is, we may use only a part of the available voltage for first crossover formation, reserving the remainder for final focusing; or, the entire available potential may be used for first crossover formation and final focusing may be accomplished by a magnetic lens or an electrostatic lens of the retarding electrode type.

The significance of these two considerations may be evaluated in the following manner: The useful beam current in a crossover of radius r is given by (11). For purposes of analysis we may suppose the cathode current to be space-charge limited according to the conventional three-halves-power law. In this event

$$I_s \propto \frac{(\text{cathode diameter})^2}{(\text{cathode-to-crossover distance})^2} E^{3/2}.$$

Inasmuch as the spread of the beam is directly proportional to the ratio of the cathode diameter to the cathode-to-crossover distance, this ratio is limited by the permissible beam spread for any particular potential distribution; in practice, therefore, $I_s \propto E^{3/2}$.

If we use full second anode voltage for first crossover formation, the object and image spaces of the final focusing lens will have the same index of refraction and the magnification will depend simply upon the ratio of object-to-image distance. On the other hand, if the first crossover is formed at some voltage E_1 which is a fractional part of

[11] D. W. Epstein, "Electron optical system of two cylinders as applied to cathode-ray tubes," Proc. I.R.E., vol. 24, pp. 1095–1139; August, (1936).

the total voltage E_2, final imaging may give a demagnification due to the differing indexes of refraction in the object and image spaces. Because of this demagnification, we should be willing to accept a larger first crossover at low voltage. This characteristic may be readily analyzed if we neglect the shift in position of the equivalent thin lens and consider the magnification to be

$$m = \frac{\text{image distance}}{\text{object distance}} \sqrt{\frac{E_1}{E_2}}.$$

In this event, a first crossover formed at low voltage might be $\sqrt{E_1/E_2}$ times as large and still give the same final spot size. To illustrate, suppose that the object and image distances are equal, let the required final spot size be one millimeter, and let the available voltage be ten kilovolts. If all the voltage is used for first crossover formation, $E_1 = E_2 = 10$ kilovolts and the magnification is unity. The first crossover defining aperture should then be one millimeter in diameter. If on the other hand the first crossover were formed at some lower voltage, say $E_1 = 2$ kilovolts, the magnification would be $\sqrt{E_1/E_2} = \sqrt{2/10} = 0.45$ and the first crossover defining aperture would be $1/0.45 = 2.22$ millimeters in diameter for the same final spot size. The ratio of the current through the final aperture to the total space current in the two cases is, however, seen to be the same for both cases; that is, $r^2E = (2.22)^2\,(2) = (1)^2\,(10) = \text{constant}$, or, the ratio of beam current to total space current is theoretically the same for either a high or a low voltage first crossover.

From the viewpoint of electron gun design, however, we are not so much concerned with the ratio of beam current to total space current as we are with the actual amount of beam current that can be concentrated into a spot of given size. If we assume the total cathode current to be space-charge limited and to vary approximately as the three-halves power of the voltage, we immediately see the benefit to be derived from using high voltage for first crossover formation for any given value of the coefficient a. Because the ratio of beam current to total space current for a given final spot size is independent of voltage, the total space current and likewise the beam current vary approximately as the three-halves power of the voltage applied to the first crossover forming system. To return to our preceding example where ten kilovolts are available, we would expect an increase in beam current of $(5)^{3/2}$ or approximately tenfold when we changed from a two-kilovolt first crossover forming voltage to one of ten kilovolts. For a given potential distribution in a particular electron beam forming structure which gives a beam of specified spread, it would therefore appear desirable to use all available voltage for first croossover formation provided the permissible cathode emission density is not exceeded.

Details of Electron Gun Design

The detailed design of an electron gun based on these principles is best illustrated by a specific example. Fig. 11 shows a projection Kine-

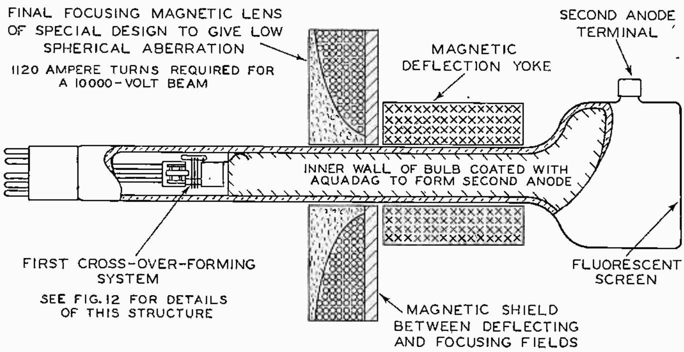
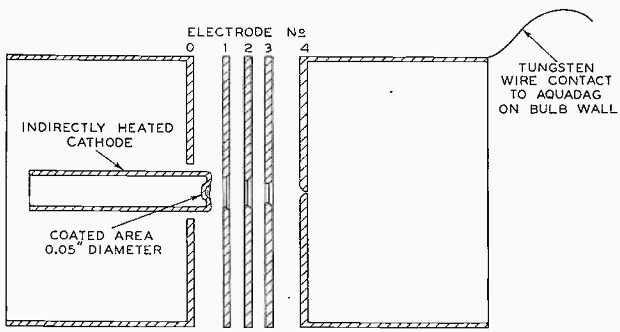


Fig. 11—General assembly of a developmental projection Kinescope.



ELECTRODE No	APERTURE SIZE	ELECTRODE VOLTS
0	0.152"	0
1	0.086	100
2	0.067	200
3	0.052	2000
4	0.004	10000

Fig. 12—Details of the electron gun.

scope utilizing such an electron gun. Fig. 12 gives an enlarged view of the first crossover forming system.

This electron gun uses full available voltage for first crossover formation and has a first crossover defining aperture located at the first crossover. This first crossover defining aperture serves to fix the size of the electron object imaged on the screen by the final focusing lens. The relative voltages applied to the intermediate electrodes Nos.

1, 2, and 3 determine the potential distribution in the first crossover forming system. Modulation of beam current is accomplished by varying the potentials on electrodes Nos. 1 and 2.

Inasmuch as full second anode voltage is used for first crossover formation, the final focusing lens object and image space have the same index of refraction and the final spot size is given by

$$\text{final spot size} = (\text{first crossover defining aperture size}) \times \left(\frac{\text{image distance}}{\text{object distance}}\right).$$

The minimum image distance is fixed by the available deflecting power. The maximum object distance is determined by the available aperture of the final focusing lens and the spread of the beam. It is therefore desirable to keep the spread of the beam low. We have already seen that the spread of the beam emerging from the first crossover increases with cathode diameter. Consequently, the cathode should be as small as is consistent with the desired total space current at a practical emission density. For the particular electron gun here described, it was desired that a total space current of about 4 milliamperes should be available. If we assume 0.5 ampere per square centimeter to be the maximum permissible emission density, the minimum permissible cathode diameter will be about one millimeter.

Because of the effects of space charge, the state of affairs in the cathode region is not well understood. However, experience with beam forming structures of the type illustrated in Fig. 6 shows that a properly curved cathode surface improves the performance of the first crossover forming system. Such a curved surface, limited area cathode also possesses advantages in assembly in that a suitable spacer may be interposed between the cathode and first control-grid electrode for positioning accurately the cathode without contaminating the active emitting surface.

Although final focusing may be accomplished by either magnetic or retarding type electrostatic lenses, the electron gun illustrated in Fig. 11 uses a magnetic lens. This choice was based on an experimental study which showed that larger aberration-free apertures could be obtained with magnetic lenses than with conventional concentric cylinder electrostatic lenses. The reason for this is simple. Although the aberration-free aperture of conventional concentric cylinder electrostatic lenses may be increased by enlarging the lens, this is only accomplished by a sacrifice in magnetic deflection sensitivity which depends upon the bulb-neck diameter. Magnetic lenses located outside the tube envelope are not restricted by bulb-neck diameter and may therefore be made sufficiently large to give aberration-free apertures several times greater than conventional concentric cylinder electrostatic lenses. The magnetic final focusing lens illustrated in Fig. 11 is wound on a spool of special shape in an effort to obtain a more advantageous flux distribution. The iron end-plate provides adequate magnetic shielding to prevent appreciable interaction between the focusing and deflecting fields. This lens has been found to give negligibly small spherical aberration provided the beam diameter does not exceed six millimeters.

Inasmuch as the spread of the beam emerging from the first crossover forming system illustrated in Fig. 12 is about six degrees, the effective object distance should not exceed 60 millimeters. Since the minimum image distance must be about 160 millimeters to give adequate deflection sensitivity, the first crossover defining aperture must be about 0.1 millimeter in diameter to give a 0.25-millimeter spot on the screen. The choice of a 0.25-millimeter final spot is based on a consideration of the picture size and number of scanning lines. The picture size is in turn influenced by the optical system used for projection.

The use of such a small first crossover defining aperture presents problems in heat dissipation and alignment. The edges of this defining aperture are subjected to intense electron bombardment, particularly when the electron beam is defocused by modulation. This defining aperture disk accordingly has been made of molybdenum which is very refractory and has good thermal conductivity. The electron beam must be well centered in the defining aperture if a large fraction of the total space current is to get into the final beam without the use of a centering magnetic field or other adjustment. The necessary precision of alignment has been secured in practice by the use of a special V block method of assembly. The precision of alignment attained is demonstrated by the fact that more than ninety per cent of the total space current may be focused through the 0.1-millimeter first crossover defining aperture under conditions of reduced cathode emission where space-charge defocusing effects are minimized.

Performance of Electron Gun

The projection Kinescope illustrated in Fig. 11 utilizing this improved electron gun readily gives beam currents of 1.5 to 2 milliamperes in a 300-micron spot at a ten-kilovolt operating potential.

The modulation characteristic and current to each electrode with various degrees of modulation is shown in Fig. 13. Inasmuch as the final spot on the screen is an image of an electron object whose size is

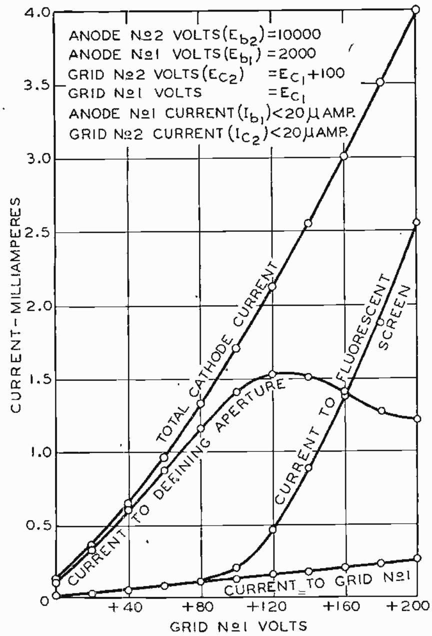


Fig. 13—Characteristics of the electron gun.

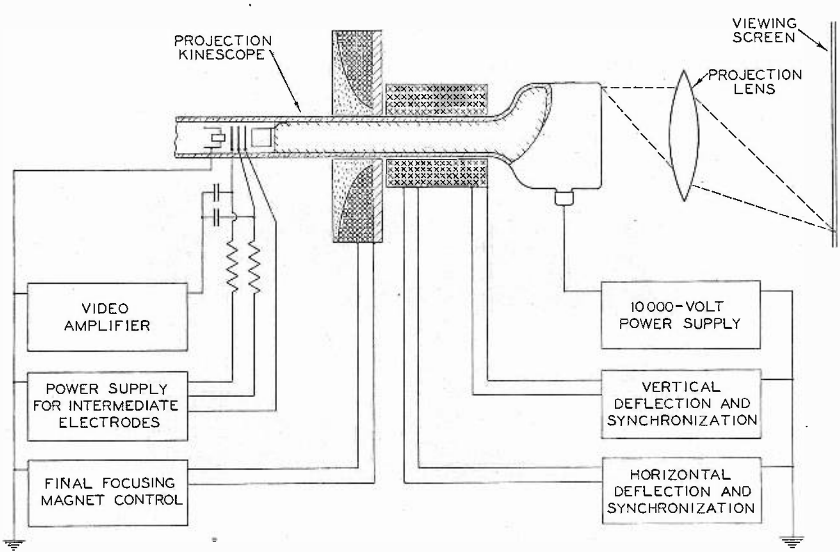


Fig. 14—Block diagram of a projection Kinescope and its associated equipment.

fixed by the first crossover defining aperture, the spot size is substantially independent of beam current provided the permissible space-charge density is not exceeded. Although beam currents of 2.5 to 3 milliamperes can be obtained by extending the grid swing, as shown in Fig. 13, the potential distribution in the first crossover forming sys-

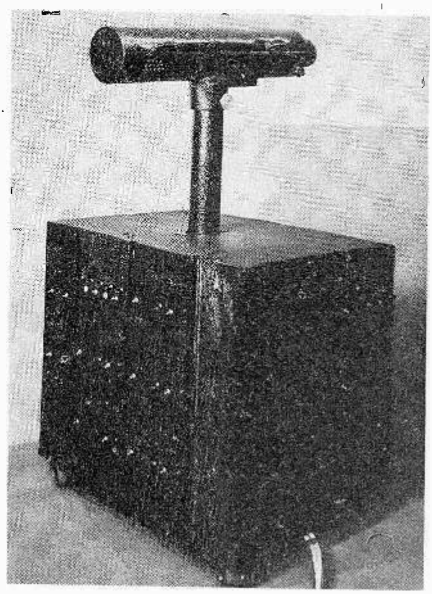


Fig. 15—Laboratory set for demonstrating projection Kinescopes.

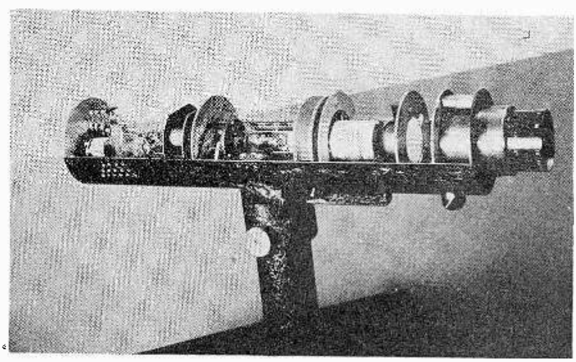


Fig. 16—Projection Kinescope housing opened to show details of the tube mounting and the optical system.

tem becomes unfavorable when the beam current is carried beyond two milliamperes so that the spread of the beam emerging from the first crossover becomes excessive and the spot on the screen is spoiled by the aberrations in the final focusing system.

The complete setup for reproducing television pictures is indicated in the block diagram of Fig. 14. Figs. 15 and 16 show photographs of the projection tube demonstration set shown at the May, 1937, I.R.E. convention in New York City. Fig. 17 shows a photograph of a projected televised image on a 3-×4-foot viewing screen. This picture should not be used as a basis for judging the present status of television, but rather as indicating what can be accomplished with the present projection Kinescope under almost ideal conditions.

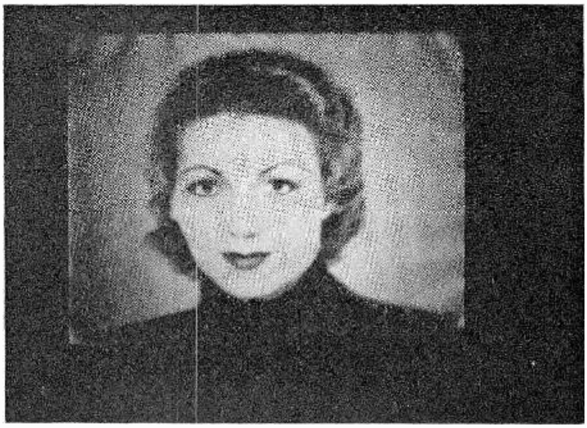


Fig. 17—Photograph of a projected televised image on a 3-×4-foot viewing screen.

The light output of this projection tube using an RCA phosphor No. 3 screen, which is a yellow willemite, in conjunction with an f 1.4 lens of twelve-centimeter focal length, is sufficient to give an 18-×24-inch picture having high lights with an apparent brightness of about 2.7 foot-lamberts when viewed on a 480 per cent directional screen. Although the recommended high-light brightness on motion-picture screens is about ten foot-lamberts, the adaptation of the human eye renders a projected television picture having a brightness of 2.7 foot-lamberts reasonably satisfactory for observation in a darkened room.

There is good evidence for believing that the electron gun is not the limiting factor in this projection Kinescope. The fluorescent screen is definitely overburdened. This is strikingly demonstrated by scanning the fluorescent screen with a heavy unmodulated beam and observing the variation in light output as the electron beam is passed through focus by adjusting the final focusing lens. Although the beam current is constant, the light output is very markedly reduced when the spot is sharply defined showing that the screen material is saturating at the higher energy densities.

Conclusion

It should be pointed out that the particular electron gun here described is in the early stages of development. Further, it is recognized that the present projection system using this electron gun is far from the final goal. It is too early to say that this is the gun best adapted to projection tube work, or that the particular type of projection tube here described is the best way to obtain a large television picture. The writer hopes, however, that this paper will prove to be a useful contribution to the knowledge of the fundamental principles governing electron beam formation and that this electron gun will prove helpful in future developments wherever large beam current in small spot size is required.

Acknowledgment

It is a pleasure here to express my indebtedness to Dr. D. B. Langmuir who pointed out the value of a small defining aperture at the first crossover; to Dr. D. O. North who assisted materially with the background work on the crossover theory; and to Mr. C. E. Burnett whose readiness to help with televised image tests has been of inestimable aid.

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THEORETICAL LIMITATIONS OF CATHODE-RAY TUBES*

By

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Summary—*The current density in a focused beam of cathode rays is shown to have an upper limit defined by* $I = I_0(Ee/kT+1)\sin^2\phi$, *where* I *is the maximum current density obtainable in the focused spot,* I_0 *is the current density at the cathode,* E *is the voltage at the focus relative to the cathode,* T *is the absolute temperature of the cathode,* e *is the electronic charge,* k *is Boltzmann's constant, and* ϕ *is the half angle subtended by the cone of electrons which converge on the focused spot. The cases in which the focused spot is an image of the cathode, and in which it is a pupil, or "crossover", are considered separately, and the above formula is shown to apply to both. The necessary initial assumptions are (1) that electrons leave the cathode with a Maxwellian distribution of velocities, and (2) that the focusing system is free from aberrations and obeys the law of sines. Aberrations may reduce the current density, but nothing can raise it above the value defined.*

In the Appendix the focusing properties of a uniform accelerating field are calculated. The virtual image of a plane cathode formed by such a field suffers from spherical aberration. The diameter of the circle of least confusion formed by electrons from a single point is approximately equal to the distance the electrons can travel against the field by virtue of their initial velocities. This aberration may be the factor which limits the resolving power of some kinds of electron microscopes.

I. INTRODUCTION

MOST electron-optical devices[1] may be classified in two groups. The purpose of one group is to form an image of a surface which emits or is irradiated by electrons in such a way that variations in current density from point to point on the surface are reproduced. Examples of such devices are the electron microscope[1] and the image tube or electron telescope.[2,3] In the other group the aim is to focus electrons from all points of an extended surface into as small an area as possible. The X-ray tube, Kinescope,[4] and cathode-ray oscillograph[1] tube are examples.

* Decimal classification: R388. Original manuscript received by the Institute, June 29, 1937.

[1] No attempt is made here to present a complete list of references. The reader is referred to an excellent summary of the literature: E. Brüche and O. Scherzer, "Geometrische Elektronenoptik," Springer, Berlin (1934).

[1] *Loc. cit.*, p. 214.

[2] W. Schaffernicht, "The electron optical picture transformer, *Zeit. für Tech. Phys.*, vol. 17, p. 596, (1936).

[3] V. K. Zworykin and G. A. Morton, "Applied electron optics," *Jour. Opt. Soc. Amer.*, vol. 26, p. 181; April, (1936).

[4] Registered Trade mark, RCA Manufacturing Company, Inc.

[1] *Loc. cit.*, p. 166.

The existence of a focusing system reasonably free from aberrations is a prerequisite to both these problems. Considerable work has been done experimentally[5,6,7] and theoretically[8] to study and reduce errors in electron lenses. Even though a perfect focusing system existed, there would still be definite limitations upon the performance of any electron-optical device. That the resolution of an image forming type of tube cannot rise above the value determined by the wave length of the electron has been discussed in the literature.[1] Fundamental optical principles define an upper limit also to the intensity of the electron beam produced in the second group of tubes mentioned above.

This paper is primarily concerned with the derivation of formulas for the latter case. In the Appendix some calculations are presented which indicate that in practical cases spherical aberration is more likely to be the limiting factor in image forming tubes than is the electron wave length. The main part of the paper is based on fundamental laws of optics. Brüche and Scherzer have discussed the bearing of these on electron optics in a general way,[1] but so far as the author knows the explicit formulas derived below have not been previously published.

II. Optical Laws Used

Three laws are assumed to be valid. These define, respectively, the quantity which is analogous to the index of refraction in electron optics, the distribution in energy and angle of emitted electrons, and the behavior of rays in an ideal focusing system.

The trajectory of a particle whose total energy is W in a dynamical system where the potential energy is $V=V(x, y, z)$ has the same form as the path of a ray of light in an optical system in which the index of refraction n has a distribution defined by the following equation:[9]

$$n(x, y, z) = \text{const} \sqrt{W - V(x, y, z)}. \tag{1}$$

The quantity, $\sqrt{(W-V)}$, which is proportional to the speed v of the particle in the dynamical system, is therefore analogous to the index of refraction in a corresponding optical system. The ratio of the indexes of refraction at two different points 1 and 2 of either system may then be defined as

[5] M. Knoll, "Electron optics in television technique," *Zeit. für Tech. Phys.*, vol. 17, p. 604, (1936).
[6] D. W. Epstein, "Electron optical system of two cylinders as applied to cathode-ray tubes," Proc. I.R.E., vol. 24, pp. 1095–1139; August, (1936).
[7] R. R. Law, Proc. I.R.E., this issue, pp. 954–976.
[8] O. Scherzer, "The problems of theoretical electron optics," *Zeit. für Tech. Phys.*, vol. 17, p. 593, (1936); and W. Glaser, "Theory of image defects in an electron microscope," *Zeit. für Phys.*, vol. 97, p. 177; October, (1935).
[1] *Loc. cit.*, p. 270.
[1] *Loc. cit.*, p. 39 and p. 171.
[9] Whitaker, "Analytical Dynamics," Third Edition, p. 288.

$$\frac{n_1}{n_2} = \sqrt{\frac{W - V_1}{W - V_2}} = \frac{v_1}{v_2}. \tag{2}$$

If particles of charge e are emitted from a surface with initial kinetic energy equal to E_1e, and then fall through an applied potential difference E_2, the ratio of the final speed to the initial speed will be $\sqrt{(E_1+E_2)/E_1}$. The region immediately adjacent to the emitting surface may be considered as the object space (1), and the region throughout which the potential is E_2 as the image space (2). The ratio of the indexes of refraction of image space to object space is then

$$\frac{n_2}{n_1} = \sqrt{\frac{E_2 + E_1}{E_1}}. \tag{3}$$

It is assumed that electrons are emitted with initial energies defined by the Maxwellian distribution, which can be written as follows:

$$B(E_1)dE_1 = B_0 \frac{E_1e}{kT} \epsilon^{-E_1e/kT} d \frac{E_1e}{kT} \tag{4}$$

where $B(E_1)dE_1$, a function of E_1, is the number of electrons with initial energies between E_1 and E_1+dE_1 emitted per second per unit area per unit solid angle normal to the emitting surface; B_0 is the total number of electrons emitted per second per unit area per unit solid angle; E_1e the kinetic energy with which an electron is emitted; e, the charge on the particle; k, Boltzmann's constant; T, the absolute temperature of the cathode; and $\epsilon = 2.718$. The total number of electrons emitted per second per unit area is $I_0 = \pi B_0$. The quantity B_0 is analogous to the brightness of an optical source.

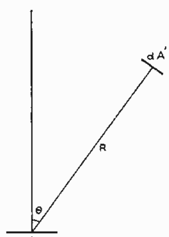

Fig. 1

Lambert's law states that if an area A emits radiation at the rate I_0 per unit area, then an element dA' perpendicular to the line of length r passing through A (Fig. 1) receives the amount of radiation dI' where

$$dI' = \frac{I_0}{\pi} A \frac{dA'}{r^2} \cos \theta. \tag{5}$$

θ is the angle between r and the perpendicular to A.

The amount of radiation between θ and $\theta+d\theta$ will be

$$dI(\theta) = 2I_0A \sin \theta \cos \theta \, d\theta. \tag{6}$$

The total amount of radiation emitted within a cone whose axis is normal to A and whose half angle is α will be found by integrating (6) from zero to α, with the result:

$$I(\alpha) = I_0A \sin^2 \alpha. \tag{7}$$

For small angles we may write $\pi \sin^2 \alpha = \omega$, the solid angle included within the cone, so that then

$$I(\alpha) = \frac{I_0}{\pi} A\omega = B_0A\omega. \tag{8}$$

In any axial focusing system which produces a true image of an extended area (as distinguished from a single point) Abbe's sine law must be satisfied.[10] This states that

$$n_1y_1 \sin \theta_1 = n_ky_k \sin \theta_k \tag{9}$$

where n_1 and n_k are the indexes of refraction; y_1 and y_k, the linear magnitudes of the object and image; and θ_1 and θ_k equal the angles of inclination to the axis of any ray, in the object and image spaces, respectively.

Consider a focusing system which satisfies this law and in which there is an object of brightness B_1 emitting according to Lambert's law. The radiation leaving the object between θ_1 and $\theta_1+d\theta_1$ is, by (6),

$$dI = 2\pi B_1(\pi y_1^2) \sin \theta_1 \cos \theta_1 d\theta_1. \tag{10}$$

In the image space this radiation will intersect the axis at the angle θ_k which is found from (9) to be given by

$$\sin \theta_k = \frac{n_1y_1}{n_ky_k} \sin \theta_1. \tag{11}$$

Differentiating this gives

$$\cos \theta_k d\theta_k = \frac{n_1y_1}{n_ky_k} \cos \theta_1 d\theta_1. \tag{12}$$

Substituting (11) and (12) in (10), there results

$$\begin{aligned} dI &= 2\pi B_1 \left(\frac{n_k}{n_1}\right)^2 (\pi y_k^2) \sin \theta_k \cos \theta_k d\theta_k \\ &= 2\pi B_k(\pi y_k^2) \sin \theta_k \cos \theta_k d\theta_k. \end{aligned} \tag{13}$$

[10] Drude, "Theory of Optics," First Edition, p. 58.

The angular distribution of the radiation is thus the same for the image as for the object. That is, if Lambert's law is obeyed by an emitter, it will be also obeyed by any optical image of that emitter formed by an aberrationless focusing system. In two ways the behavior in the image space differs from that in the object space, and both of these are of special significance in electron optics. First, although radiation may be emitted in all directions from the object, rays converge on the image only through a limited angle defined by setting $\theta_1 = \pi/2$ in (11). Therefore

$$\sin \theta_k \leqq \frac{n_1 y_1}{n_k y_k}. \tag{14}$$

In actual focusing systems this is sometimes of no significance because θ_k may be confined to a still smaller upper limit by the aperture stop. This case will be considered later. We assume for convenience that $n_k h_k > n_1 h_1$.

Second, the brightness of the image is different from that of the object and by comparison of (10) and (13) is seen to be

$$B_k = \left(\frac{n_k}{n_1}\right)^2 B_1. \tag{15}$$

$$= \frac{E_k + E_1}{E_1} B_1 \tag{16}$$

Equations (14) and (15) are so related as to satisfy the conservation principle (of energy for ordinary optics, of current for electronoptics). Since no radiation is absorbed by an ideal focusing system, the amount striking the image must equal the amount leaving the object. If $n_2 = n_1$, (15) becomes the familiar law for ordinary optical instruments that the apparent brightness of a source of light cannot be changed by any focusing process.

III. Current Density in a Focused Electron Beam

A. Focused Spot an Image of Cathode

The reasoning which led to (7) and (13) makes it possible to write down an expression for the current density at an image of the cathode. Consider the particles whose initial energies lie between E_1 and $E_1 + dE_1$, and let $B_2(E_1)$ be the "brightness" of the image formed by this group; i.e., the current per unit area per unit solid angle of these electrons at the image. Then from (7)

$$dI_2 = \pi B_2(E_1) \sin^2 \theta_2 dE_1. \tag{17}$$

The value of B_2 can be found from (15) and (4), while θ_2, which is the angle in the image space between the axis and the path of an electron which left the cathode at grazing incidence, is given by (14). The value of θ_2 will depend upon E_1. If there is an aperture stop in the system, only groups of electrons with initial energies below a certain critical value E_c will pass through the system in their entirety. A group with a higher initial energy will lose part of its current to the aperture. If the half angle subtended by the largest exit pupil permitted by the physical apertures in the system is β, then E_c may be determined from (11) by squaring and setting $\sin\theta_1 = 1$,

$$\sin^2\beta = \frac{n_1^2}{n_2^2}\frac{y_1^2}{y_2^2}$$
$$= \frac{E_c}{E_2 + E_c}\frac{1}{M^2}$$

where M is the linear magnification.

$$E_c = E_2 \frac{M^2\sin^2\beta}{1 - M^2\sin^2\beta}. \tag{18}$$

By substitution in (17) in accordance with (14), (15), and (4) and setting $(n_2/n_1)^2 = (E_2+E_1)/E_1$, the following equations are obtained:

$$dI_2 = \frac{\pi B_0}{M^2}\frac{E_1 e}{kT}\epsilon^{-E_1e/kT} d\frac{E_1 e}{kT} \qquad \text{for } E_1 < E_c \tag{19a}$$

$$dI_2 = \pi B_0(E_2 + E_1)\frac{e}{kT}\epsilon^{-E_1e/kT} d\frac{E_1 e}{kT}\sin^2\beta \text{ for } E_1 > E_c. \tag{19b}$$

The total current density at the image will be given by the sum of the integral of (19a) from zero to E_c, and of (19b) from E_c to infinity. Carrying out this process and substituting $I_0 = \pi B_0$ for the total cathode current density gives

$$\frac{I_2}{I_0} = \frac{1}{M^2}\left[1 - (1 - M^2\sin^2\beta)\epsilon^{-(E_2e/kT)(M^2\sin^2\beta/1-M^2\sin^2\beta)}\right]. \tag{20}$$

The limiting values for large and small M are of interest

$$\frac{I_2}{I_0} = \frac{1}{M^2} \qquad M \text{ large} \tag{21a}$$

$$\frac{I_2}{I_0} = \left(\frac{E_2 e}{kT} + 1\right)\sin^2\beta \qquad M \text{ small.} \tag{21b}$$

Fig. 2 shows a plot of (20). The right-hand portion of the curves corresponds to the case where, since M is large, θ_2 for most of the velocity groups is smaller than β so that only a small fraction of the electrons are intercepted by the aperture. The current density in the image approaches asymptotically the value I_0/M^2 as M is increased. As the magnification is reduced, a larger fraction of the current is intercepted by the limiting aperture and the curve begins to fall below this value. At the left practically all the velocity groups have an initial energy high enough to fill the aperture. In this case, decreasing magnification

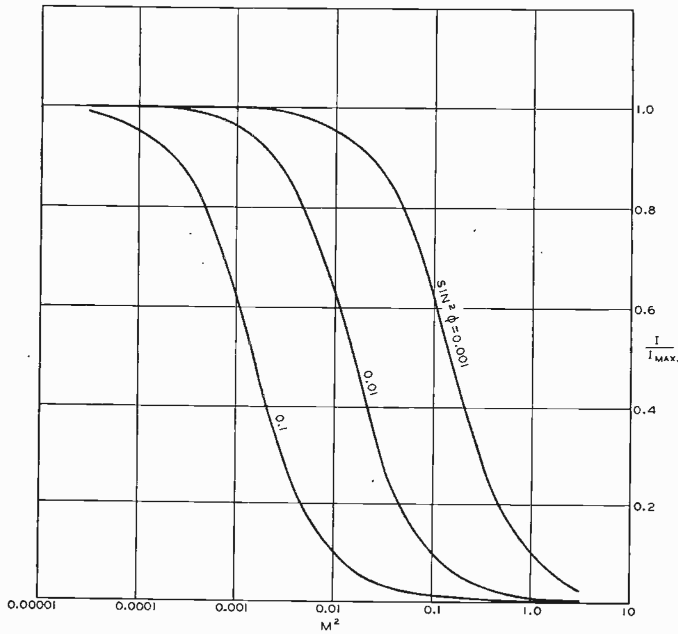

Fig. 2—Current density at image as function of magnification (M) and half angle subtended by beam (ϕ) when $E_2e/kT=10{,}000$. $I_{max}=I_0((E_2e/kT)+1)\sin^2\phi$.

can produce no appreciable further increase in current density. Equation (21b), therefore, defines the maximum current density which can be produced in any image of a cathode.

B. Focused Spot an Image of Exit Pupil

In many types of cathode-ray tubes the focused spot is not an image of the cathode, but instead is either a concentration of rays of the type illustrated at P in Fig. 3, or an image of such a section of the beam. In Fig. 3 rays from the object O have been traced through a thin lens in the conventional way. An image is formed in the plane I. The cross section of the beam in the plane P, sometimes called "crossover," is the exit pupil of the system. The pupil may be defined as the cross section of the beam in the plane perpendicular to the axis at the point where the principal rays intersect the axis.[10] A principal ray is one which occupies the center of the conical bundle of rays which emanate from a point on the object and pass through the system.[10] In ordinary optical instruments the size of the pupil is usually determined by the

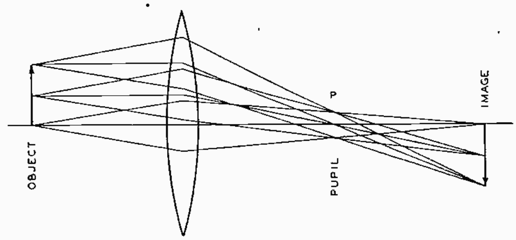

Fig. 3

limiting physical aperture stop. Due to the relatively very high values of refractive index this is frequently not the case in electron optics. All of a certain velocity group of electrons, including those which leave the cathode at grazing incidence, may pass through a focusing system without being intercepted by any aperture. At the cathode the conical bundle mentioned above then fills an entire hemisphere, and the principal rays are the trajectories of electrons emitted normal to the cathode surface.

The diameter of the pupil will depend upon the initial energy of the particle, but in the hypothetical aberrationless focusing field postulated here all energy groups of emitted particles will form their pupils in the same plane. The properties of pupil and image are very dissimilar. With a given focusing system the image size depends upon object size and magnification, independent of initial energy, while the pupil diameter depends only upon initial energy and is independent of object size and magnification. The angle through which rays converge upon

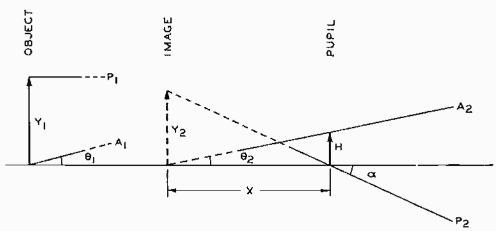

Fig. 4

[10] *Loc. cit.*, p. 73.
[10] *Loc. cit.*, p. 74.

the pupil, provided they are not intercepted by a stop, is a function only of object size. The values of the maximum obtainable current densities at a pupil and an image are identical, however, as now will be shown.

In Fig. 4 let an image y_2 be formed of the object y_1. Let P_1 be a principal ray which intersects the axis at P, and let A_1 be a ray starting at the angle θ_1 from the intersection of the axis with the object. For simplicity it is assumed that the pupil is in a medium of constant index of refraction. From (9)

$$n_1 y_1 \sin \theta_1 = n_2 y_2 \sin \theta_2. \tag{9}$$

From the figure it is also clear that

$$y_2 \tan \theta_2 = h \tan \alpha. \tag{22}$$

Equation (9) is rigorous and holds exactly (in a perfect focusing field) for all values of θ. At the cathode, θ_1 varies from zero to ninety degrees; and, therefore, the exact formula is necessary. If n_2 is considerably larger than n_1, θ_2 will usually vary over a smaller range than θ_1. The following discussion will be limited to the case in which θ_2 and α (Fig. 4) are sufficiently small that the sine of either angle can be substituted for its tangent. When this restriction is applied to (9) and (22), there results

$$n_1 y_1 \sin \theta_1 = n_2 y_2 \sin \theta_2 = n_2 h \sin \alpha \tag{23}$$

$$h = \sqrt{\frac{E_1}{E_1 + E_2}} \frac{y_1}{\sin \alpha} \sin \theta_1 \tag{24}$$

$$dh = \sqrt{\frac{E_1}{E_1 + E_2}} \frac{y_1}{\sin \alpha} \cos \theta_1 d\theta_1. \tag{24a}$$

The current passing through the ring between h and $h+dh$ will be that which is emitted from the cathode between the angles θ_2 and $\theta_2+d\theta_2$; namely,

$$2\pi B_1 A_1 \sin \theta_1 \cos \theta_1 d\theta_1.$$

The current density will be this quantity divided by $2\pi h dh$. On substituting (24) and (24a), the current density in the ring becomes

$$I = B_1 A_1 \frac{E_1 + E_2}{E_1} \frac{\sin^2 \alpha}{y^2}. \tag{25}$$

Each velocity group thus forms a pupil whose radius is given by setting $\sin \theta_1 = 1$ in (24). The current density over the pupil area has the constant value defined by (25). The total current density at a point distant h from the axis will be the sum of the densities for all pupils with radii greater than h; namely,

$$I(h) = A_1 \frac{\sin^2 \alpha}{y^2} \int_{E_1(h)}^{\infty} \frac{E_1 + E_2}{E_1} B_1(E_1) dE_1 \tag{26}$$

where $B_1(E_1)$ is given in (4). $E_1(h)$ is found by solving (24) for h, (setting $\sin \theta_1 = 1$), so that

$$E_1(h) = E_2 \frac{h^2/y^2 \sin^2 \alpha}{1 - h^2/y^2 \sin^2 \alpha}. \tag{27}$$

The integral is

$$1(h) = A_1 B_0 \frac{\sin^2 \alpha}{y^2} \left\{ 1 + \frac{E_2 e}{kT} \left(1 + \frac{h^2 \sin^2 \alpha / y^2}{1 - h^2 \sin^2 \alpha / y^2} \right) \right\} \epsilon^{-(E_2 e/kT)(h^2 \sin^2 \alpha / y^2)/(1 - h^2 \sin^2 \alpha / y^2)}. \tag{28}$$

The current density at the pupil falls off with distance away from the axis.[11] The maximum value occurs on the axis. This value, when $h = 0$, $A = \pi y^2$, and $\pi B_0 = I_0$ are substituted, becomes

$$I_{\max} = I_0 \left(\frac{E_2 e}{kT} + 1 \right) \sin^2 \alpha. \tag{29}$$

Since α is the half angle subtended by the cone of electrons at the spot, this equation is identical with the value obtained for an image, in equation (21b).

IV. Discussion

It is of interest to compare the results derived above from general optical principles with the characteristics of a specific focusing field whose properties are known. Ruska[12] has calculated the trajectories of particles between concentric spheres. Between outer and inner spheres of radius r_a and r_i, respectively, the potential varies as $1/r$. After reaching the anode sphere (which may be either a or i), the electron is assumed to travel in a straight line tangent to the orbit at the anode surface. The result for small angles, when the notation of Fig. 4 is used and the outer sphere is assumed to be the cathode, are

$$h = r_a \frac{E_1}{E_1 + E_2}, \qquad \phi = \frac{y_1}{r_a}$$

[11] See the accompanying paper by R. R. Law;[7] the formulas there are the same for practical purposes as the ones derived here.

[12] E. Ruska, "Focusing of cathode-ray beams of large cross section," *Zeit. für Phys.*, vol. 83, p. 684; July, (1933); and Brüche and Scherzer, "Geometrische Elektronenoptik," p. 101.

so that

$$I_2 = \frac{1}{\pi h^2}\pi y_1^2 I_0 = I_0 \frac{E_2 + E_1}{E_1}\phi^2.$$

If the Maxwellian distribution of velocities is taken into account, E_1 in this formula will be replaced by kT/e, and the value of the current density will be the same as is given by (29).

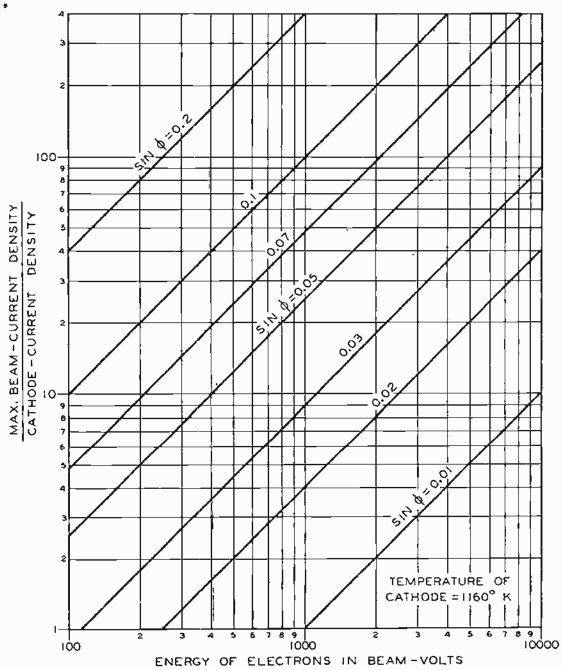

Fig. 5—Curves showing maximum current density obtainable in a focused spot of electrons as function of final voltage and half angle of beam.

Another example is the system consisting of concentric spheres, of which the outer emits an electron current of density I_0. The inner is maintained at a positive potential E and acts as collector. Due to orbital motions some of the emitted electrons clear the anode and fly back to the cathode. As the diameter of the inner sphere is decreased this group becomes an increasingly large fraction of the total emission. The current density at the collector, therefore, does not increase as the reciprocal of its area, but instead approaches a limiting value[13] equal to $I_0(Ee/kT+1)$. This corresponds to (29), with[14] $\sin\phi = 1$.

[13] I. Langmuir and K. T. Compton, "Electric discharges in gases—Part II," *Rev. Mod. Phys.*, vol. 3, p. 229; April, (1931).

[14] The author is indebted to Dr. C. J. Davisson for pointing out this example in the course of a helpful discussion.

Fig. 5 presents the results contained in (29) graphically. In Table I the theoretical current densities obtainable in a focused spot are calculated for some specific cases.

TABLE I

THEORETICAL MAXIMUM CURRENT DENSITY IN FOCUSED SPOT OF CATHODE RAYS

Final voltage $=E_2$
Cathode temperature $=1160°$K

Half angle subtended by beam $=\phi$
Cathode current density $=1$ amp/cm²

E_2 volts	Sin ϕ		
	0.01	0.032	0.10
100	0.1 amp/cm²	1 amp/cm²	10 amp/cm²
1000	1	10	100
10,000	10	100	1000

V. Conclusions

The maximum current density obtainable in a cathode-ray beam is equal to

$$I_0\left(\frac{E_2e}{kT}+1\right)\ \sin^2\phi.$$

Aberrations may reduce the actual value of the current density below this value.

The factors which limit the current density in a cathode-ray beam are therefore:

(1) Aberrations of the focusing system
(2) The cathode current density, I_0
(3) The temperature of the cathode, T
(4) The final voltage, E_2
(5) The half angle subtended by the beam at the final spot, ϕ.

The total voltage is usually limited by practical considerations, and no great gain can be expected from reduction of the cathode temperature. Two major points of attack upon the problem of producing more intense electron beams are, therefore, indicated; namely, the development of cathode surfaces from which higher current densities can be drawn at a given temperature, and the development of focusing fields which can handle beams of wider angle without aberration.

Appendix

In the preceding discussion it was assumed that a perfect focusing system existed. An inquiry into the validity of this assumption has been made by calculating the properties of what seems to be the simplest possible electron-optical system; namely, a plane uniform field. As is shown below, this system shows considerable spherical aberration. These calculations are a specific instance in support of a recent proof by Scherzer[15] that a pure electrostatic field in the absence of space charge cannot constitute a focusing system free from spherical aberration.

Let particles be emitted with initial kinetic energy E_1e at all angles from a plane cathode, and let them move under the influence of a uniform field F normal to the cathode. Consider one emitting point, and let the line through this point normal to the cathode be the axis (Fig. 6)

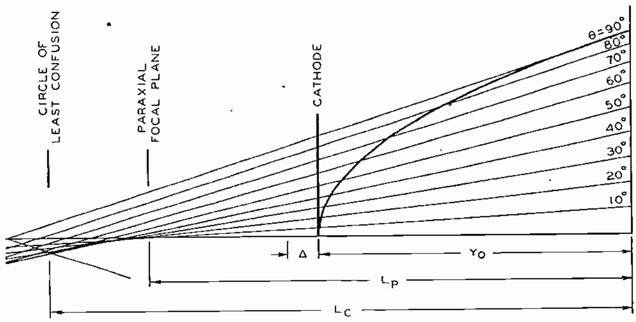

Fig. 6—Spherical aberration in a bundle of trajectories formed by the electrons accelerated in a uniform electric field. Electrons are all emitted with the same speed from the point where the axis intersects the cathode. Tangents to parabolic orbits are drawn at plane S. Heavy curve is trajectory for an electron emitted parallel to the cathode.

Let tangents be drawn to the trajectories at their points of intersection with a plane S which is parallel to the cathode and distant y_0 from it. The point at which a tangent at S extended meets the axis will correspond to an image of the emitting point formed by rays which leave the cathode at a given angle. This image will act as virtual object for a lens, placed at S, which forms an image of the cathode. Spherical aberration in the virtual image formed by the uniform field will be present in a real image formed later even though the rest of the lens system is perfect. Furthermore, the effect of this aberration cannot be corrected by any variation in the focusing means on the side of the plane S away from the cathode. The errors computed here, therefore, are inherent in any image forming device in which electrons are accelerated away from the cathode by a uniform field.

If L equals the distance of the image from the plane S in the negative direction (the image is formed behind the cathode) simple analytic geometry gives the equation

$$\frac{L}{2y_0} = 1 + \frac{\Delta}{y_0}\cos^2\theta - \sqrt{\frac{\Delta}{y_0}\cos^2\theta + \frac{\Delta^2}{y_0^{\,2}}\cos^4\theta}. \tag{30}$$

[15] O. Scherzer, "Errors of electron lenses," *Zeit. für Phys.*, vol. 101, p. 593; July, (1936).

Here $\Delta = E_1/F$, the distance an electron can travel against the field due to its initial energy, and θ = the angle between the axis and the direction of initial emission of the electron. Fig. 7 shows the positions of the paraxial focus and circle of least confusion, and also the diameter of the circle of least confusion as a function of y_0/Δ.

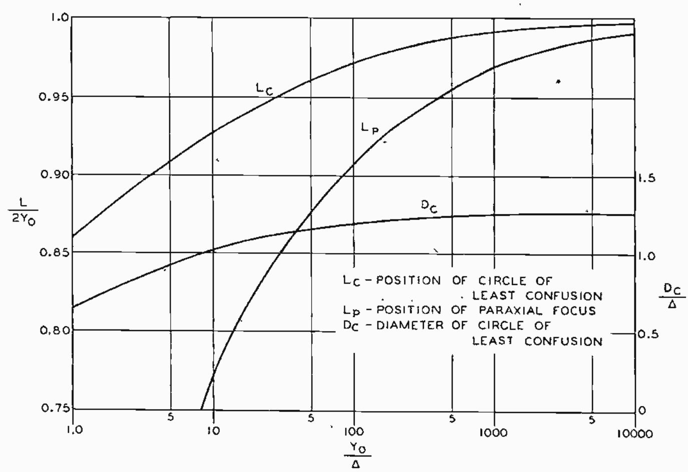

Fig. 7—Image forming properties of uniform field as function of y_0/Δ equals the distance which the electron can travel against the field by virtue of its initial energy.

A significant result is that the diameter of the circle of least confusion is approximately equal to Δ, and is practically independent of y_0/Δ. For large values of y_0/Δ the diameter approaches asymptotically a value equal to about 1.2 Δ. The resolution obtainable for electrons with a given initial energy, therefore, depends only upon the intensity of the electric field which accelerates them away from the cathode. For electrons with 0.1 volt initial energy, a field of 4000 volts per centimeter is necessary to make $\Delta = 2.5 \times 10^{-5}$ centimeter. This value corresponds approximately to the limiting resolving power of an ordinary microscope using visible light. To make $\Delta = 40 \times 10^{-8}$ centimeters, equal approximately to the wave length of a 0.1-volt electron, the field must be 250,000 volts per centimeter.

Symbols

A_1—area of cathode.

B—emission per unit area per unit solid angle in direction normal to surface.

B_0—total emission per unit area per unit solid angle in normal direction.

E_1—initial kinetic energy of emitted electron, in electron volts.
E_2—voltage at focus of electron beam relative to cathode.
e—charge on electron.
h—distance from axis of optical system in plane of pupil.
I_0—total emission per unit area from cathode.
I_2—total current per unit area at focus of electron beam.
M—linear magnification.
n—index of refraction.
k—Boltzmann's constant.
T—absolute temperature of cathode.
y_1—linear magnitude of object.
y_2—linear magnitude of image.
α—angle between axis and principal ray at pupil.
β—largest angle permitted by aperture stop between axis and ray at image.
ϕ—half angle subtended by cone of electrons converging on focused spot. (Includes α and β as special cases.)
θ—angle between axis and any ray.

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A CIRCUIT FOR STUDYING KINESCOPE RESOLUTION*

By

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Summary—*Several of the characteristics of a cathode-ray tube which determine its usefulness as a Kinescope*[1] *for television reception are outlined. Various means for studying these characteristics are discussed.*

A system is outlined for studying Kinescope resolution by breaking the picture into alternate black-and-white picture elements arranged in checkerboard fashion. A practical application of this system is described for a television system using a picture frame of approximately 340 lines repeated thirty times per second. The deflection and grid-signal frequencies that are involved are discussed. The problem of synchronizing these frequencies is covered and the circuits developed for this purpose are described. Some of the results obtained with these circuits are shown.

Introduction

The cathode-ray tube has been considerably improved since it was first suggested for television reception. This special usage has resulted in the development of certain tube characteristics. As the television art has progressed, the resolving power of the cathode-ray tube for television purposes has been increased to keep pace with the other parts of the system. To obtain information for carrying on the development of the Kinescope, it has been necessary to make numerous tests. Many of these tests have required the development of special circuits which, in some cases, have become rather complicated. One such circuit arrangement is described in this paper.

For convenience and clarity this paper is separated into four sections. Some of the fundamental tests and problems of Kinescope resolution are described in Section I. The deflection and grid-signal frequencies that are required for some of the tests, the necessity for synchronization, and the conditions for the selection of the frequencies involved are explained in Section II. The choice of a particular type of circuit for these tests is outlined in Section III; also, a detailed explanation of the developed circuit is given. Photographs and a brief description of the results obtained are presented in Section IV.

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[1] Registered trade-mark, RCA Manufacturing Company, Inc.

I. Tests for Determining Kinescope Resolution

1. Spot Size

One of the most pertinent characteristics of a Kinescope affecting its resolving power is the apparent spot size[2] at optimum focus for various beam currents. The apparent dimensions of the spot can be measured with a calibrated telescope while the beam is stationary, but such readings do not yield satisfactory information for television purposes because the screen luminescence is dependent upon the duration of excitation. Therefore, it is desirable to deflect the beam at a speed comparable to that to be used in regular television scanning and then to read the apparent line width with the telescope. With this system, measurements can be made under the same bias and focus conditions as those used for television reception.

Saw-tooth scanning frequencies are now in use which give a picture frame of approximately 340 lines repeated thirty times per second. Such a pattern may be spread until the individual lines can be examined through a telescope and the width measured. With a 340-line picture, this spread may be obtained with sufficient power in the deflection circuits, but another type of scanning gives equivalent test results and is more convenient for test purposes.

For measuring apparent line width, a sine-wave deflection may be substituted for the usual horizontal saw-tooth deflection. The test results will be the same when the readings are made at the center of a sine wave of such frequency that the velocity at the center of the wave is equal to the velocity of the scan portion of the usual saw tooth. With the same pattern size this method reduces the number of lines in the pattern from 340 to approximately 120 and as a result less deflection power is required to spread the pattern for telescope observations. In the sine-wave pattern, the apparent spot shape may be seen at the edge of the pattern as the beam slows up and then reverses. This affords a convenient means for determining optimum focus conditions and for detecting any peculiarities of the spot.

2. Spot Shape

Most Kinescope tubes are designed so that the beam will give a round spot on the fluorescent screen. Mechanical or electrical imperfections in the electron gun or other parts of the tube or external electrostatic or electromagnetic fields may cause the spot to be distorted. It is desirable, therefore, to be able to check for such distortion when a

[2] For definitions of various cathode-ray terms see T. B. Perkins, "Cathode-ray tube terminology," Proc. I.R.E., vol. 23, pp. 1334–1344; November, (1935).

Kinescope of a new design is being developed and when tubes of the same design are being manufactured.

If no deflection is used and the beam is sufficiently defocused, a good electron image of the cathode can be seen on the screen. This image will reveal any "dead spots" or cracks in the emitting surface. While the spot is thus defocused, the uniformity of cutoff can be observed by varying the control-grid bias. However, under some conditions the spot shape may be different on various parts of the screen or may change with bias and focus conditions. It is preferable, therefore, to make checks on spot shape under normal operating conditions.

When deflection is used on the Kinescope, some idea may be obtained of the spot shape by varying the focus and the bias and watching the variation in light intensity in the scanned line. By noting the edge of a sine-wave pattern, a very good image of the apparent spot shape can be seen. When line-width measurements are made, this method can be used for setting the focus to give the optimum shape.

Experience has shown that it is desirable to determine the spot shape under similar conditions for various points on the screen. One method for doing this consists in moving the pattern about the screen with direct-current fields and making observations on the same portion of the pattern each time. Care should be exercised in using direct-current fields as they may cause spot distortion unless properly applied. Another system which has proved quite useful utilizes a grid signal on the Kinescope to break the pattern into elements of a size approximately equal to the theoretical picture element size for the particular scanning system being used. This method has the advantage of providing for tests under normal bias and focus conditions, of applying the same type signal to all parts of the screen so they may be compared directly, and of showing the response of the Kinescope to a signal which is approximately equal to the highest frequency which is to be reproduced; i.e., of testing the resolving power for such signals. If a portion of the elements are removed by suitable circuit arrangements, the shape of the individual elements can be easily examined. Any distortion of the apparent spot shape is strikingly revealed even though the element is not exactly the apparent spot shape but a slightly elongated spot which results from the movement of the beam by the deflection during the finite time that the grid signal is positive.

As the grid voltage of a Kinescope approaches zero, the spot size may increase due to the inability of the electron gun to focus larger amounts of current. The last-mentioned system can be used very effectively to detect this action if a low frequency, such as twice the vertical deflection frequency, is added to the high-frequency grid signal.

If the low frequency is allowed to drift slightly with respect to the high frequency, the level of the grid signal will change gradually in various parts of the pattern. In reality, this shows the grid-modulation characteristic of the Kinescope under dynamic conditions and more nearly reproduces operating conditions than does a static test made by varying the direct-current grid bias. Fig. 1 illustrates various combinations

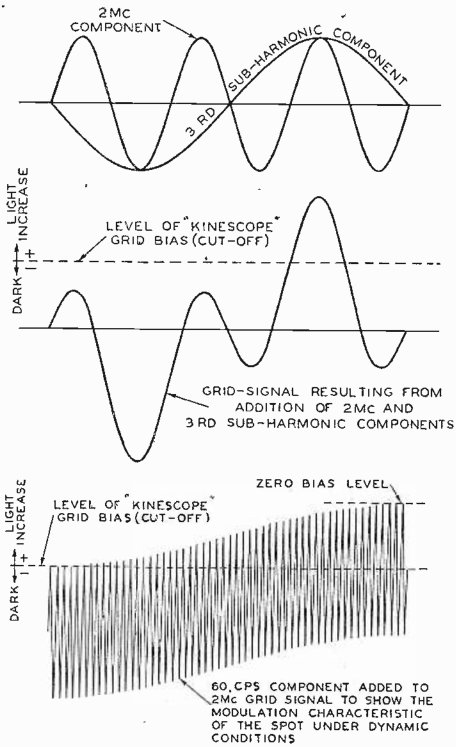

Fig. 1—Grid-signal components.

of frequencies for such a grid signal. It is for this system of using various grid signals that the majority of the circuits which will be discussed was developed.

II. Deflection and Grid Signal Frequencies for Tests

1. Deflection Frequencies

For the purposes of illustration, a television picture of 340 lines repeating thirty times per second will be used. This requires a vertical deflection frequency of 30 cycles and a horizontal frequency 340 times greater or 10,200 cycles. For normal television reception, a saw-tooth deflection can be used which has a ratio of ten to one for the scan and return-line times.

For test equipment, it has been found desirable to reproduce television conditions reasonably accurately, but for some tests a deviation from these is of benefit, such as for the sine-wave scanning previously mentioned. A sine-wave frequency suitable for replacing the horizontal saw-tooth frequency of 10,200 cycles may be found by substitution in the following equation:

$$f_2 = \frac{L_1 R f_1}{L_2 \pi} \tag{1}$$

$$= \frac{R f_1}{\pi} \text{ if } L_1 = L_2 \tag{2}$$

where,

f_1 = frequency of saw tooth
f_2 = frequency of sine wave
L_1 = length of saw-tooth line
L_2 = length of sine-wave line
R = ratio of time for whole saw-tooth cycle to that for scan time

$$f_2 = \frac{11/10 \times 10{,}200}{\pi} = 3570 \text{ cycles, approximately.}$$

The sine-wave frequency will have the same velocity at the center as that of the saw-tooth when the same size pattern is used. If it is necessary to use a slightly different frequency, the velocity may be made equal by varying the pattern size.

2. *Grid-Signal Frequency*

The grid-signal frequency which will break the pattern into alternate black-and-white picture elements can be found from the deflection frequencies and from the aspect ratio which may be taken as five to four.

The following will give the grid-signal frequency:

$$f = \frac{\text{horizontal deflection frequency} \times \text{number of lines} \times \text{aspect ratio}}{\text{number of picture elements per cycle of grid signal}}$$

$$f = \frac{10{,}200 \times 340 \times 5/4}{2} = 2.17 \text{ megacycles, approximately.}$$

3. Synchronization

Various ratios of grid-signal and deflection frequencies can be chosen so as to give a variety of patterns. However, if a definite pattern is to be formed, the grid-signal and deflection frequencies must be synchronized; i.e., a definite ratio between these frequencies must be maintained at all times. If a pattern is selected with a white picture element occurring under a black element the detail may be examined more readily due to the checkerboard appearance. This arrangement may be further improved by suppressing two thirds of the white elements and leaving every third in view. Then if the pattern is spread vertically, each white element remaining will stand out plainly by itself. This manner of bringing every third white element into prominence can be accomplished by adding a frequency, which is the third subharmonic of the grid signal, to the grid signal in proper phase. Of course, this frequency must be synchronized with the others. The grid bias of the Kinescope should be adjusted so that only the positive peak of the resultant grid signal causes beam current to flow. This arrangement is illustrated in Fig. 1.

The values previously given for the deflection and grid-signal frequencies determine the order of magnitude of the frequencies but the final values chosen must have exact ratios which will make them suitable for synchronizing. The choice of these operating frequencies will be outlined in the following paragraph.

4. Choice of Operating Frequencies

Certain conditions must be fulfilled to give a checkerboard pattern.

1. The grid signal must end on a half cycle with respect to the end of each horizontal scanning cycle.

2. There must be an even number of lines in the picture or two checkerboard patterns will be formed which are displaced by a half cycle of the grid signal and each will repeat at one half the vertical frequency. As a result the pattern will appear not to be synchronized when it actually is.

3. The frequencies selected must have ratios which can be maintained with suitable synchronizing.

The frequencies which were selected to meet these conditions are outlined below. The values given are carried out accurately to give a resultant of 30 cycles for the vertical frequency. In practice the system may drift slightly from these values, but the ratios of frequencies will be maintained by the synchronizing.

1. A frequency of 493,920 cycles was selected for the master oscil-

lator. It will be seen that this value has definite ratios with other frequencies selected.

2. The grid signal was chosen as 2,222,640 cycles. Another signal of one third this value or 740,880 cycles was selected to add to the grid signal for suppressing two thirds of the white picture elements resulting from the grid signal. The relations of these frequencies to the master oscillator frequency are seen to be $493{,}920/2\times3\times3=2{,}222{,}640$ cycles and $493{,}920/2\times3=740{,}880$ cycles which is equal to $2{,}222{,}640/3=740{,}880$ cycles. With this choice of frequencies the grid signal will end on a half cycle at each horizontal cycle and thus form the desired checkerboard pattern. This relation accounts for the factor, one half, used in the above equations. A 60-cycle signal was selected for adding to the grid signal to reveal the modulation characteristic. This frequency is not synchronized with the others because it is desirable to have it drift slowly with respect to the other frequencies so that all parts of the pattern will be subjected to the same condition from time to time.

3. The horizontal saw-tooth deflection frequency was taken as 10,080 cycles which is $493{,}920/(7\times7)=10{,}080$ cycles. This gives a picture of $10{,}080/30=336$ lines which is an even number as set down in the conditions.

4. The horizontal sine-wave deflection was taken as 3780 cycles which is $493{,}920/(7\times7\times8)\times3=3780$ cycles. This is higher than the value of 3530 cycles which would be given by (2) for the 336-line picture, but the same velocity as the saw-tooth may be obtained at the center if the horizontal sine-wave deflection is made $3530/3780=93.3$ per cent of the normal picture width. 3780 cycles is the closest frequency to the desired value which can be synchronized conveniently.

5. The vertical saw-tooth deflection was taken as 30 cycles which is $493{,}920/(7\times7\times8\times7\times6)=30$ cycles.

III. Circuits Used for Test

1. Choice of Type of Circuit

The type of circuit selected must be capable of synchronizing frequencies of approximately 30 cycles, 10 kilocycles, 2.2 megacycles. The synchronization must be very "tight" to prevent pattern shift or drift so that examination can be made with a telescope. From a maintenance and operation viewpoint, the circuits should have good operating stability.

A low-frequency oscillator with frequency multiplication was tried, but numerous stages of multiplication and filtering made this system undesirable. This arrangement places severe demands on the frequency stability of the master oscillator because all the variations are multiplied.

The reverse arrangement is to use a high-frequency oscillator and to divide down to the desired frequencies by synchronizing other oscillators on various subharmonics. This arrangement has the advantage of dividing the errors of frequency drift. Various types of oscillators were tried for synchronizing on subharmonics and the following general conclusions were drawn from the results obtained:

Oscillators using tuned circuits of L and C have too much frequency stability to synchronize "tightly." Blocking type oscillators[3] synchronize satisfactorily but fail to oscillate above 300 kilocycles without spe-

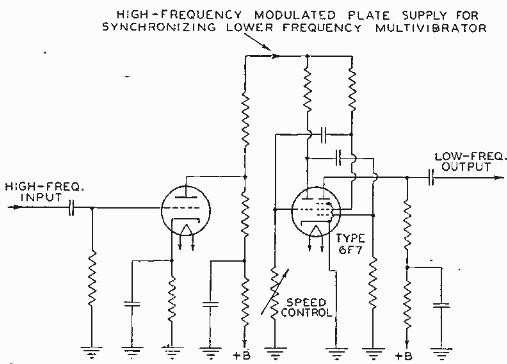

Fig. 2—Circuit showing type 6F7 as multivibrator arranged to synchronize on subharmonic of higher frequency supplied through another tube.

cial arrangements. Multivibrators[4] made with the 6F7 type of tube require only R's and C's for circuit constants, but fail to oscillate above 300 kilocycles without special arrangements.

A multivibrator made with a 6F7 type of tube utilizes the triode section of the tube and the cathode, control grid, and the screen grid of the pentode section to form the multivibrator. The electronic coupling to the plate of the pentode section permits loading in this circuit without affecting the action of the multivibrator particularly. Reference to the circuit diagram in Fig. 2 will clarify this arrangement.

A compromise circuit arrangement was found to meet the conditions of the problem. A master oscillator with a stable frequency char-

[3] For explanation of the blocking oscillator see R. S. Holmes, W. L. Carlson, and W. A. Tolson, "An experimental television system," Proc. I.R.E., vol. 22, p. 1277; November, (1934).

[4] The multivibrator is a two-stage resistance-coupled amplifier in which the voltage developed in the output of the second tube is applied to the input of the first tube, and as a result, the system oscillates. For a further explanation of the multivibrator see F. E. Terman, "Radio Engineering," p. 273–277; (1932), published by McGraw-Hill.

acteristic was chosen to give a frequency which was as high as possible but still sufficiently low to permit the use of multivibrators for synchronizing on subharmonics. The grid signal was obtained by frequency multiplication and the scanning frequencies by subdivision of frequencies. This system has the advantage of good frequency stability and of "tight" synchronization.

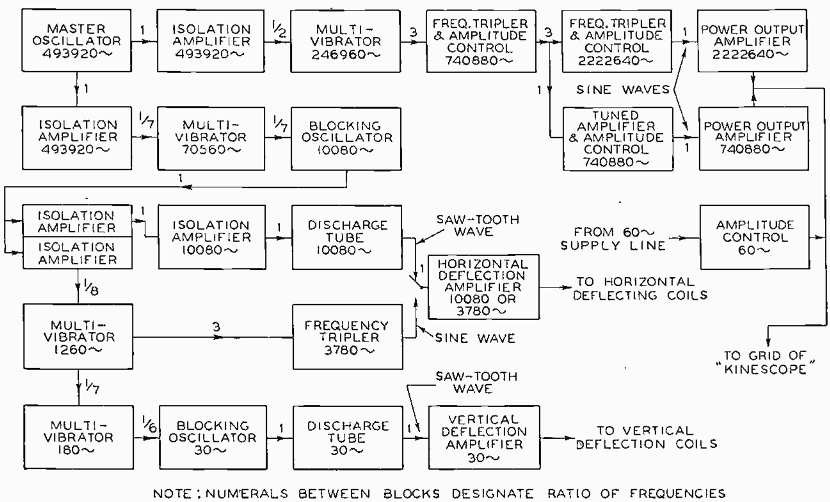

Fig. 3—Block diagram of circuit for studying Kinescope resolution.

2. Arrangement of Circuits Developed

a. Grid Signal

A multivibrator is synchronized on the second subharmonic of the master oscillator frequency which is supplied through an isolation amplifier. The multivibrator frequency is $493{,}920/2 \doteq 246{,}960$ cycles. See Fig. 3.

A combination amplitude control and frequency tripler is driven from the plate of the pentode section of the 6F7 used for the multivibrator. A supercontrol type of tube is used for this purpose and the grid bias is varied to obtain an amplitude control which is relatively free from phase shift. The frequency tripler is tuned in the plate circuit to $246{,}960 \times 3 = 740{,}880$ cycles.

Another combination amplitude control and frequency tripler is driven from the first tripler. A supercontrol type of tube is used with a tuned plate circuit which is resonant at $740{,}880 \times 3 = 2{,}222{,}640$ cycles. This is magnetically coupled to the tuned-grid circuit of a power output tube to increase the selectivity to the desired 2,222,640 cycles. A resistive plate impedance is used with the power tube to give a broad-band response for use with the 740,880 and 60 cycles which are added to the Kinescope grid signal at this point.

A third amplitude control is made with a supercontrol type of tube and driven from the first frequency tripler. The plate circuit of this tube is tuned to 740,880 cycles. A small variable condenser across the tuned circuit serves for a phase control so that this frequency and the 2,222,640 cycles can be added in the desired phase. This system gives sufficient phase control without seriously affecting the amplitude of the lower frequency. The low-frequency output is obtained through a power tube similar to that used for the high frequency. A resistive plate impedance is used to transmit the necessary band of frequencies. The grid of this tube may be grounded when desired to remove all of the 740,880-cycle frequency component.

The 60-cycle component used for showing the grid modulation characteristic is introduced from the supply line, and the rate of drift with respect to the other frequencies is controlled by varying the frequency of the master oscillator. A suitable potentiometer is used for an amplitude control and isolating resistors are used to avoid shunting the plate impedances of the power tubes.

b. Horizontal Deflection

A multivibrator is synchronized on the seventh subharmonic of the master oscillator frequency by using a plate supply modulated with the master oscillator frequency which is supplied through an isolation amplifier. This multivibrator frequency is $493{,}920/7 = 70{,}560$ cycles.

A blocking type oscillator is synchronized on the seventh subharmonic of this multivibrator frequency by introducing a small amount of the frequency into the grid circuit of the blocking oscillator. The frequency of the blocking oscillator is $70{,}560/7 = 10{,}080$ cycles.

The impulse from the blocking oscillator is used to control a discharge tube which with a condenser is used for generating the saw-tooth wave for horizontal deflection. The amplitude of the saw-tooth is controlled with a suitable potentiometer.

The sine wave for the horizontal deflection is obtained as follows: A multivibrator is synchronized on the eighth subharmonic of the blocking oscillator frequency by using a plate supply modulated with the blocking oscillator frequency which is supplied through an isolation amplifier. The multivibrator frequency is $10{,}080/8 = 1260$ cycles.

A frequency tripler is driven with part of the output of the multivibrator and works into the power output tubes which have a load tuned to the tripler frequency of 3780 cycles. The grid circuit and plate circuit of the tripler are tuned to 3780 cycles and a high impedance potentiometer is used across the output of the tripler so that the amplitude of the sine wave may be varied from zero to maximum.

The horizontal deflection can be changed from sine-wave to saw-tooth or vice versa by means of a small toggle switch that simultaneously removes the resonating condenser used across the load for the sine-wave and connects the grids of the power output tubes to the saw-tooth voltage.

c. Vertical Deflection

A multivibrator operating at 180 cycles is synchronized on the seventh subharmonic of 1260 cycles by using a plate supply modulated with 1260 cycles. This supply is taken from the pentode plate of the 6F7 forming the 1260-cycle multivibrator.

A blocking type oscillator is synchronized on the sixth subharmonic of the 180 cycles by introducing a small amount of the multivibrator output into the grid circuit of the blocking oscillator. This frequency is $180/6 = 30$ cycles.

The impulse from the blocking oscillator is used to control a discharge tube which with a condenser is used for generating the saw-tooth wave for vertical deflection. The amplitude of the saw-tooth is controlled with a suitable potentiometer that works into the power output tube. When a normal size picture is used, a saw-tooth wave of good linearity is desired, but when the pattern is spread vertically, this wave shape may be distorted on the ends provided the central portion which will show on the screen has good linearity. Therefore, in addition to the potentiometer used for controlling the vertical deflection, a small toggle switch is used to change to large deflections, or vice versa, by simultaneously increasing the saw-tooth voltage on the potentiometer and reducing the grid bias on the power output tube. This results is increased deflection with good linearity on the portion of the pattern showing on the Kinescope, but distorts the saw-tooth wave which produces that part of the pattern deflected off of the screen by the increased amplitude.

Both the horizontal and the vertical deflection circuits are arranged so that a direct-current component may be added to the deflection and thus give a control for the centering of the pattern on the screen of the Kinescope.

IV. Examples of Results

Figs. 4 to 11 inclusive, are photographs made of various pattern arrangements obtained with the test circuits. Fig. 4 shows a normal size picture consisting of 336 lines. Approximately five of these lines occur during the vertical return-line time and may be seen distributed across the pattern. If the pattern is examined through a magnifying glass, a checkerboard arrangement of small white dots can be seen over

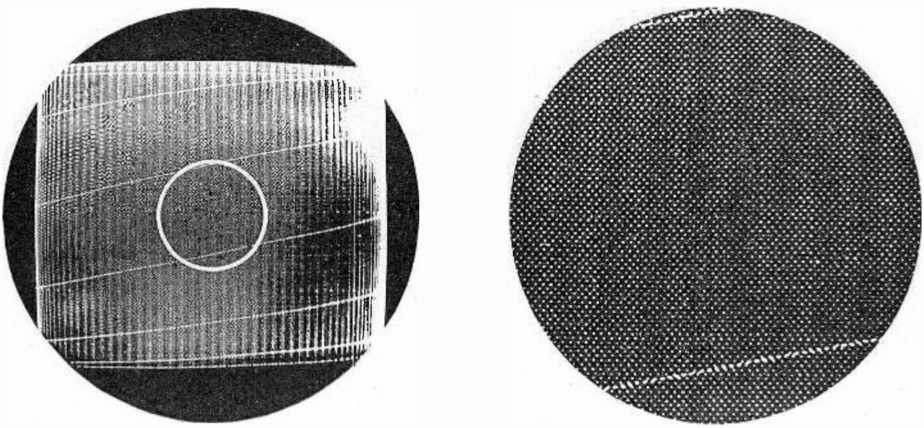

Fig. 4
(Left)—Initial test pattern.
(Right)—Area within white circle shown on above pattern enlarged four times to show detail.

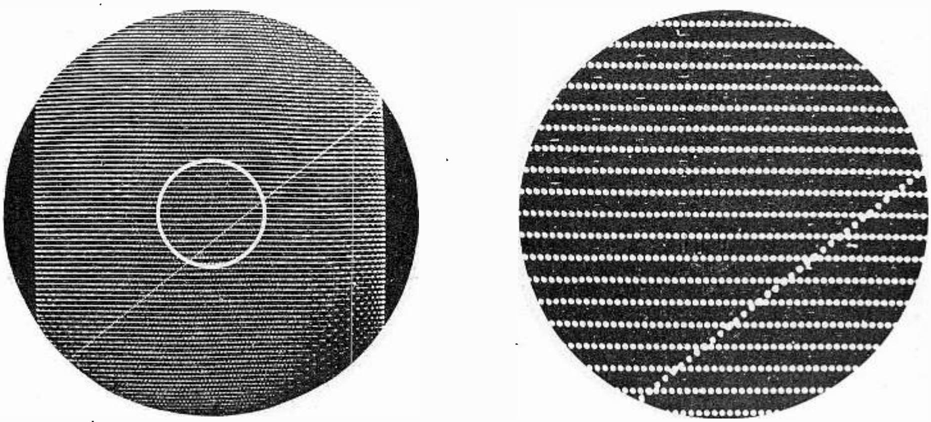

Fig. 5
(Left)—Same test pattern as shown in Fig. 4 but spread vertically to show individual scanning lines.
(Right) Area within white circle shown on above pattern enlarged four times to show detail.

most of the pattern. This is the pattern which results when the control grid is modulated with the two-megacycle (approximately) signal suitably synchronized with the deflection frequencies. The vertical bars are formed by the modulation which occurs during the horizontal return-line time. Because the velocity of the return line is approximately ten times that of the scan line, the dot becomes a dash which is ap-

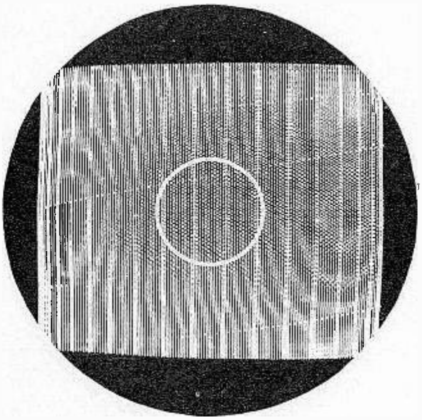
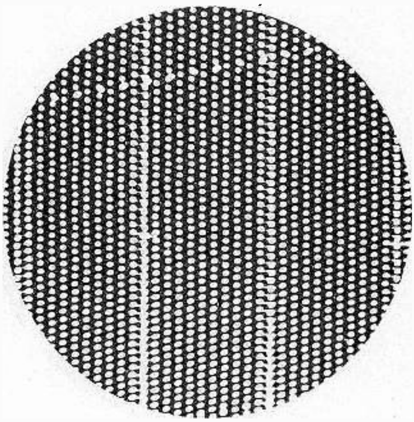

Fig. 6
(Left)—Same test pattern as shown in Fig. 4 except that two thirds of white elements are removed.
(Right)—Area within white circle shown on above pattern enlarged four times to show detail.

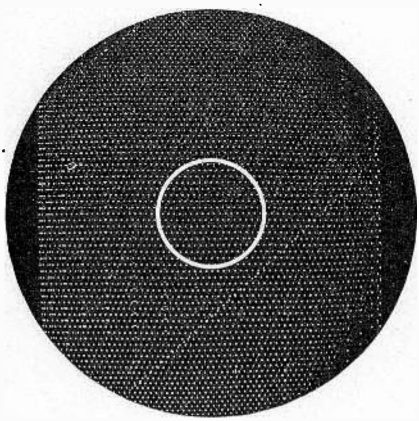
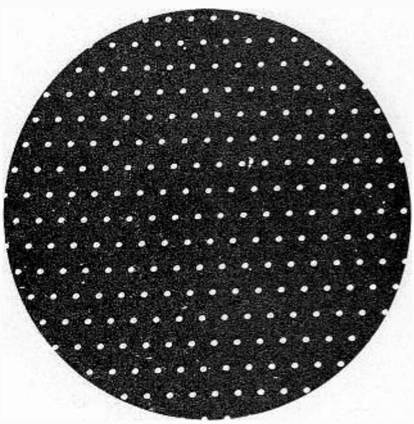

Fig. 7
(Left)—Same test pattern as shown in Fig. 6 but spread vertically to show individual scanning lines.
(Right)—Area within white circle shown on above pattern enlarged four times to show detail.

proximately ten times the length of the dot. Since these dashes occur at the same locations in the lines, they give the pattern the appearance of having vertical bars. In some portions of the pattern, the individual dots cannot be seen because the beam has become defocused. This demonstrates how detail is lost in a picture when the Kinescope focus is not sufficiently sharp or when the beam is too large. It may be seen

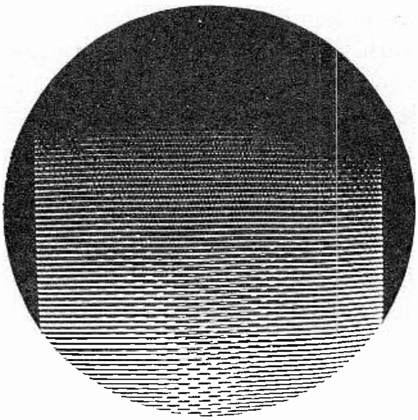
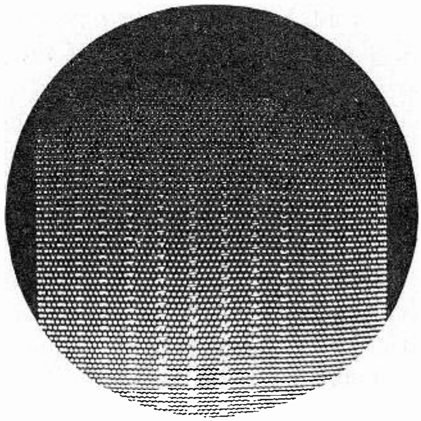

Fig. 8 Fig. 9

Fig. 8—Test pattern showing dynamic modulation characteristic.

Fig. 9—Same test pattern as shown in Fig. 8 except that two thirds of white elements are removed.

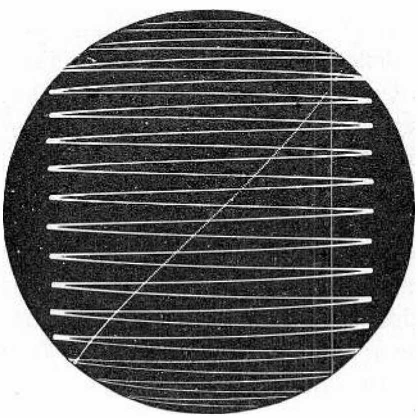
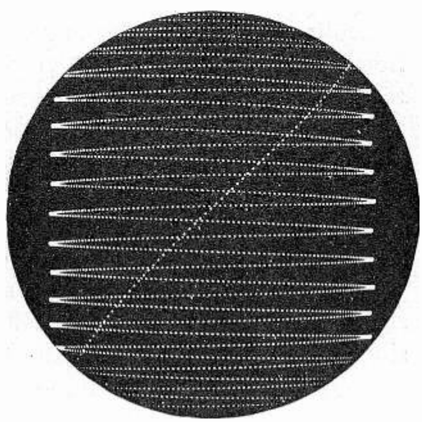

Fig. 10 Fig. 11

Fig. 10—Same test pattern as shown in Fig. 5 except that sine-wave instead of saw-tooth horizontal scanning is used.

Fig. 11—Same test pattern as shown in Fig. 10 except that two thirds of white elements are removed.

that there is a small amount of irregularity in the checkerboard formation. This results from a small amount of pickup in the horizontal deflection circuits. From a practical viewpoint this is not objectionable because it only affects the symmetry of the pattern slightly.

Fig. 5 is the same as Fig. 4 except the vertical deflection has been increased until each individual line may be seen. In this picture the horizontal return lines can be traced from line to line by following the dashes. Around the edges of the pattern the defocusing is clearly revealed.

It is evident from Figs. 4 and 5 that in certain portions of the pattern the beam is larger. This can be more clearly shown if two thirds of the dots are removed. Fig. 6 shows a normal size picture with such a condition, but this does not make the situation as clear as might be. If the pattern is spread vertically as shown in Fig. 5, the dots will stand out sharply so each may be seen without difficulty. This condition is shown in Fig. 7. From a close examination, it may be seen that the spots may even vary in shape in various portions of the pattern. Some indication as to whether this difficulty is being caused by the tube or the deflection system can be obtained by revolving the tube with respect to the deflection coils while such a pattern is being used and noting any change in the shape of the spots.

As more beam current is caused to flow by changing the voltage on the control grid of the Kinescope toward zero, the beam may increase in size and cause a loss in detail. It was pointed out that this difficulty could be shown under dynamic conditions by using a low frequency, such as twice the vertical deflection frequency, and adding to the grid signal. Figs. 8 and 9 show two examples of such a test. The pattern in each case has been spread vertically to permit close examination. Fig. 8 shows the pattern with all of the dots present while Fig. 9 shows the same with two thirds of the dots removed. The gradual increase in spot size is clearly shown as the beam current increases when the mean value of the control-grid voltage approaches zero.

It was pointed out that for some tests it was desirable to use a sine wave for the horizontal deflection provided the velocity of the sine wave at the center was the same as the scan portion of the sawtooth deflection. Figs. 10 and 11 show two samples of such a sine wave; Fig. 10 with all of the dots, and Fig. 11 with two thirds of the dots removed. A check on the equality of the velocity of the two deflections may be made by comparing the spacing of the dots in the center of the sine wave with those on the scan portion of the saw tooth.

Fig. 12 shows a rear and front view of the completed test circuits as built in rack and panel form. In addition to amplitude controls, speed controls are brought out on the panels for the individual multivibrators and oscillators because it is sometimes desirable to vary them slightly if the system falls out of synchronism. The high degree of synchronism which has been obtained is shown by the fact that the pic-

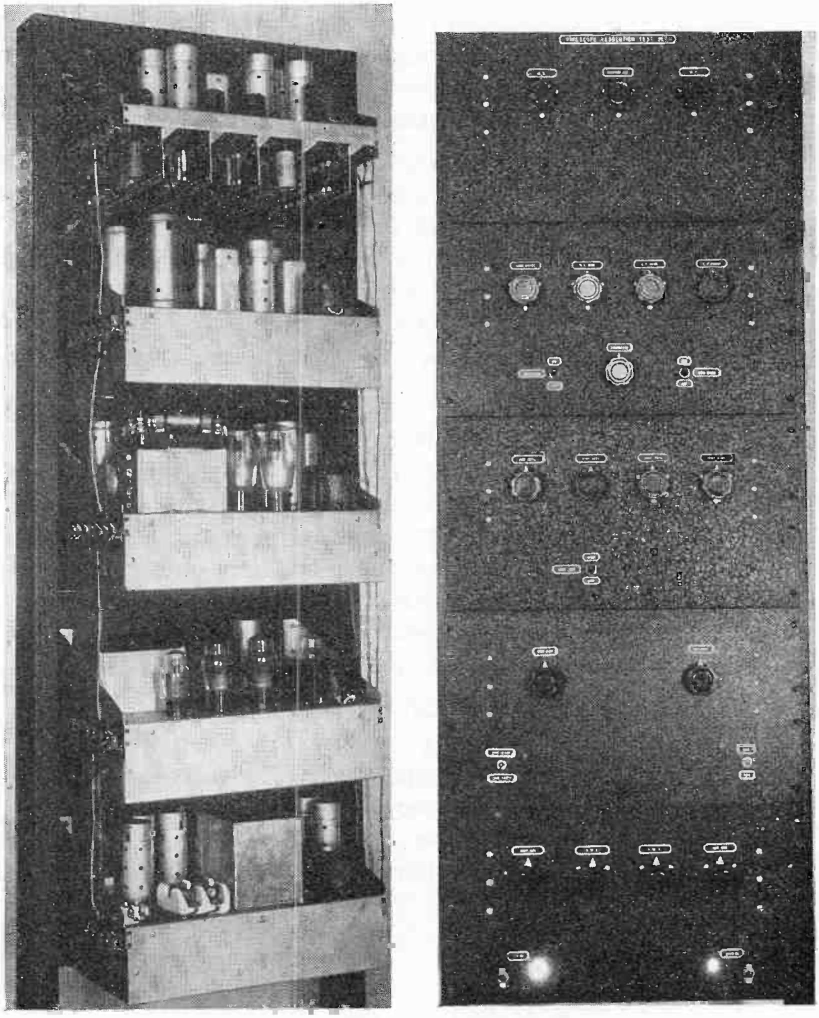

Fig. 12—Rear and front views of test equipment for studying Kinescope resolution.

tures of the various patterns were made with time exposures varying from ten to twenty seconds. The general operating stability of the whole system, since its completion over a year ago, has been very gratifying.

ACKNOWLEDGMENT

The writer wishes to express his appreciation to Mr. J. P. Smith, Victor Division, RCA Manufacturing Company, who first explained to him the intricacies of the synchronizing problem and in particular for his suggestion to use the 6F7 type of tube as a multivibrator for this purpose.

SUPPLEMENT

A variety of interesting patterns can be made with the test equipment if various voltages which occur in the synchronizing chain are added to the usual Kinescope grid signal. The patterns shown in the following photographs were made on a nine-inch Kinescope using full magnetic deflection and a second anode potential of 6000 volts. The outline given below shows the deflection frequencies and the grid signal frequencies which were used to form the patterns. All of the frequencies were synchronized.

No. 1. Deflection: Vertically, 30 cycles saw-tooth
Horizontally, 10,080 cycles saw-tooth

Grid
1. 30 cycles square-wave, negative portion the width of vertical deflection return-line time
2. 10,080 cycles square-wave, negative portion the width of horizontal deflection return-line time
3. 246,960 cycles square-wave
4. 1260 cycles square-wave

No. 2. Deflection: Vertically, 30 cycles saw-tooth
Horizontally, 10,080 cycles saw-tooth

Grid
1. 30 cycles square-wave, negative portion the width of vertical deflection return-line time
2. 10,080 cycles square-wave, negative portion the width of horizontal-deflection return-line time

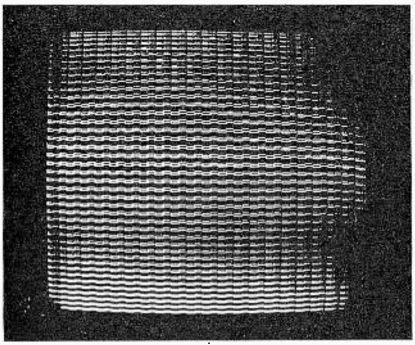

Fig. 1

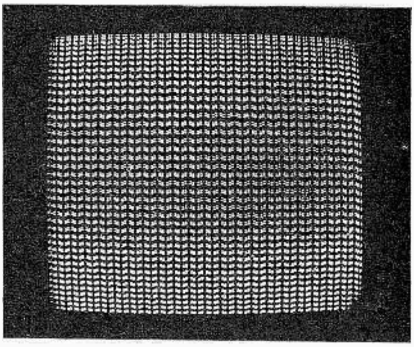

Fig. 2

3. 740,880 cycles sine-wave
4. 246,960 cycles square-wave
5. 1260 cycles square-wave.

No. 3. Deflection: Vertically, 30 cycles saw-tooth
Horizontally, 10,080 cycles saw-tooth

Grid
1. 30 cycles square-wave, negative portion the width of the vertical-deflection return-line time
2. 10,080 cycles square-wave, negative portion the width of the horizontal-deflection return-line time
3. 2,222,640 cycles sine-wave
4. 740,880 cycles sine-wave
5. 246,960 cycles square-wave
6. 70,560 cycles square-wave
7. 1,260 cycles square-wave
8. 180 cycles square-wave

No. 4. Deflection: Vertically, 30 cycles saw-tooth
Horizontally, 3780 cycles sine-wave plus small component of 1260 cycles

Grid
1. 30 cycles square-wave, negative portion the width of the vertical-deflection return-line time
2. 70,560 cycles square-wave

No. 5. Deflection: Vertically, 30 cycles saw-tooth
Horizontally, 3780 cycles sine-wave plus small components of 1260 and 180 cycles
Phase of horizontal deflection is changed from that in No. 4.

Grid
1. 30 cycles square-wave, negative portion the width of the vertical-deflection return-line time
2. 70,560 square-wave

No. 6. Deflection: Vertically, 30 cycles saw-tooth
Horizontally, 3780 cycles sine-wave plus small components of 1260 and 180 cycles
Phase is shifted slightly from No. 5

Grid
1. 30 cycles square-wave, negative portion the width of the vertical-deflection return-line time
2. 3780 cycles sine-wave
3. 70,560 cycles square-wave

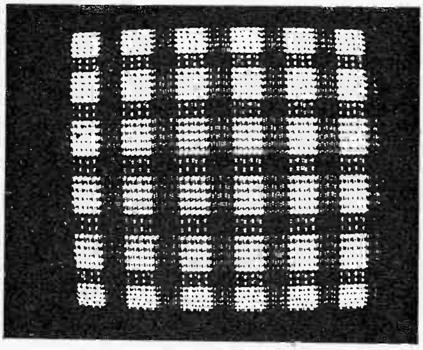

Fig. 3

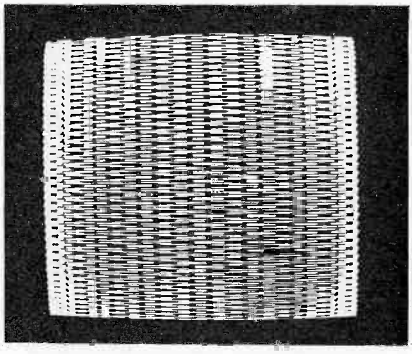

Fig. 4

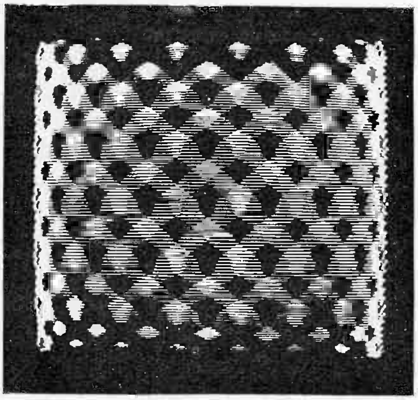

Fig. 5

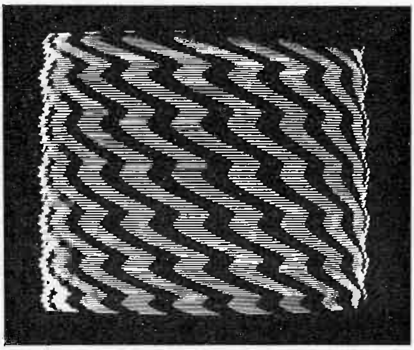

Fig. 6

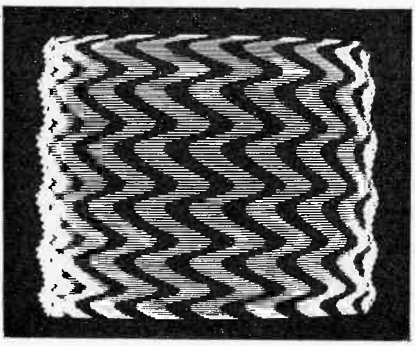

Fig. 7

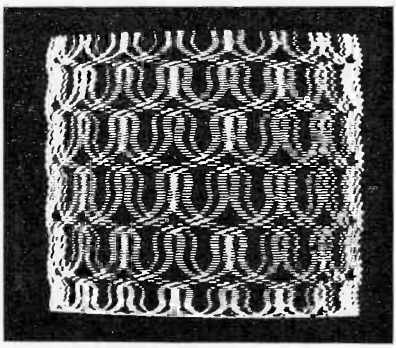

Fig. 8

No. 7. Deflection: Vertically, 30 cycles saw-tooth
Horizontally, 3780 cycles sine-wave plus small components of 1260 cycles and 180 cycles
Phase is shifted slightly from No. 5
Grid 1. 30 cycles square-wave, negative portion the width of the vertical-deflection return-line time
2. 3780 cycles sine-wave
3. 70,560 cycles square-wave

No. 8. Deflection: Vertically, 30 cycles saw-tooth
Horizontally, 3780 cycles sine-wave plus small components of 1260 and 180 cycles
Phase is shifted some from No. 5, is almost same as that for No. 6
Grid 1. 30 cycles square-wave, negative portion the width of the vertical-deflection return-line time
2. 70,560 cycles square-wave
3. 246,960 cycles square-wave

No. 9. Deflection: Vertically 30 cycles saw-tooth
Horizontally 3780 cycles sine-wave plus small components of 1260 and 180 cycles
Phase is shifted considerably from No. 5.
Grid 1. 30 cycles square-wave, negative portion the width of the vertical-deflection return-line time
2. 70,560 cycles square-wave
3. 246,960 cycles square-wave

No. 10. Same as No. 9, except the pattern was shifted during the photographic exposure

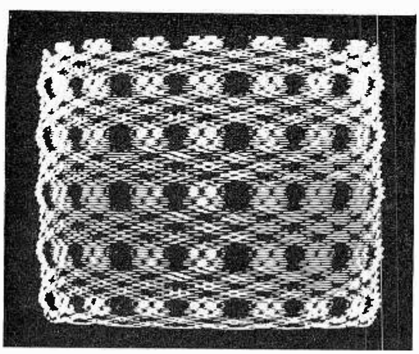

Fig. 9

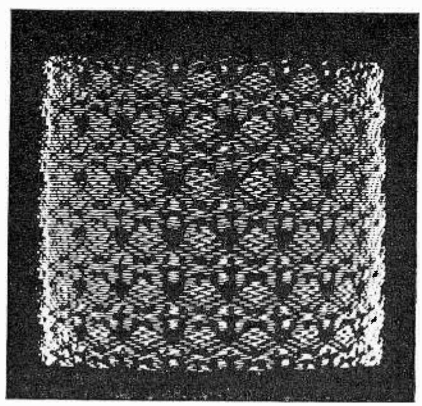

Fig. 10

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AN OSCILLOGRAPH FOR TELEVISION DEVELOPMENT*

By
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During the past few years there has been a gradual but widespread swing to the use of the cathode-ray oscillograph for electrical measurements of almost every variety, a swing caused jointly by the commercial availability of inexpensive portable instruments with good performance, and by the increased accuracy of measurement necessitated by modern design requirements. The exceptional results obtained from these small instruments has aroused interest in better oscillographs, and it is the purpose of this paper to describe a laboratory instrument[1] designed especially for television development with its extremely rigid requirements for response to high-frequency transients, and offering all the performance possible with the tubes and circuit elements commercially available.

Strange as it may seem this extended range instrument is not the outcome of experience gained with the smaller oscillographs, but is their predecessor, the basic design from which the small design was taken.

The recent history of the cathode-ray oscillograph is closely related to the development of high quality television. In 1930 when many experimenters turned to all-electronic scanning devices, the problems associated with synchronizing and scanning circuits made a good oscillograph necessary. The signals to be studied were transient in nature, occurring at a repetition frequency of several thousand cycles, automatically ruling out all string or Duddell movements because of the inertia of their moving parts, and leaving only the cold cathode high voltage DuFour oscillograph and the low voltage gas-filled tubes, the former being too bulky and the latter to dim for really satisfactory use in the research laboratory. The television engineers were forced, therefore, to develop the test instruments with which to develop television. The high vacuum, electrostatically focused cathode-ray tube, similar to that suggested for television, seemed the proper choice, and, as a matter of fact, the first satisfactory model of the oscillograph was built around a television tube altered for electrostatic de-

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[1] Type TMV-136B of the RCA Manufacturing Company.

flection by the addition of tin-foil electrodes cemented to the outside of the glass bulb.

Since that day, television and the cathode-ray oscillograph have grown up hand in hand, each serving as a third degree for the other, each contributing essential information on the weaknesses of the other, and it is only through this process of mutual evolution through six

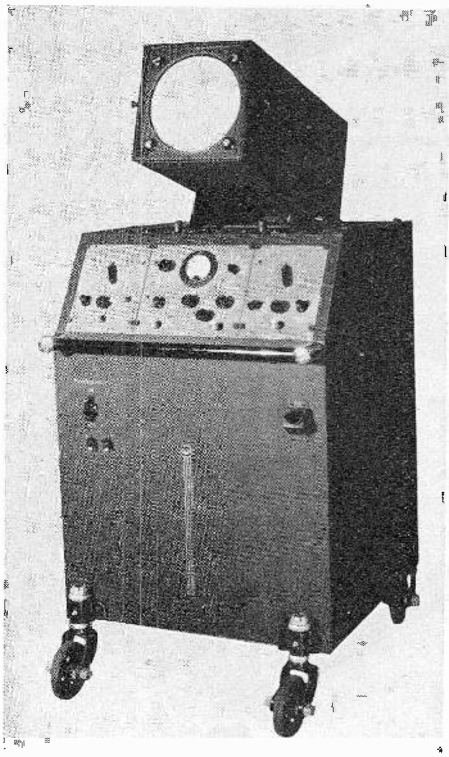

Fig. 1—Front view of cathode-ray oscillograph.

years of intensive research that each has reached its present state of performance. The experience of these years of work is expressed in the cathode-ray oscillograph here described, this being a commercial product based on the design of the research engineers.

The body of the instrument is a rack, or framework, of welded aluminum, in which are mounted the two power supplies, the vertical and horizontal voltage amplifiers, and the reference axis supply circuit, each on its own removable chassis. See Figs. 1 and 2. Surmounting this frame is the cathode-ray oscilloscope mount, which also houses the power output stages of both amplifiers and an auxiliary amplifier for grid excitation. This mount carries all the controls for the oscilloscope itself, may be set and locked at any angle from horizontal to thirty degrees, and is fitted with a sliding hood for use in brightly illuminated localities. All controls for the amplifiers and reference axis supply are mounted on inclined panels finished in a fine medium gray wrinkle

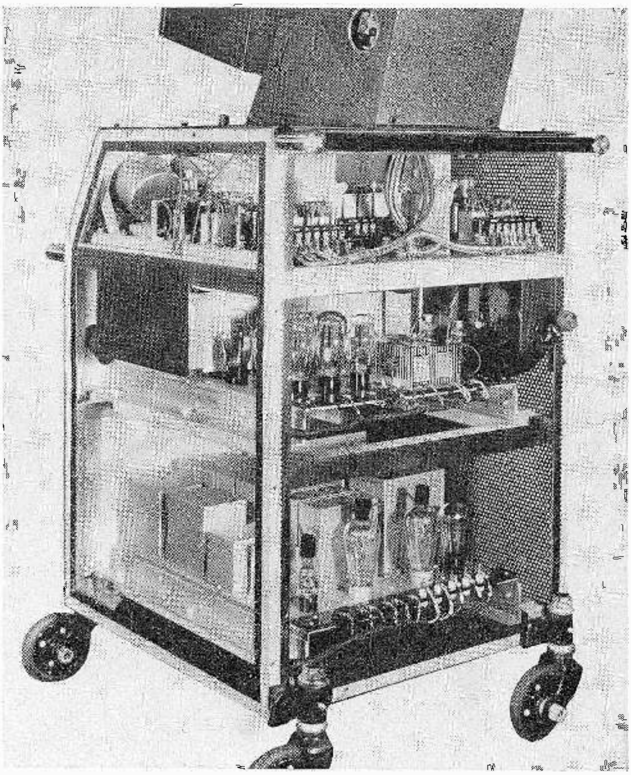

Fig. 2—Back view of cathode-ray oscillograph.

which contrasts pleasingly with the heavy black wrinkle finish on the frame and the glossy black controls and hand rails. Practically all the cover plates are hinged or removable to provide easy servicing, and safety is maintained by breaking the power supply circuit when the covers over the high voltage terminals are removed. The power cable, which is carried on a spring retracting reel at the rear of the frame, has a third wire for ground to encourage safety further, and the main switch is an overload circuit breaker. The frame is mounted on large rubber-tired casters loaded to only a fraction of their rating and two unswitched power outlets and a soldering iron holder are provided for the user's convenience.

This cathode-ray oscillograph is a precision instrument, designed for use in the research laboratory. The nine-inch oscilloscope with 2000 volts on the second anode affords a large, brilliant trace suitable for either visual or photographic observation, yet deflection is made easy by the high gain amplifiers incorporated. The amplifiers have constant response from twenty cycles to two megacycles, making possible the accurate reproduction of irregular wave shapes of both high and low fundamental frequency, and are equipped with input attenuators suitable for the same frequency range, permitting use on input voltages as high as 400 volts peak. Means are provided for calibrating at sixty cycles so that the instrument may be used as an instantaneous-value voltmeter reading from 0.05 to 400 volts at any frequency within its range.

A time axis oscillator is provided for the horizontal axis so that wave shapes may be shown plotted against a linear time scale. This oscillator has a frequency range of 10 to 100,000 cycles per second, and is provided with means for synchronizing on either the positive or negative peaks of the signal in the vertical amplifier, or any signal connected to a binding post on the time axis panel.

For those tests wherein a sinusoidal time axis is desired, means are provided for connecting the horizontal axis amplifier to a source of sixty-cycle voltage of variable phase. If any other time axis wave shape or frequency is desired, it need only be connected to a binding post on the horizontal amplifier panel. This amplifier is identical to the vertical amplifier so the same frequency and voltage limits apply.

The similarity of the amplifiers and their wide input voltage range make the instrument eminently suited to the measurement of phase delay in amplifiers and networks.

The instrument was designed for use in the television laboratory where it is necessary that it show exactly the wave shape of the signals being studied so that the wave generating circuits may be adjusted to give maximum performance. These television signals are a continuous succession of transients, so it is necessary to supply amplifiers whose characteristics are good, not only in the steady-state condition but also during the transient time, and it is in this field of transient response that the instrument is exceptional.

The rigorous requirements of a circuit designed to transmit transient phenomena without distortion preclude the use of any interstage coupling means wherein reactance plays a major part; so transformers, auto transformers, and plate choke coils are all rejected in favor of resistors. This alone is no complete solution but simply a first step, making the solution possible, and it is necessary to utilize corrective reactances, and correctly proportion the circuit by very painstaking design, before satisfactory transient response is obtained.

There are two general types of transient conditions under which an oscillograph must operate.

The best known is that of the extremely sharp wave front which must be followed with a minimum of delay, yet without overshooting the peak value and without any tendency toward oscillation. This type of transient is well known to the power transmission engineer, who has studied it for years with the DuFour oscillograph.

The other type of transient is that caused by a wave having an extremely low rate of voltage change over part of its period, the transient arrising within the amplifiers themselves through the tendency of the grid blocking capacitors to discharge through the grid leaks. This is the transient following application of a direct potential, such as a battery, to the amplifier input, and although it is essentially a relaxation phenomenon the varying discharge times of the individual grid circuits unusually cause it to appear as a damped oscillation of extremely low frequency.

Consider a simple resistance coupled amplifier to which is applied a potential wave rising from rest to its maximum value in zero time, and holding its maximum value constant for sufficient time to permit the completion of the resulting transient. Although the circuit of the amplifier shows no reactance, there is the unavoidable ground capacitance of the wiring and tube elements; the circuit is actually a resistance-capacitance network in which the input voltage is applied to the resistor and the output taken from the capacitor, so the voltage wave will, of course, follow the well-known exponential law. There is a lower limit beyond which it is impossible to reduce the circuit capacitance with practical layouts, and it is impractical to reduce the time constant very materially by reducing the values of plate and grid resistors, as the gain drops so rapidly that many extra stages are required to hold a constant over-all gain. There is, however, the possibility of introducing a small reactor to obtain a partial correction. There have been developed several circuits wherein the introduction of small inductors caused an extension of the higher limiting frequency, when tested on sine waves, but of these circuits, that wherein the inductor is introduced in series with the lowest resistor paralleling the wiring capacitance (usually the plate resistor) seems to be the only one affording an improvement in the initial transient response. This circuit is shown in Fig. 3.

The action of this circuit is quite simple. The square wave of voltage applied to the grid of the left-hand tube produces a square-wave increment of current in its plate circuit (high impendance tubes are used throughout), which divides between the plate resistor-in-

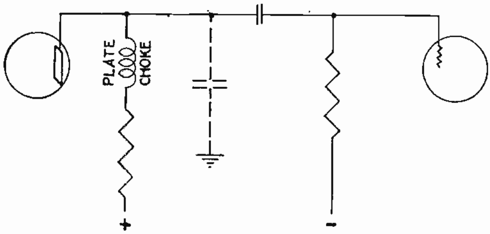

Fig. 3—Basic circuit for correction of initial transient response.

ductor channel, and the wiring capacitance. Obviously, the voltage across the wiring capacitance, and therefore, the voltage on the grid of the following tube cannot assume its correct value until a certain quantity of electricity has flowed into the capacitance. The inductor aids this action by opposing the flow of current during that important first increment of time, thereby forcing most of the current wave into the capacitor, raising its voltage much more rapidly than would otherwise be the case. Obviously this inductor must be used with care. Fig. 4 shows

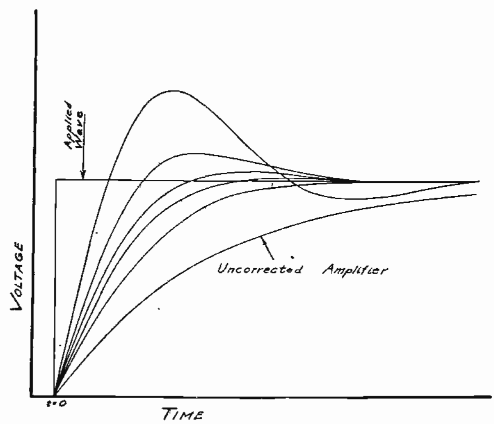

Fig. 4—Response to initial transient. Amplifier uncorrected and with varying degrees of correction.

the wave shape impressed, the response of an uncorrected amplifier, and the result of different values of correcting inductance. The delay at ninety per cent response may be reduced by a factor of slightly more than three, with only four per cent overshoot. The process in designing an amplifier for these high speed transients is, then, first, a reduction of the circuit capacitance to as low a value as is compatible with a good mechanical layout, second, a reduction of the plate resistor to that value which, with the wiring capacitance, gives approximately three times the desired delay, and third, the addition of the proper amount of compensating inductance.

After completion of the initial transient there is a subsequent transient or relaxation caused by the tendency of the grid side of the interstage coupling capacitor to return to the potential of the bias source, by the passage of current through the grid resistor. While this relaxa-

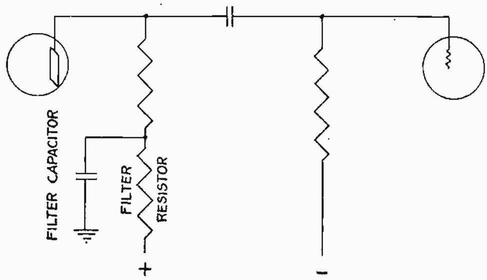

Fig. 5—Basic circuit for correction of relaxation transient.

tion begins as soon as the grid potential departs from the bias voltage, the amount of relaxation accomplished during the time of the initial transient is so extremely small that it may be neglected and the two transients considered as independent phenomena. The time constant of this circuit can be raised and the consequent relaxation reduced by raising either the grid capacitor or resistor, but a practical limit is soon reached beyond which an increase in capacitance entails too great an increase in the wiring to ground capacitance, and an increase in resistance causes grid current troubles with some tubes. Even this solution is unsatisfactory as the time constant, although large, is always finite, and there is some subsequent relaxation.

This situation may be corrected by the circuit of Fig. 5 wherein a plate circuit by-pass and filter resistor have been added. In this circuit the relaxation of the grid condenser is compensated for by an equal and opposite relaxation in the filter capacitor, the resultant transient having either positive, zero, or negative slope over a first fraction of its time. Being a true relaxation phenomenon, the output voltage must, in the end, return to zero, so the circuit constants for an oscillograph amplifier must be such that the period of the slowest signal to be handled is materially less than the relaxation time. Since in a practical amplifier the circuit is complicated by resistance-capacitance filters in the screen-grid and bias-supply circuits, each of which has its own relaxation characteristic contributing to the final result, calculation of circuit constants permitting standard manufacturing tolerances in all parts is extremely difficult. From a manufacturing standpoint it is more practicable to adjust one or more of the circuit elements to give the best performance with the other elements existing in that particular stage.

The circuit of the vertical amplifier is shown in Fig. 6. The attenuator shown at the left is the main sensitivity control permitting the use of constant amplifier gain with any input voltage between 0.05 and 400 volts. It is of the parallel element, resistance and capacitance type, offering constant attenuation to all frequencies. The steps average a 2:1 voltage ratio, so it is rarely necessary to resort to the fine gain control. The attenuation of the individual steps is adjusted to an accuracy of two per cent, so that the instrument may be used as a voltmeter by simply calibrating the amplifier. The exceedingly flat frequency characteristic makes a calibration at sixty cycles satisfactory.

Three 6C6 tubes and a 42 provide adequate sensitivity. The compensating inductors and the tapped plate resistor with its by-pass condenser are plainly indicated; the latter condenser is a large and a small unit in parallel as the physical dimensions of the large unit necessitate its being mounted at a distance from the amplifier so the small unit has been mounted within the amplifier itself to insure adequate by-passing at all frequencies. The lower type 42 tube is a phase inverter. Its grid is supplied with an attenuated portion of the voltage appearing on the plate of the upper 42, so its plate carries a signal exactly equal to that of the upper but reversed in phase.

These two equal but opposite signals are applied to the grids of the power stages in the oscilloscope housing. See Fig. 7. The amplified signal is then impressed upon the oscilloscope. In this portion of the circuit very careful attention is paid to balance, as experience has shown that a signal voltage unbalanced in any manner causes rather serious defocusing of the cathode-ray tube. A direct voltage, also balanced to ground, is applied to the deflecting plates to permit shifting the zero or axis position of the plotted pattern, a very convenient feature when asymmetrical waves are being studied.

In this figure may also be seen the 6F7 amplifier used to supply a signal to the grid of the oscilloscope whenever it may be so desired. The polarity switch throws in or out the low gain triode section permitting phase inversion at will. This amplifier is very useful for blank-

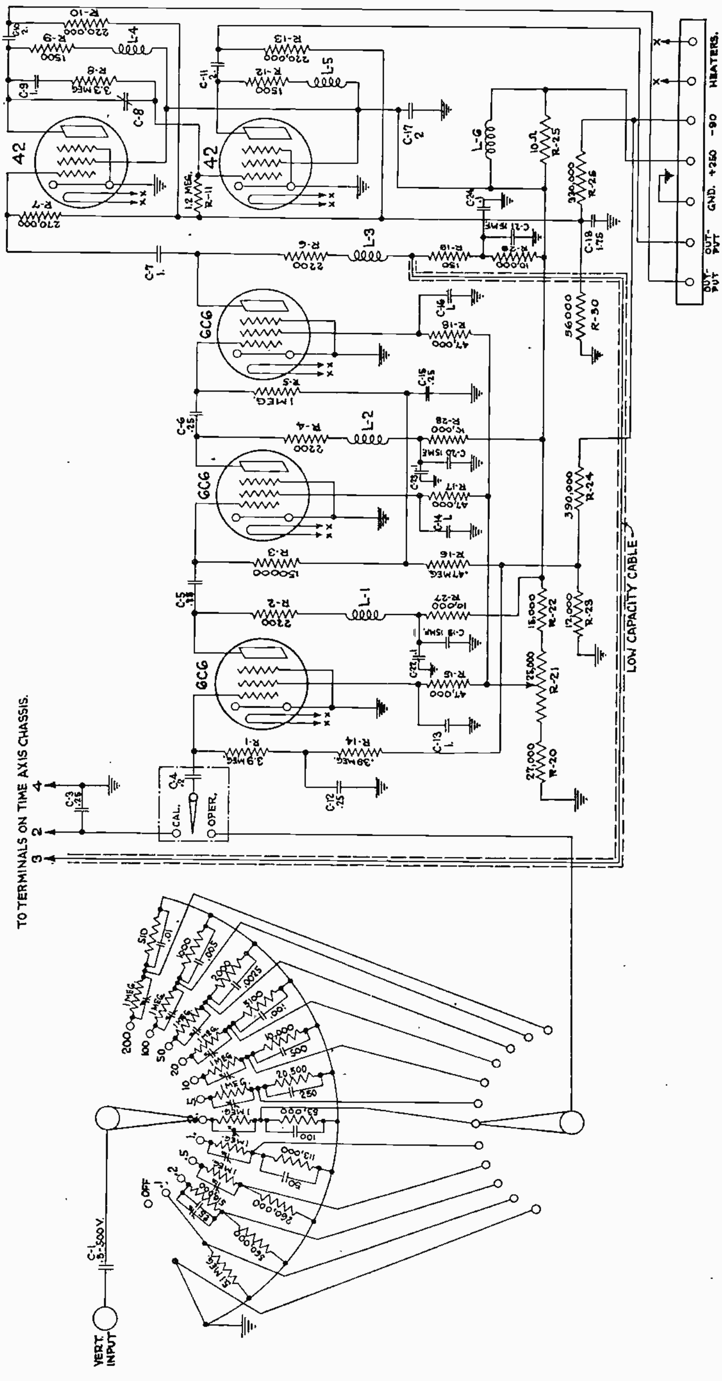

Fig. 6—Schematic diagram—vertical amplifier of cathode-ray oscillograph.

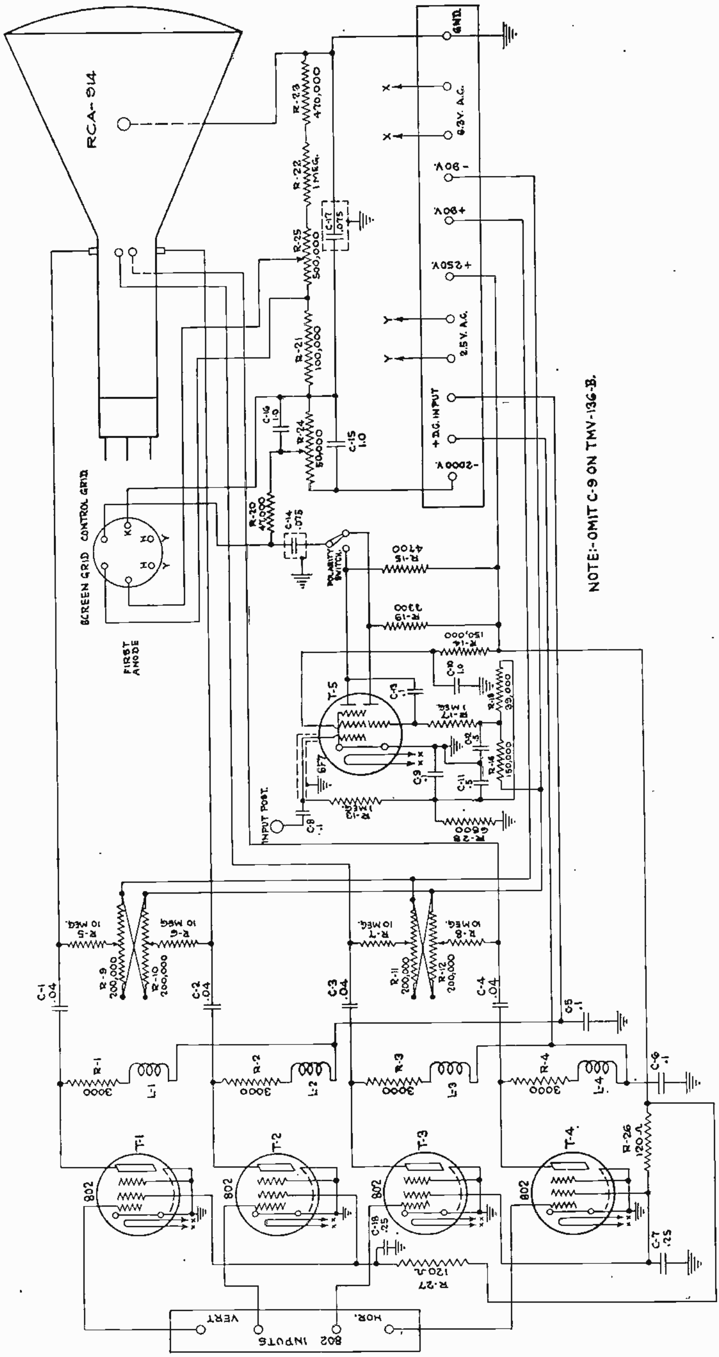

Fig. 7—Schematic diagram—oscilloscope mount of cathode-ray oscillograph.

ing out unwanted portions of the pattern when the studied phenomenon occupies only a small portion of the repetition time, and for the formation of bright spots on the pattern for phase or frequency measurements.

The circuit of the reference axis supply panel is shown in Fig. 8. The 6F7 at the left is the synchronizing amplifier, arranged to supply a signal in either phase to the grid of the 885 oscillator, which is operated in an entirely conventional circuit. The 6C6 amplifier separates the oscillating circuit from the high capacitance lead to the horizontal amplifier and is designed to effect some correction on the sawtooth wave shape.

The reference axis panel also supplies a sixty-cycle sine wave of variable phase, and the known voltage for calibrating the amplifiers.

Power for the voltage amplifiers, the reference axis supply, and the screens of the output tubes is provided by a rectifier-filter unit, equipped with a vacuum tube regulator to hold its output voltage constant with varying load and line voltage conditions. The regulator gives this power unit an apparent output impedance of about three ohms and includes a time-delay system so that the plate voltage is maintained at a low value until the cathodes are hot. See Fig. 9. Power for the output tube plates and for the oscilloscope is obtained from two higher voltage rectifiers mounted on another chassis.

This instrument is alternating-current-operated throughout, the only batteries being the voltage standard for the regulated power supply, used for more precise regulation. The circuits are familiar types: artificial expedients have not been employed, the exceptional performance being obtained through accurate design and careful adjustment.

One of the major questions arising on manufacture of such an instrument is that of the test methods to be used. The tests must be accurate, they must indicate clearly the cause of any imperfection, they should not require complicated setups or difficult equipment maintenance, and both collecting and interpreting the data should be so easy that the operator will not be fatigued beyond the point where interest is lost. The tests must, of course, indicate the extent to which the transient response of the amplifier is affected by such imperfections as exist.

The response of any given amplifier may be studied by examining its amplitude and delay versus frequency characteristics in the light of our knowledge that constant gain and constant phase delay at all frequencies is the necessary condition for distortionless operation. All amplifiers, however, have rather definitely limited frequency bands and

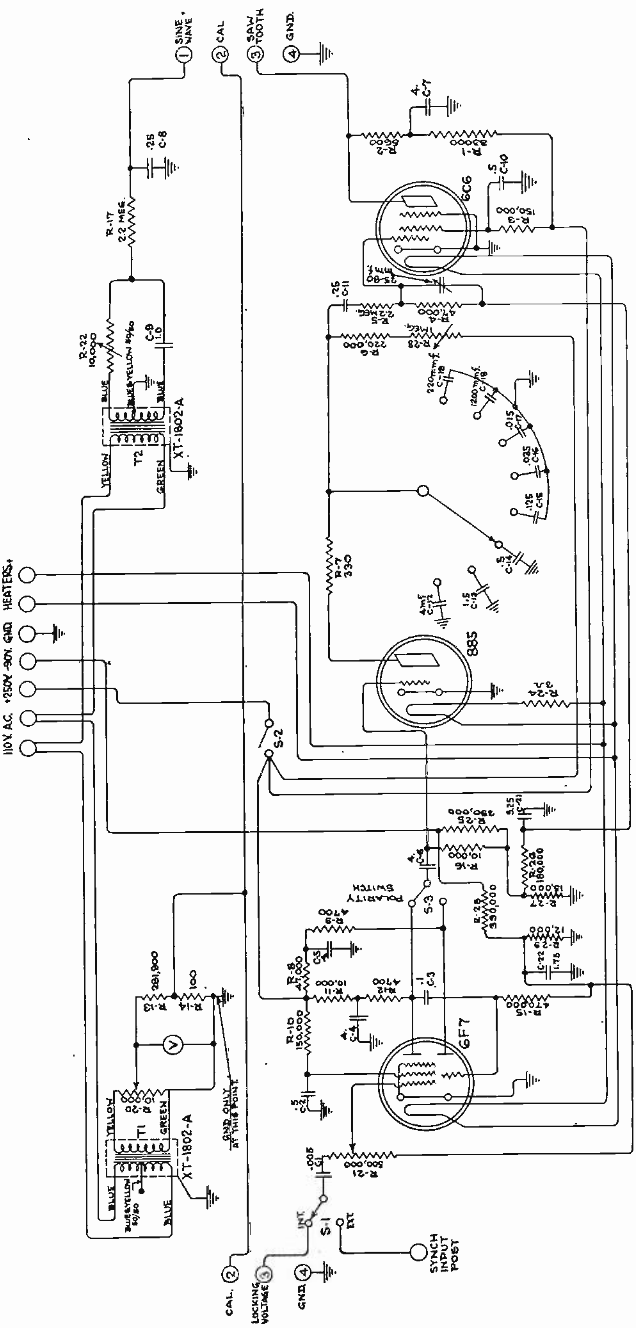

Fig. 8—Schematic diagram—reference axis supply of cathode-ray oscillograph.

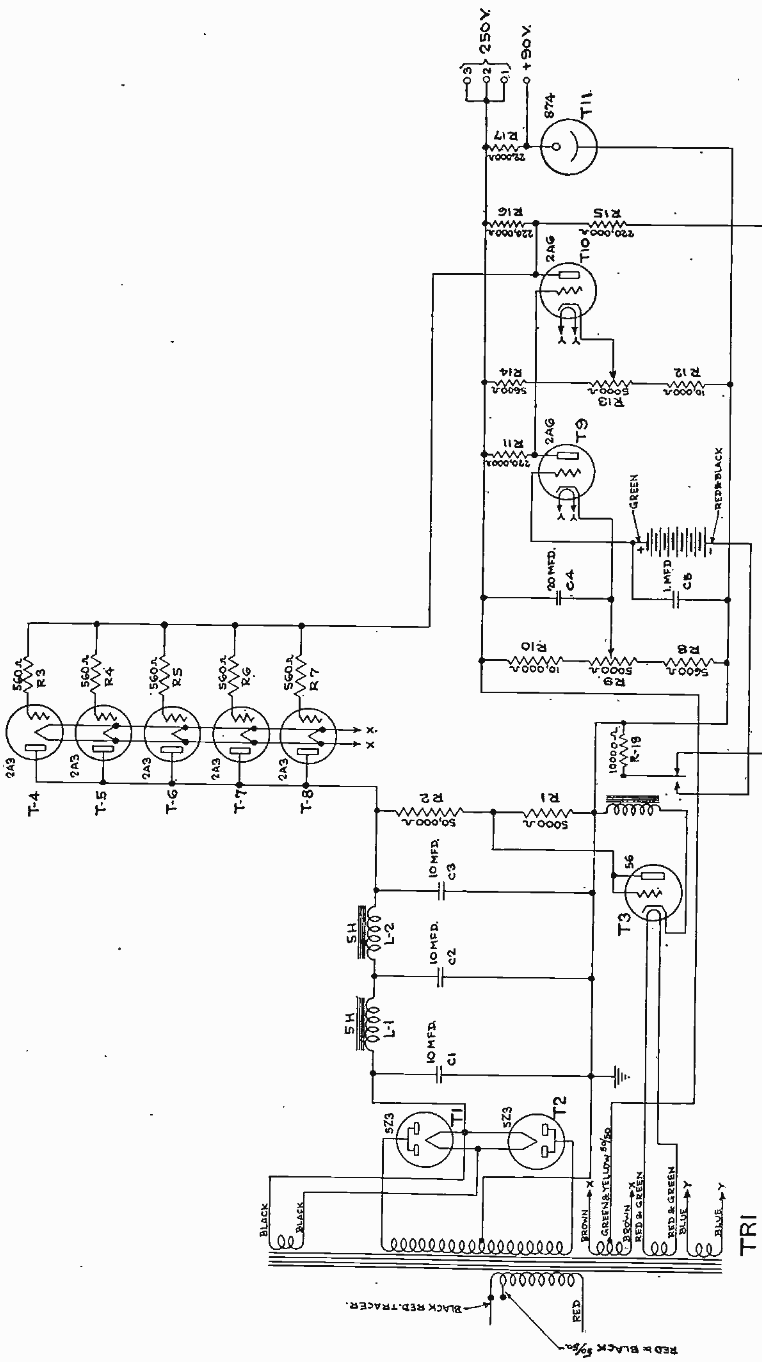

Fig. 9—Schematic diagram—regulated power supply of cathode-ray oscillograph.

the transient performance in regions bordering on these limiting frequencies, where the amplitude and delay characteristics are beginning to become poor, is unknown, nor can it be determined without a laborious synthesis of the wave from the known condition of its components. The very mass of data required precludes use of this method wherever time is of any importance.

The response of an amplifier may also be determined by suddenly applying a voltage, and maintaining that voltage constant for sufficient time to permit the completion of all transient phenomena. (This may be done analytically by the application of a "unit function" of voltage, solving for the resultant wave shape by differential calculus.) The output voltage wave will be the transient response of the amplifier first to the steep wave front, and then to the constant voltage wave, and it is necessary simply to plot this voltage function against time to have a complete solution. The presence of the cathode-ray tube and its auxiliaries to make the output voltage wave visible makes this test method exceedingly attractive.

Unfortunately, the simple application of a constant voltage giving a single nonrecurrent tracing of the output wave is not suitable for accurate measurements by other than photographic means, and it is, therefore, necessary to create a test signal whose voltage changes from one extreme to the other in as near zero time as is possible, and holds the extreme values for sufficient time to permit completion of the resultant transient. This succession of rectangular wave shapes permits use of the customary saw-tooth oscillator to give a recurrent and, therefore, apparently stationary pattern on the screen of the oscilloscope.

It was mentioned previously that the widely different times consumed by the two types of transient permit their treatment as independent phenomena. The fact is that the times are so extremely different that separate treatment is necessitated. A time axis slow enough to show any reasonable amount of the relaxation transient compresses the initial transient to such an extent that it cannot be measured. Several waves, varying widely in base frequency, are, therefore, required.

Waves of suitable shape may be produced by electronic means or by intermittent contactors in a direct-current circuit, but the latter is only suitable for low frequencies. Square-wave shapes may quite readily be produced by electronic means, by simply overexciting the grid of an amplifier tube. By driving the grid considerably beyond cutoff and well into the positive region a wave of fairly square shape may be produced in one tube but to obtain a wave of suitably square form for test purposes it is necessary to pass this wave through several more stages operated in the same manner. Of course, these tubes are all amplifiers handling waves of a transient nature so they must be treated much as the amplifiers they are intended to test. Square waves have been produced by this means at frequencies as high as 500 kilocycles.

It may reasonably be asked how we can use a wave for test standard, when it is produced by a circuit similar to the circuit under test, especially as the latter is designed to give the utmost in performance. Like the standard candle, a standard square wave at high frequencies cannot be reproduced with any certainty from the mechanical constants of the instrument. However, square waves may be produced by testing the wave with a special cathode-ray oscillograph using low second anode voltage, permitting direct deflection by the square-wave generator. Such an oscillograph would be useless for circuit test, due to its low sensitivity and lack of illumination, but, as it guarantees the operation of the square-wave generator, it is invaluable.

Mathematical analysis of the circuit of Fig. 3 had shown a relationship between the initial transient response, the phase-delay characteristic, and the amplitude charactristic such that the amplitude characteristic alone could be used to set the transient response to any desired value. The high-frequency square waves were used to check this fact, which had previously been indicated by the results obtained on television signals, permitting use of the amplitude characteristic with complete faith in its ability to indicate with the desired accuracy. Also, the oscillograph is used by some enginners as a radio-frequency voltmeter, comparing the deflection produced by the unknown with the deflection produced by a known sixty-cycle voltage so it is necessary that the frequency characteristic be as flat as possible. Experience has proved the amplitude characteristic the more satisfactory test, as the correct adjustment of the compensating coil is a matter of compromise between the amount of delay and the amount of overshoot, neither readily measurable, while the percentage variation from constant gain and the maximum frequency are familiar values to the test personnel.

For these reasons, the extreme high-frequency characteristic of this oscillograph is adjusted by means of an amplitude versus frequency characteristic measured with sine waves. The over-all characteristic is held flat to 500 kilocycles, five per cent variation is permitted at 1000 kilocycles, and ten per cent at 2000 kilocycles. The manufacturing variation in twelve production units is shown in Fig. 10. The transient response of one of these instruments to a square wave of 250 kilocycles fundamental is shown in Fig. 11. Analysis shows the delay in reaching ninety per cent to be 0.146 microsecond and the overshoot to be 30.8 per cent. This overshoot, representing 5.5 per cent

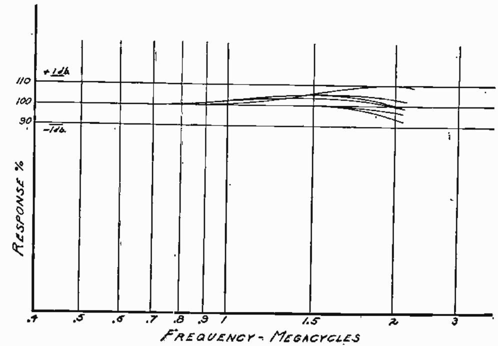

Fig. 10—Composite frequency versus response curve first twelve amplifiers in production.

in each of the five stages, lasts only eleven one hundredths of a microsecond (11×10^{-8} seconds) and is negligible in service.

In each amplifier there are eleven attenuating units, each of which comprises a resistance attenuator and a capacitance attenuator in

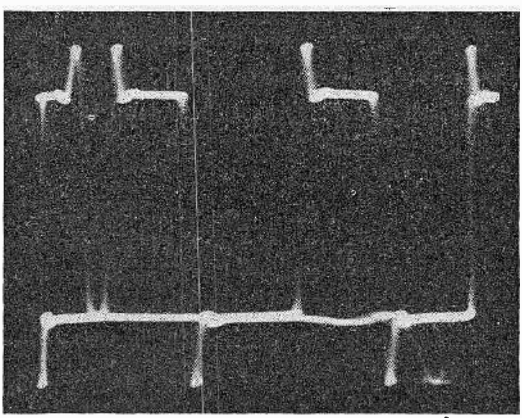

Fig. 11—Response to a square wave of 250 kilocycles fundamental.

parallel. The capacitance attenuator has one element variable so that its attenuation may be adjusted to that of the resistance attenuator, thus obtaining constant attenuation at all frequencies. This may be accomplished by measuring the attenuation at two frequencies so widely separated that the two types of attenuator act essentially independently. This process entails accurate measurement of two voltages, one at radio frequencies, over a voltage range of one-tenth to several hundred volts, and is not entirely satisfactory from the standpoint of accuracy. Some of the original oscillographs of the "A" type were adjusted by this method, the adjustment of each amplifier requiring about two and a half hours and affording questionable accuracy.

Recourse has been taken to the square-wave generator. Square waves of about ten kilocycles may be produced with rugged equipment and the adjustment is not so critical as to cause trouble for the test maintenance personnel. These square waves contain an exceedingly

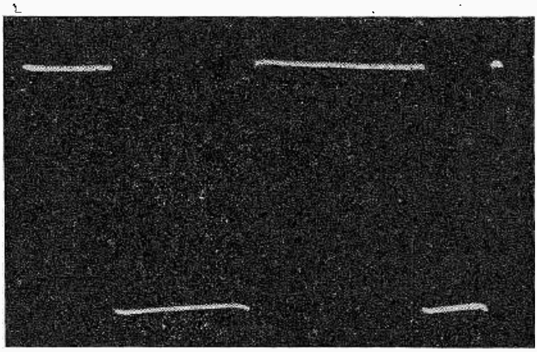

Fig. 12—Square-wave, ten-kilocycle fundamental. Output of square-wave generator used as test signal for all attenuator adjustments.

wide frequency band so that the flatness of the attenuated wave top may be used as an indication of the state of adjustment. The wave given by this generator is shown in Fig. 12. That the initial transient shown in Fig. 11 is immaterial as stated is proved by its absence in this photograph. All attenuators are now adjusted by means of these waves, the accuracy of adjustment is greatly improved, and the time for this portion of the test cut to approximately five minutes. Fig. 13 is an attempt to show a motion picture of this adjustment on one film. The eight curves shown were made with eight different settings of the adjusted capacitor, differing by approximately one micromicrofarad. The final adjustment is shown by the square wave at about the center of the adjustment range covered. That the different attenuator steps may be trusted as distortionless is shown in Fig. 14, wherein the wave shapes obtained by impressing appropriate voltages upon the amplifier input direct, and through each of the attenuator steps, are shown. The voltage range covered is approximately one thousand to one.

For adjusting the circuit elements controlling the low-frequency response there is no choice of test method; square waves provide the

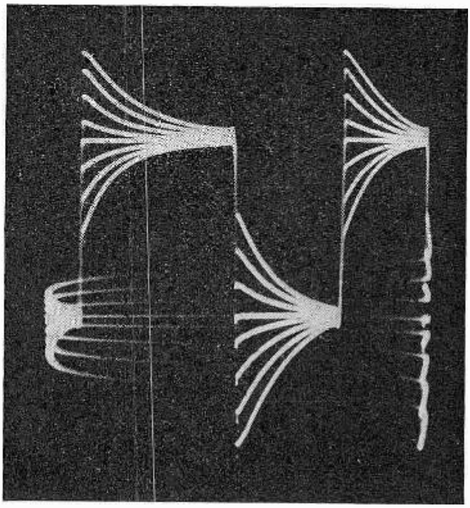

Fig. 13—Wave shapes obtainable during adjustment of attenuators. Final adjustment shown by square wave near center of range.

only test known at present that predicts the performance of the unit in service. The waves for this test have a fundamental frequency

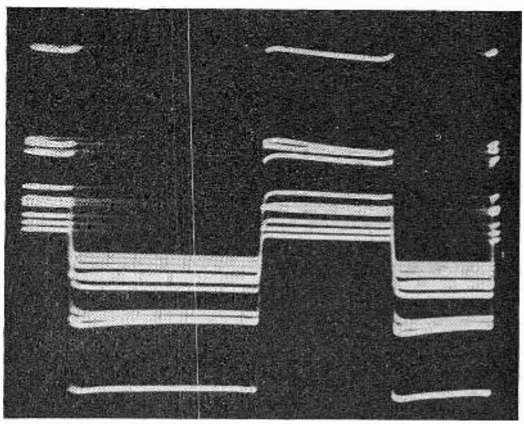

Fig. 14—Agreement of attenuator steps. One exposure on each step. Input voltage range shown, about sixty decibels.

of thirty cycles and are obtained by commutating a direct-current circuit with a vacuum tube controlled relay. Five per cent tolerance is permitted between the highest and lowest points on the flat top of the resultant wave, a value that has proved quite satisfactory in service. As an example of the results obtainable with a square-wave test, in Fig. 15 is shown the transient in an amplifier whose frequency characteristic was two per cent low at thirty cycles in only one stage.

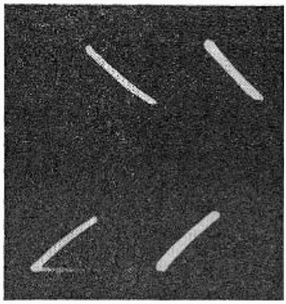

Fig. 15—Response to thirty-cycle square wave. The response characteristic of this amplifier was two per cent low at thirty cycles.

That this amplifier would be useless in an oscillograph is patent. The thirty-cycle square wave reproduced by the TMV-136B is shown in Fig. 16.

It was stated previously that the low-frequency transient is a true relaxation phenomenon, modified during its beginning by a similar

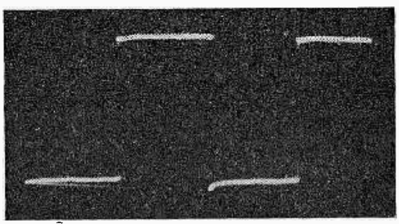

Fig. 16—Response of the described instrument to a thirty-cycle square wave.

phenomenon in opposition. In Fig. 17 is shown the trace obtained upon connecting a direct voltage to the input terminal. The time axis was operating at twenty-four cycles per second and the direct voltage was applied with the inception of one of the return strokes. There is a faint dot at the right end of the pattern at the height of the highest portion of the top line, showing that the direct voltage was applied as the spot was just starting on its return path. The left end of the top line is, then, the start of the transient within a very small fraction of a second. As may be seen the initial portion of the subsequent transient is practically flat; it is not the most sharply sloping portion as it would be with a simple relaxation following the exponential law. After eight hundredths of a second the opposing phenomenon has died out and the slope of the transient is about as would be expected. The varying time constants of the different portions of the circuit cause the transient to go negative after about fourteen hundredths of a second, the negative peak being reached in about one-quarter second, after which the voltage gradually subsides, reaching zero after about one second. It is the flatness of the initial portion of this curve that makes the low-frequency response of the instrument possible.

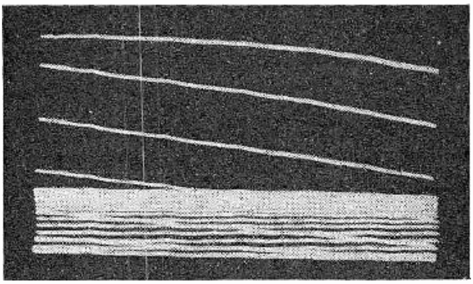

Fig. 17—Response to application of a direct potential.

This oscillographic equipment offers, we believe, the best performance possible with the circuit components and tubes available at present. It is suitable for sine wave tests at any frequency between about ten cycles and two megacycles. It will faithfully reproduce any wave shape in the frequency band between thirty cycles and fifty kilocycles, and will reproduce any but the very sharpest wave shapes to about three hundred kilocycles.

The photographs presented in this paper were taken on a production instrument that had been in service for approximately six months. No special adjustment was made. This, and the lack of field complaints, leads us to believe that the instrument is sufficiently rugged to withstand the effects of shipment and continuous service.

The performance of the instrument would have been impossible of attainment had it not been for the development of the square-wave generator, for, as has been shown, the necessary information on the transient responses could not have been obtained by any other manner within the time available for industrial development. Even had time been available to obtain this information by the slower methods, the question of test would have remained.

The performance of the instrument has been made possible by recent developments in tubes and circuit components. Undoubtedly a better oscillograph will be possible with components and tubes now being developed.

The oscillographs which we have built have been designed upon the premise that it is better to maintain the wave shape as faithfully as possible than to attempt to make corrections. Similarly, inverse feed-back has not been attempted. The most important single reason for this course is the feeling that the care and time required to design and manufacture the correcting or feed-back network would be no less than that required to design and build the amplifier, itself, distortionless. Of course, we are not, here, required to operate a number of ampli-

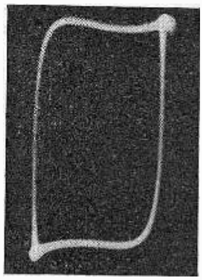

Fig. 18—Demonstration of time of transmission. Vertical deflection—input, wave shape as shown in Fig. 11. Horizontal deflection output.

fiers in cascade nor to maintain constant gain with varying battery voltages. It would be interesting, however, to predict what improvement in performance could be obtained with the other type of circuit. The correction available with inverse feedback is effected by adding to the original output wave, a portion thereof that has been reintroduced in the amplifier and reamplified, thus effecting partial cancellation of those components generated within the amplifier. There is a time interval, therefore, between the appearance of the original signal upon the output terminals, and the appearance of the reamplified signal used for correction, when the original signal is the only voltage present. During this time there can, of course, be no correction, and since correction is effected with a reduction of output voltage, the output during this period will be high. The interval during which this condition exists is the time required for the original signal to pass through the feed-back network and repass through the amplifier, a time that obviously cannot be less than the latter alone. A measurement of the time required for passage through the amplifier should, then, be of interest.

The time required for one passage through the amplifier may be determined by impressing both the input and output of the amplifier upon the cathode-ray tube. The input must be a reasonably high voltage to give a usable size of trace, so it is logical to use another amplifier to supply the input. The square-wave generator operating at 250 kilocycles was connected to the vertical amplifier, and the voltage on one vertical deflecting plate applied to the input of the horizontal amplifier. The vertical deflection of Fig. 18 is, therefore, the input to the horizontal amplifier, and the horizontal deflection the output. It may be seen that the vertical deflection is complete and has subsided to its trough before the horizontal deflection has reached half its final value. The time of the positive half cycle of this initial transient was previously determined as one-tenth microsecond, so the time required for passage through the amplifier is approximately the same.

The amplifier as built shows a higher than normal output voltage for fourteen hundredths of a microsecond, approximately the same wave shape as predicted for a perfect feed-back circuit, so there seems to be little choice between the two methods.

Acknowledgment

An instrument as complicated as the one under consideration cannot be the result of one man's work. It is necessarily the result of considerable co-ordinated effort in the television research laboratory, the laboratory equipment section, the manufacturing department, and the test organization. Along this route a great deal of interest was taken in the instrument, and a great many good suggestions were offered by our collaborators; accordingly our thanks is due these men. There are also a number of men whose contributions to this instrument were outstanding and to whom recognition is due. The mathematical work of Mr. W. J. Poch and his original investigations in transient phenomena made the device possible. To Mr. J. P. Smith should go the credit for combining the theoretical work with a wide experience with high fidelity amplifiers and for creating the first instrument of this type. From this excellent, if slightly academic design, Mr. H. E. Paschon built the present type, his able mechanical work resulting in a lighter and stronger instrument with considerable savings in cost.

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THE BRIGHTNESS OF OUTDOOR SCENES AND ITS RELATION TO TELEVISION TRANSMISSION*

By

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Summary—*The average brightness of typical outdoor scenes has been determined by computation and by measurement. The average brightness of some scenes was found to be over 1000 candles per square foot, and of other scenes nearly zero. In many cases the average brightness lay between twenty and 200 candles per square foot. The sensitivity of a present-day television system using the Iconoscope has been found to be sufficient to permit the transmission of pictures with good quality when the average brightness of an average scene was greater than about fifteen candles per square foot. This sensitivity is sufficient for the transmission of parades, races, baseball games, and many other outdoor events. Football games, which last until near sunset, cannot always be satisfactory reproduced.*

Some of the Iconoscopes used in these tests are of added sensitivity, which has been achieved by means of a silver evaporation process, as well as by careful control of the purity of the materials.

DURING the early stages of television, both the transmitting and receiving systems were crude, and experimenters were glad to obtain a recognizable picture. The last few years have witnessed great improvement in the quality of the picture. The adoption of cathode-ray tubes has permitted a large increase in the number of scanning lines, and use of interlaced scanning and a greater number of frames per second has practically eliminated flicker. As the system improved, larger and brighter pictures became possible.

A comparable change has also taken place in the sensitivity of devices for converting light into television picture signals. The earliest apparatus required so much light that transmission was largely limited to films. At best, direct pickup could be obtained only when the scenes were in direct sunlight or under blinding artificial light. With the advent of such electronic devices as the Iconoscope,[1,2] direct transmission of outdoor scenes became practicable even on cloudy days.

Since the illumination requirements for television transmission now fall within practical limits, let us consider the relation between light available under average conditions and the sensitivity of the ap-

* Decimal classification: R583. Original manuscript received by the Institute, June 30, 1937. Presented before Silver Anniversary Convention, New York City, May 12, 1937.

[1] Registered trade-mark, RCA Manufacturing Company, Inc.

[2] V. K. Zworykin, "The Iconoscope—A modern version of the electric eye," PROC. I.R.E., vol. 22, pp. 16–32; January, (1934).

paratus. In the transmission of motion pictures or studio scenes, the amount of light used may be controlled; out-of-doors it is usually necessary to operate with whatever light the sun provides. In considering how much light is available for the illumination of a scene which is to be transmitted, we shall, therefore, largely limit the discussion to outdoor scenes in daylight.

The matter will be discussed from two angles: (1) the surface brightness and contrast of typical outdoor scenes, and (2) the brightness and contrast which are necessary for the transmission of a satisfactory television picture. Because of the complexity of the subject it will be necessary to make some approximations, but these approximations are relatively unimportant in view of the wide range of brightness encountered and the tolerance of the television apparatus.

Illumination of Outdoor Scenes

When commercial television broadcasting is well established, it is probable that the public will wish to see varied events, such as basegall games, boat races, parades, and political gatherings. The illumination encountered will vary over a tremendous range at different pickup points, and even change in a short period of time at a given place. A successful broadcast must make allowance for the variations that may occur, for, unlike motion pictures, the unsatisfactory scenes cannot be discarded. Neither would it be satisfactory to postpone or stop a broadcast because of adverse conditions.

It is desirable, therefore, to know how much light to expect from a given scene. From data already published the required information may be judged for a general case; this we have supplemented with data obtained by measurement of some specific subjects.

Since the intensity of the light which the lens focuses on the apparatus depends on the surface brightness of the object, irrespective of the object distance, surface brightness (usually measured in candles per square foot)[3] is the best measure of the light available for the transmission of a scene.[4] This quantity can be directly measured for each scene that is to be transmitted, or a fair estimate may be made by a simple computation. If the intensity of illumination received from the sun and the sky under different conditions is known, the surface brightness of different diffusely reflecting objects can be calculated by the use of the relationship

[3] Care should be taken to distinguish foot-candles from candles per square foot. The foot-candle is a measure of the illumination received at any given point from a source of light, while candles per square foot is a measure of the intrinsic brightness of a source of light.

[4] W. N. Goodwin, Jr., "The Photronic photographic exposure meter," *Jour. S.M.P.E.*, vol. 20, pp. 95–118; February, (1933).

$$B = RI/\pi \tag{1}$$

where,

B is the surface brightness of the object in candles square feet
R is the reflection coefficient of the object
I is the illumination received by the object in foot-candles.

The illumination at any place and time can be computed from such factors as the sun's distance, its radiation, and the absorption and scattering of the atmosphere. However, since experimental data have already been taken by several observers, it is more convenient to use

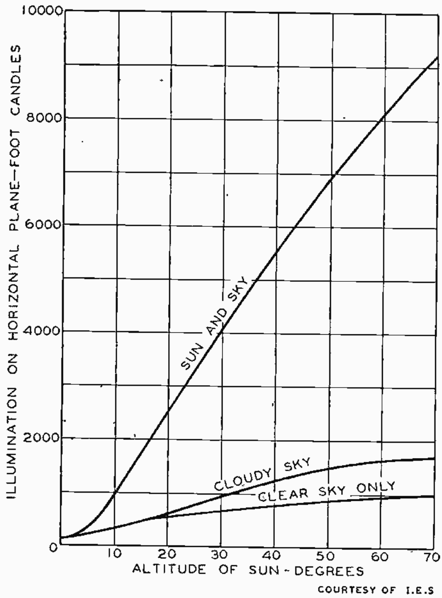

Fig. 1—Illumination from the sun and sky on a horizontal plane for different altitudes of the sun.

their results. For example, Kunerth and Miller,[5] using a MacBeth illuminometer have measured the illumination on a horizontal plane, as a function of the altitude measured in degrees of the sun above the horizon. Fig. 1, reproduced with permission of the Illuminating Engineering Society, illustrates some of their results. Although these data were taken at latitude 42° N and longitude $93\frac{1}{2}$° W, they may be used, with sufficient accuracy for the present purpose, in almost any locality. The altitude of the sun, as given by Kunerth and Miller, for different hours of the day during several illustrative days of the year is shown in

[5] W. Kunerth and R. D. Miller, "Variations of intensities of the visible and of the ultraviolet in sunlight and in skylight," *Trans. Ill. Eng. Soc.*, vol. 27, pp. 82–94; January, (1932); and vol. 28, pp. 347–353; April, (1933).

Fig. 2. These curves, unlike those of Fig. 1, must be corrected when they are applied to any other latitude or relative position in a time zone. As shown, they represent quite closely the situation in New York City or Philadelphia.

The curves of Fig. 1 show the average of data taken during a great many days. Wide variations from these average values may be expected on particular days. Nevertheless, a fair estimate can be made of the illumination to be expected at a given time by combining the information included in the two figures. For instance, on November 5 at 4:30 P.M., an illumination of about 350 foot-candles can be ex-

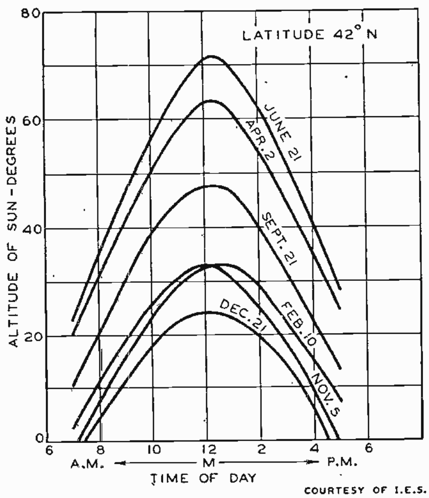

Fig. 2—Altitude of the sun for different times of the day and year at 42° N latitude and $93\frac{1}{2}$° W longitude.

pected in sunlight if the day is clear, or about 200-foot candles if the scene is in the shade or the sky is cloudy. As another example, on June 21 at noon, an object in full sunshine will be illuminated with about 9100 foot-candles; in the shade, about 1000 foot-candles. In the latter example, it is interesting to notice that the illumination of an object in the shade will probably be greater on a cloudy day than on a perfectly clear one.

The reflection coefficients of many surfaces have already been measured; of the information available, the list in International Critical Tables is one of the most complete. Several illustrative items are given in Table I.

The surface brightness of a simple scene may be estimated by substituting in (1) values taken from Fig. 1 and Table I. A shady football field at 4:30 P.M. on November 5 can be expected to have a surface

TABLE I

Material	Reflection Coefficients	Material	Reflection Coefficients
Snow	0.93	Plaster	0.65
White paint	0.71	Brown soil	0.32
Light gray paint	0.49	Green leaves	0.25
Medium gray paint	0.30	Black velvet	0.01

brilliance of about $(0.25\times200)/\pi=16$ candles per square foot (assuming R for grass to be the same as for green leaves). Near noon on June 21, the brown soil in the infield of a baseball diamond will show a surface brightness of about $(0.32\times9100)/\pi=930$ candles per square foot.

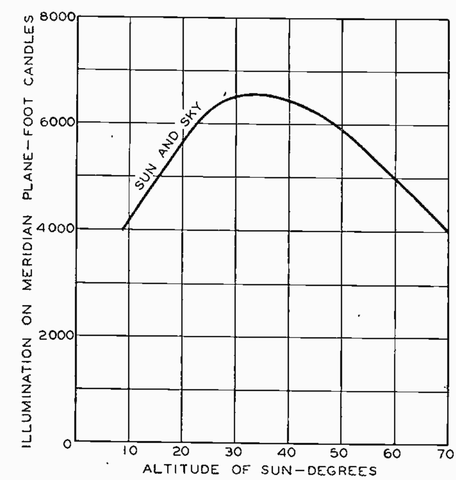

Fig. 3—Illumination from the sun and sky on a meridian plane for different altitudes of the sun.

Few scenes are as simple as those which have been assumed so far. For one thing, the subject of interest in a picture being transmitted is more likely to be vertical than horizontal. Therefore, from the data of Fig. 1, we have computed the illumination on a vertical surface facing the sun, as a function of the sun's altitude. Results are shown by the curve of Fig. 3, which is much flatter than the curve for a horizontal surface. When the sun is low and the light strikes the object squarely, much light is lost by atmospheric absorption; at midday, although atmospheric losses are small, the principal illumination is from the sky and reflection from near-by objects. It is interesting to observe that on clear summer days some scenes will be brighter in midmorning and midafternoon than at noon.

Reflected light must be taken into account. This is of particular importance in the case of vertical surfaces where reflection from near-by objects will change the expected illumination. In one test we found that the brightness of a vertical wall was reduced fifteen per cent when a large sheet of white cardboard on the ground was covered with black velvet. Snow may also cause a very considerable increase, and white billowy clouds in the sky have some effect.

Local conditions may still further affect the situation. These have been treated quite thoroughly by J. E. Ives and co-workers,[6] who simultaneously measured illumination in New York City where the air was very smoky, and at a point several miles distant where the air was comparatively free of smoke. The measured illumination in the city was usually less than at the outside station, and was sometimes as much as fifty per cent lower. In general, the loss was greatest when the sun was low in the sky, the sky cloudy, the relative humidity high, and the wind velocity low.

The color of light from the sky is usually unlike that from the sun. Due to scattering, skylight is stronger in the blue section of the spectrum than direct sunlight. Reflection surfaces which change the color of the illumination of the scenes, as well as the differential reflection of the scenes themselves should, for completeness, be taken into account. This will be treated more thoroughly later in the paper.

Although the data of Kunerth and Miller illustrate quite well what average illumination is to be expected at different times and under different conditions, they do not show the rapid fluctuations that may occur. Ives has illustrated, by means of several curves, these rapid variations. On a clear day the average illumination due to the sun may be as high as 10,000 foot-candles, but clouds passing over the sun may cause this to drop within one minute to 3000 foot-candles. One minute later the illumination may return to its original value. Such changes are not particularly noticeable to the eye, but may be quite bothersome in the use of a television transmitter. Smoke on a clear day can also cause variations which are, however, much smaller.

From the discussion so far given, the conclusion may be drawn that the probable brightness of a simple scene can be computed from information already available in the literature, but that the number of doubtful factors involved in an average scene is great enough to make the answer an approximation, at best. For this reason we have depended chiefly upon the results obtained by actually measuring the brightness of hundreds of typical subjects for a television broadcast. Because of its convenience, a Weston exposure meter was used for this survey. The spectral sensitivity of the meter is much the same as that

[6] "Studies in Illumination—Part III," Public Health Bulletin, No. 197, U. S. Treasury Department.

for the human eye, so that the readings are comparable with the surface brightness calculated by the method previously described.

An exhaustive investigation of the brightness of different views would involve measuring separately each object in the field of view. Because of the labor involved, and the fact that approximations are sufficiently accurate for the purpose, we have recorded only the average brightness in most cases. Table II gives several representative

TABLE II

Scene	Location	Time (E.S.T.)	Date	Weather	Surface brilliance (candles/sq. ft.)
Sixth Avenue	New York, N.Y.	9:30 A.M.	4–25–35	Clear	$6\frac{1}{2}$
Sixth Avenue	New York, N.Y.	1:15 P.M.	4–25–35	Overcast	40
Times Square	New York, N.Y.	1:30 P.M.	11– 6–34	Light rain	40
Parade	East Orange, N.J.	10:30 A.M.	11–29–34	Light rain	40 to 60
Street	Rockland, Me.	1:15 P.M.	7– 5–36	Overcast	100
Street	Warrenton, N.C.	3:15 P.M.	6–30–35	Clear	130
Street	Harrison, N.J.	3:30 P.M.	8–15–34	Hazy	130
Street	Harrison, N.J.	9:30 A.M.	8–15–34	Rain	16
River	New York, N.Y.	2:30 P.M.	10–24–35	Hazy	50
River	Pennsville, Del.	1:30 P.M.	6–29–35	Hazy	350
Bay	Cape Charles, Va.	10:00 A.M.	6–30–35	Clear	250
Beach	Atlantic City N.J.	2:00 P.M.	8–18–34	Hazy	500
Football game	New York, N.Y.	1st quarter	11–17–34	Clear	55
		2nd quarter		Hazy	50
		3rd quarter		Hazy	27
		4th quarter			16
		End			2
Baseball game	New York, N.Y.	1:00 to 3:40	9– 8–35	Clear	70 to 100
Snow bank	Harrison, N.J.	10:00 A.M.	1–24–35	Bright sunshine	700
Open field	Bethel, N.C.	3:45 P.M.	7– 1–35	Severe thunderstorm	2

readings out of the many which were taken under various weather conditions at different localities, times of day, and times of the year. The readings illustrate the tremendous differences that arise. Since television pickup devices are already known to be capable of operation under favorable conditions, it is of interest to consider the cases when the surface brightness of scenes is low. These occasions are most likely to be near sunrise or sunset, during severe storms, or when the light of the sun and sky is cut off by trees or tall buildings.

The unfavorable conditions were studied at greater length by recording the brightness of one particular subject in all kinds of weather, and by checking the variations of light in the neighborhood of tall buildings. Fig. 4 illustrates the brightness of a factory yard at Harrison, New Jersey, under many conditions. During rainy days the average values dropped to as low as seven candles per square foot, and on clear days rose to as high as 130 candles per square foot. Tremendous variations over short periods of time have been observed; in one case the brightness dropped from 100 to eight candles per square foot in less than two hours. Fig. 5 shows typical variations in brightness found in the shadows near tall buildings. At each location observations were made in several directions. In the morning, when it was clear, readings

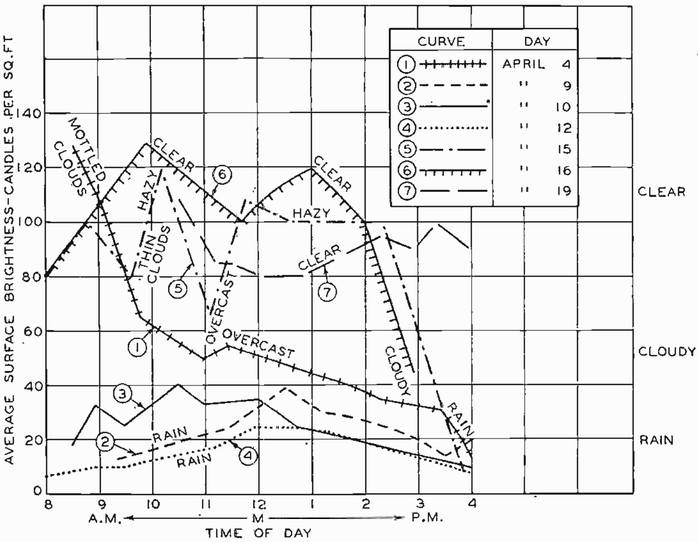

Fig. 4—Average surface brightness of a scene at Harrison, N. J., under various weather conditions during different times of the day.

ranged from two to 100 candles per square foot. Later in the day, when it was cloudy, the brightness ranged from twenty to 130 candles per square foot.

To summarize the matter of brightness of scenes encountered in

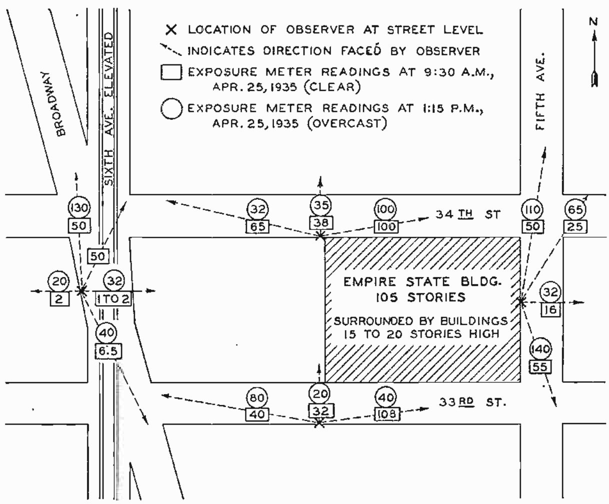

Fig. 5—Surface brightness at points around the Empire State building in clear and in cloudy weather.

nature, it may be said that almost any degree may be found; certainly from practically zero at night to over 1000 candles per square foot on a snow-covered mountain. However, during daylight hours most outdoor subjects fall in the range from twenty to 200 candles per square foot.

Brightness Necessary for the Transmission of a Television Picture

The discussion so far has disregarded the nature of the television equipment to be used for the transmission of a picture. We have been particularly interested in the performance of the Iconoscope as a tele-

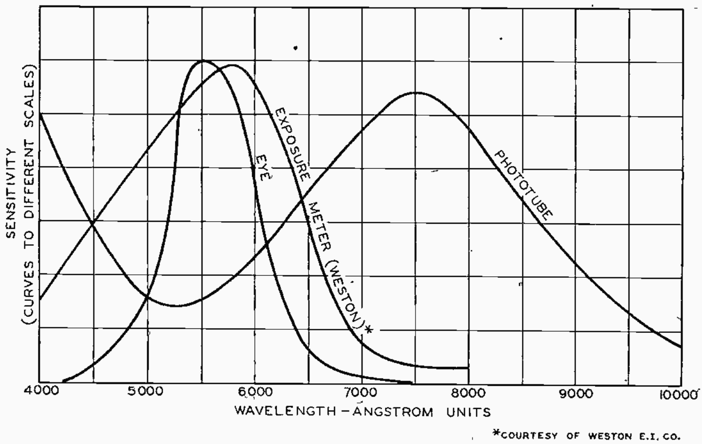

Fig. 6—Relative spectral sensitivities of the eye, the Weston exposure meter, and the usual caesium silver-oxide phototube.

vision pickup device. Hence, we have compared its sensitivity with the brightness available in natural scenes.

One matter to be considered in this regard is the relative spectral sensitivities of the eye (upon which the discussion so far has been based) and the Iconoscope. Fig. 6 shows the relative spectral sensitivities of the eye and the Weston exposure meter while Fig. 7 shows that for the present-day Iconoscope. The curves for the eye and the Weston meter are substantially the same but that for the Iconoscope is quite different. In order to determine whether the surface brightness as measured can be applied to the Iconoscope the brightness of some subjects has been measured both with the Weston meter and a phototube photometer,[7] with a special phototube having, as Fig. 7 shows, a spectral sensitivity quite similar to the Iconoscope. These measurements show that shadows will appear relatively about twenty-five per cent brighter to

[7] Designed by T. B. Perkins of RCA Manufacturing Company, Inc.

the Iconoscope than they do to the eye. The explanation is that the Iconoscope has a lower relative sensitivity in the longer visible wave lengths (except the red). Therefore, in shadows, where blue skylight is used instead of direct sunlight, the Iconoscope will be affected less than the eye. Also, blue objects in sunlight appear about twenty-five per cent brighter to the Iconoscope than to the eye, while yellow objects appear about as much dimmer. In Fig. 6 is also given the spectral sensitivity curve for the usual caesium silver-oxide phototube. This has a peak in the red and a minimum in the blue while the present Iconoscope has no read peak and is rapidly rising in the blue. In case Iconoscopes are made in the future with a spectral sensitivity more like the usual

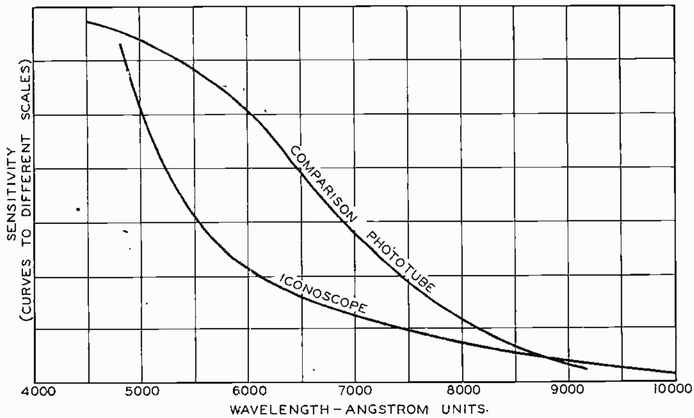

Fig. 7—Relative spectral sensitivities of the present Iconoscope and a comparison phototube.

phototube, readings have been taken with this type of phototube in the same phototube photometer. The results are about opposite from those found with the present Iconoscope. Shadows appear relatively darker to the phototube than they do to the eye. Also red objects appear about twenty-five per cent brighter to the phototube, while blue ones appear about twenty-five per cent dimmer. For highest accuracy, then, the differences in spectral sensitivity of the eye and the present Iconoscope or an Iconoscope with a red peak should be taken into account when the data of Table II are used. However, in view of the tremendous variations in natural illumination and the ability of the television transmitter to accommodate itself, these differences are, in practice, not very important.

Another matter which helps to determine the effective sensitivity of a television transmitter is the opening of the lens used to image the scene. It can be shown[4] that the illumination of the Iconoscope mosaic is given by the expression

$$I_m = \frac{0.54TB}{f^2} \text{ foot-candles}$$

where,

T is the transmission of the lens

B is the surface brightness of the scene in candles per square foot.

f is the ratio of the principal focus of the lens to its effective diaphragm opening.

For our work an f 4.5 lens with a six-inch focal length was available, and an Iconoscope having a mosaic slightly larger than four by five inches was used. In a commercial installation these factors, particularly the lens openings, may be changed to give still better results.

About two years ago a series of tests was made using an Iconoscope, one of the best then available, to find how much light was needed for the transmission of a "good" television picture. By "good" is meant one in which the sharpness of definition, contrast, and brightness are not so altered from their values in the scene transmitted as to be objectionable to the majority of observers. The amplification which could be used was found to be limited by noise from the first stages of amplification, and not from the Iconoscope. It was necessary, therefore, that the latter deliver enough signal to make the shot and thermal-agitation noises relatively very small. This signal delivered by an Iconoscope increases with the beam current used. An increase in beam current, however, was found to increase the spurious signal or so-called "dark spot" which is caused by redistribution of secondary electrons.[8] The signal output, therefore, has to be limited to a value which will allow compensation for the "dark spot" signal. Under these conditions the conclusion was reached that an average brightness of fifty candles per square foot was sufficient to give a reasonably satisfactory picture of an average scene on a cloudy day with an f 4.5 lens to focus the light on the Iconoscope mosaic. In this case, the brightest object in the field of view had a brightness of sixty-five candles per square foot, while the dimmest had fifteen candles per square foot. Another scene having an average brightness of thirty candles per square foot was generally agreed to be equally satisfactory for transmission. In the second test the brightest object had a brightness of 100 candles per square foot, and the darkest had five candles per square foot. The average brightness needed for satisfactory operation, then, is less when the contrast between objects of interest and the background is high. As a result of

[8] A more complete discussion of this spurious signal is given in a paper by V. K. Zworykin, "Iconoscopes and Kinescopes in television," *RCA Rev.*, vol. 1, p. 75; July, (1936).

these and other experiments, the conclusion was reached that an *f* 4.5 lens would allow pickup of most views brighter than fifty candles per square foot, or that if an *f* 2.7 lens were used an average brightness of twenty candles per square foot would be sufficient.

This performance is very good; five years ago it might have been called miraculous. Yet this performance is not sufficient to permit the transmission of every subject that might be of interest to the public, nor does it allow otherwise acceptable scenes to be transmitted with adequate depth of focus. Research and development work have, therefore, continued with the object of providing still higher sensitivity.

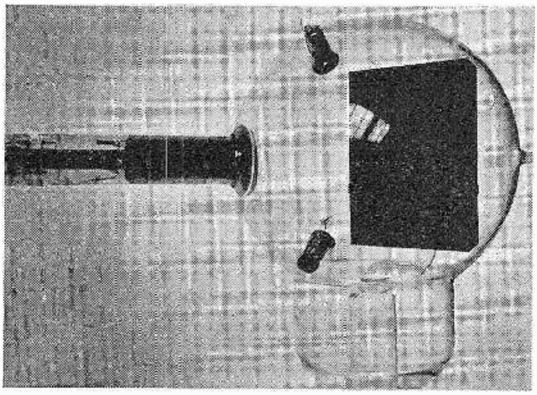

Fig. 8—Iconoscope with silver evaporation sensitization.

The problem of sensitizing an Iconoscope is more complicated than that of sensitizing a phototube, because it is necessary to maintain very high insulation between all of the tiny photosensitive particles on the mosaic, as well as to obtain good photoemission. In the past, the difficulty of maintaining good insulation has been a limitation to the photosensitivity attainable; the presence of enough caesium to provide optimum photoemission would cause too much conductivity. A film of cryolite evaporated on the mica sheet before the mosaic is formed has been found to give a marked improvement in the insulation, in fact, enough to make practical a silver-evaporation sensitization process.

According to this method, the mosaic is first sensitized as usual by oxidizing it, admitting caesium, and baking. Then, a very thin coating of silver is evaporated from filaments provided for the purpose, and the tube is baked again. A photograph of such an Iconoscope is given in Fig. 8; the side tubes in front of the mosaic contain the filaments for evaporating silver.

Not only has the sensitization process been improved, but also the quantity and purity of materials have been controlled more carefully than in the past. As a result, the best Iconoscopes today are more than three times as sensitive as the best of two years ago, and the average is more than correspondingly improved.

Quite faithful reproductions of scenes having an average brightness of fifteen candles per square foot may now be transmitted with an *f* 4.5 lens. The received pictures are not perfect, especially in regard to shading, but they are substantially the same as the original scene so that the entertainment value is little affected. An equally good picture, except for depth of focus, could, of course, be transmitted of a scene

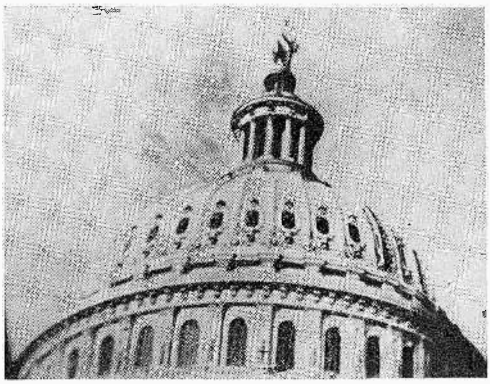

Fig. 9—Photograph of a received image when the lighting of the transmitted scene was optimum for the mosaic of the Iconoscope.

having a surface brightness of five or six candles per square foot if an *f* 2.7 lens is used. When the light is still less, it is possible to identify familiar objects, though the quality of the picture is definitely impaired. Using an *f* 4.5 lens we have been able to reproduce scenes where the average brightness was as low as 2.5 candles per square foot. Such pictures, however, do not have much entertainment value.

When greater illumination is available at the transmitted scene, pictures of better quality are obtained. Fig. 9 is a photograph of a received picture which was taken when the lighting of the transmitted scene was optimum for the mosaic of the Iconoscope.[9] The use of the word optimum, of course, implies that the illumination on the mosaic can be too strong as well as too weak. This has been found to be the

[9] This photograph is shown through the courtesy of R. M. Morris of the National Broadcasting Company.

case. Because only a small electric field is available for drawing photoelectrons away from different parts of the mosaic, the photocurrent on the strongly illuminated portions of the mosaic can be saturated. This saturation will in turn lower the signal output from these strongly illuminated parts. In using the Iconoscope, it is found that saturation shows up as a reduction in contrast. Consequently, when plenty of light is available, the illumination on the mosaic is adjusted for maximum contrast.

As a result of the tests which have been made, it is possible to tell quite well what subjects would be available for transmission if television broadcasting should start now. Motion pictures and studio entertainment are, of course, to be expected. Outdoor scenes of parades, baseball games, and races can be handled until near sunset under almost any weather conditions. It is even possible that transmission of some night baseball games is technically possible; newspaper descriptions of Crosley Field, in Cincinnati, indicate that the lighting is sufficient. Many football games would be satisfactory subjects, although in some cases the light would be too dim at the end of the game unless the starting time were advanced by half an hour.

The mention of these possibilities does not necessarily mean that such sports events will be shown as soon as television broadcasting is started. Economic considerations, rather than technical ones, may determine which subjects are feasible. In the meantime, work of improving the Iconoscope is being continued; there is hope that its sensitivity may be increased still further. Some day it will be able to "see" anything that the human eye can see and some things that the human eye cannot observe.

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TELEVISION PICKUP TUBES WITH CATHODE-RAY BEAM SCANNING*

By

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Summary—*Television pickup tubes which use cathode-ray beam scanning, although only one class of television pickup devices, may be made in a variety of ways, a number of which are described in this paper. In these tubes, the function of the electron beam is to release secondary electrons from the target, the number escaping being modulated by electrostatic fields, magnetic fields, orientation of electrodes or changes in the secondary emission ratio of the target. The Iconoscope*[1] *is a well-known example of modulation by electrostatic fields produced by photoemission from the target. A conducting photocathode when used as a target, however, acted as if its secondary emission ratio were decreased by light. A copper plate oxidized and treated with caesium transmitted a picture with some time lag. Photoconductive materials exposed to light and scanned by an electron beam were made to develop potential variations over their surface and thereby transmit a television picture. Aluminum oxide and zirconium oxide, treated with caesium, were used in this manner. Selenium, used as a photoconductive material, also transmitted a picture. Germanium used as a target sensitive to heat radiation was able to transmit a picture, probably as a result of some thermoelectric effect. The most sensitive tubes tested were those in which an electron picture was focused upon a scanned, secondary electron emissive target. The scanning and picture projection operations may be separated by using a two-sided target. Coupling between the two sides was obtained by conducting plugs through the target. Stray secondary electrons from the electron gun, which contributed a spurious signal, were eliminated by the use of apertures in the first anode. A demountable television pickup tube was used for the experiments with selenium.*

IN A cathode-ray television system the conversion of an optical image into a train of electrical impulses, known as the video signal, is accomplished by the pickup tube. While several kinds of pickup tubes have already been described in the literature, and numerous patents have been issued, the information published on the subject is still not very extensive.[2] This discussion is undertaken with the hope that it will add to the general understanding of the operation of some kinds of pickup tubes by providing simplified explanations supported by the results of comprehensive tests. The tubes which are described

* Decimal classification: R583. Original manuscript received by the Institute, June 9, 1937. Presented before Silver Anniversary Convention, New York City, May 12, 1937.

[1] Registered trade-mark, RCA Manufacturing Company, Inc.

[2] A review of patents and experimental work has been made by A. Dauvillier, *Revue Generale de l'Elec.*, vol. 23, p. 5; January, (1928).

See also bibliography at the end of "Die Wirkungsweise der Kathodenstrahl bildzerleger mit Speichwirkung," R. Urtel, *Hochfreq. und Electroak.*, vol. 48, p. 150; November, (1936).

are all in a developmental form, and the test results are given only for the purpose of illustrating the theories which are presented.

Before beginning a discussion of these devices, however, it is desirable to clarify the meaning which is attached to some of the terms to be used.

Television pickup tube: a vacuum tube used for the purpose of creating television video signals from an optical image.

Target: a vacuum tube electrode, usually having considerable area, subjected to electron bombardment.

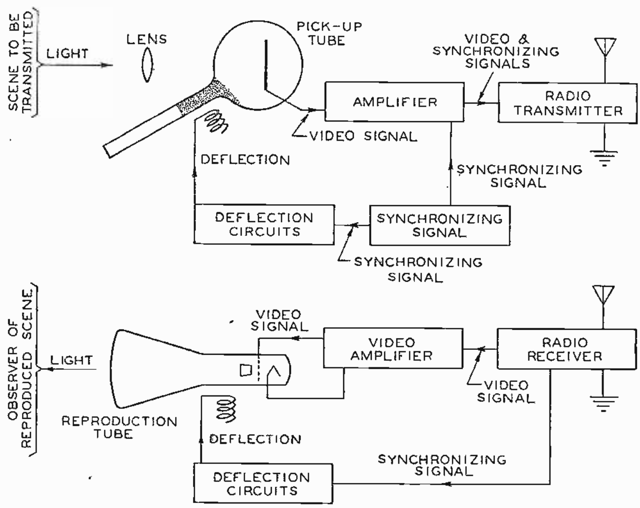


Fig. 1—Schematic diagram showing relation of pickup tube to television system.

Electron picture: a stream of electrons having variations in density over the cross-sectional area, according to the light and shade of a picture.

Reproduction tube: a vacuum tube in which the reproduced television picture may be seen.

Collector: an electrode used in a cathode-ray tube for the purpose of collecting electron emission from a scanned target.

Polarity of signal: the signal from a television pickup tube is said to be positive when an increase of light on the target makes the potential of the output lead relatively more positive.

In a television system the pickup tube occupies a position comparable with that of the microphone in a conventional radio broadcast station. As Fig. 1 shows, in a typical television transmitter the optical picture of the scene to be transmitted is focused upon the target of the pickup tube. An electron beam scans the target completely about thirty times per second, usually in a series of several hundred parallel horizontal sweeps. During the scanning the television video signals originate in variations in the current flowing from the scanned target. The weak video signals are amplified and mixed with horizontal and vertical synchronizing impulses before being used to modulate the radio transmitter.

At the television receiver the synchronizing impulses are separated from the video signals and are used to synchronize the deflection of the electron beam in the reproduction tube with that in the pickup tube. Simultaneously, the amplified video signals are impressed on the grid of the reproduction tube to modulate the intensity of the beam as it strikes the fluorescent screen in accordance with the variations in the

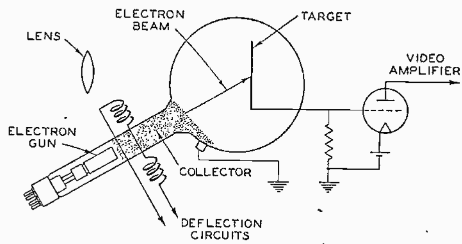


Fig. 2—Typical television pickup tube.

current flowing from the target of the pickup tube. In this way a representation of the original scene is produced on the fluorescent screen.

Few people realize the number of kinds of operative television pickup tubes already in existence. The present discussion will be confined to outlining the performance of just one classification: tubes in which an electron beam is used to scan a target which bears the focused image of the original scene. In order to cover even this limited field, the descriptions must be brief.

A pickup tube with a cathode-ray scanning beam may take many different shapes, depending upon whether the beam is formed as a result of photoemission, secondary emission, or thermionic emission. Since the latter is usually most convenient, it will be taken for purposes of illustration. A tube as shown in Fig. 2 is typical; the electron gun generates a focused beam of electrons, the deflection system causes the beam to scan the target upon which is projected a picture of the scene to be transmitted, and the amplifier observes variations in the target current as the beam moves over the surface. (The polarity of these current variations is not important, since the picture can be changed from negative to positive by adding or subtracting a stage of amplification, or by taking the signal from a different electrode in the tube.) Before satisfactory operation is obtained a number of requirements must be met; these are considered under the headings: Electron Gun, Deflection, Theory of Operation, Light-Sensitive Targets, Heat-Sensitive Targets, and Electron-Sensitive Targets.

Electron Gun

Electron guns suitable for use in cathode-ray tubes have been described by Zworykin and others.[3,4] We have, however, found it advisable to modify some of the simpler designs to insure the supression of secondary emission from the anode. Fig. 3(a), which illustrates a conventional type of electron gun, shows how a limiting aperture is usually used (in a manner comparable with a fixed lens iris) to determine the diameter of the bundle of electrons entering the focusing field at the

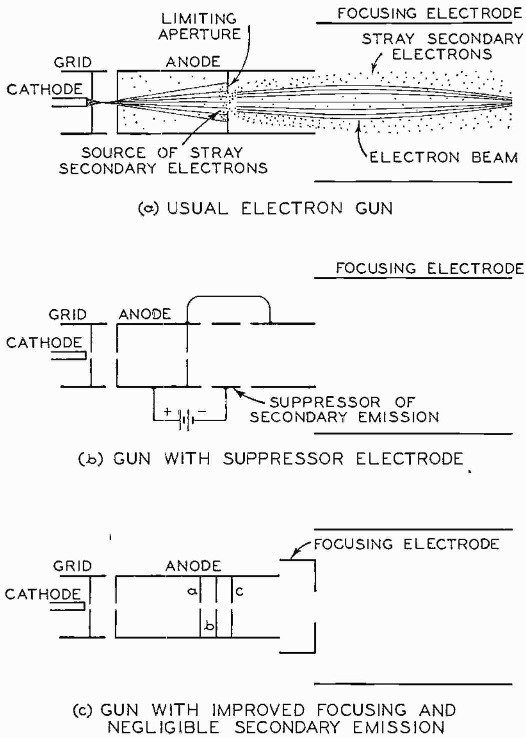


Fig. 3—Electron gun designs.

[3] V. K. Zworykin, "On electron optics." *Jour. Frank. Inst.*, vol. 215, p. 535; May, (1933).

[4] R. T. Orth, P. A. Richards, and L. B. Headrick, "Development of cathode-ray tubes for oscillographic purposes," Proc. I.R.E., vol. 23, pp. 1308–1323; November, (1935).

end of the electron gun. The electrons which are too far from the axis for good focusing strike the metal part of the aperture disk and release secondary electrons. The field from the more positive focusing electrode draws a few of the secondary electrons through the aperture and sends them toward the target or fluorescent screen. In a Kinescope[5] the effect of these secondary electrons from the anode is not very important. The secondary emission ratio of the limiting aperture is not very high; the beam current is usually much stronger than the secondary emission current; the secondary electrons are more widely deflected by the deflection fields than the beam electrons (because of the difference in velocity); and the lower speed secondary electrons do not produce as much light as those in the main beam.

On the other hand, conditions in a television pickup tube very often bring into prominence the presence of secondary electrons from the anode. The same alkali metals used to make the device light-sensitive may also cause an increased secondary emission from the apertures. In such tubes as the Iconoscope, the beam current for good operation may be only a fraction of a microampere, so that even a very small secondary emission current can represent a considerable proportion of the total. In addition, the electrical effects produced at the target of a pickup tube may be as great at low voltages as at high voltages. (Some tubes give substantially the same amplitude of signal output at fifty volts as at 2000 volts equivalent velocity of the beam.) When the scanning beam is not homogeneous, therefore, the video signals contain two scrambled components: one (due to the main beam) which can be used to reproduce a sharp picture of normal size; and the other (due to the secondary electrons) which causes a small size, poorly defined representation of the target to be superimposed on the main picture received. Fig. 4(b) illustrates the appearance of the picture transmitted by a certain Iconoscope in which there was considerable secondary emission from the anode of the electron gun; the dark rectangle in the upper center of the picture is a representation of the whole target, but the secondary electrons are so poorly focused that the details of the secondary picture cannot be discerned. The improvement in picture quality resulting from the elimination of stray electrons from the beam is shown in Fig. 4(a), which is a photograph of the picture transmitted by the same tube under the same operating conditions after the secondary emission had been suppressed by a special electrode provided for the purpose.

Several methods are effective in keeping the secondary electrons

[5] V. K. Zworykin, "Description of experimental television system and Kinescope," Proc. I.R.E., vol. 21, pp. 1655–1673; December, (1933).

from the electron gun from reaching the target. It is possible to focus the beam by making the anode voltage higher than that of the focusing electrode. (Experience has shown that, with electrostatic focusing, if the beam is focused with the anode and focusing electrode voltages in the ratio of one to n, then another condition of focus will be found when the potentials are approximately in the ratio of n to one.) While this so-called inverse focusing may not produce an electron beam as small in diameter as the more conventional method, it is able to deliver satis-

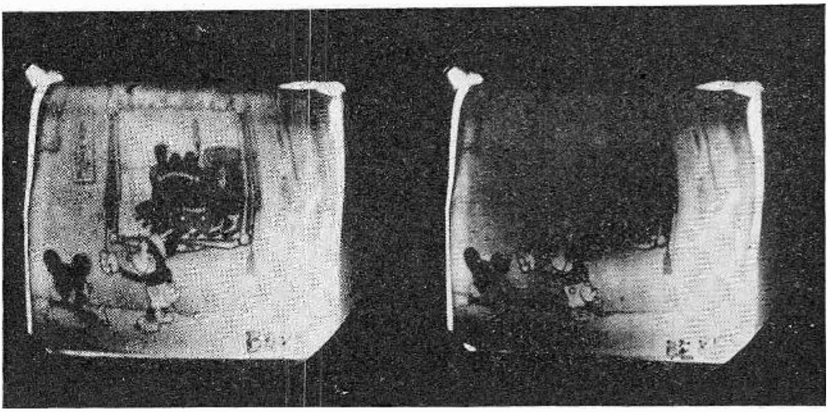


Fig. 4—Television pictures illustrating effects of secondary electrons from electron gun.

factory results with the small beam currents usually used in television pickup devices.

Another method of suppressing secondary emission from the anode is to put an extra electrode in the gun, as was done in the tests illustrated in Figs. 4(a) and 4(b). Such an electron gun is sketched in Fig. 3(b); the suppressor electrode may be operated at twenty volts negative with respect to the anode to keep the secondary emission from leaving the gun, or made slightly positive so that the effect of an excessive amount can be observed.

A third way which is simple, and usually sufficiently good, is to use a series of apertures for limiting the diameter of the beam. In the design of Fig. 3(c), aperture a is used to keep electrons reflected from the walls of the tubing from reaching the limiting aperture b, while c prevents the focusing field from drawing secondary electrons from b out of the anode. In most of the following tests a gun similar to that of Fig. 3(c) has been used.

Deflection

After an electron beam with suitable current, homogeneity, and sharpness of focus has been provided, the next problem is to cause it to scan the light-sensitive target. In some respects the problems of producing deflection in a pickup tube are simpler than those in a reproduction tube, for the electrons in the beam are generally accelerated with 1000 volts or less (as compared with 5000 volts or more in a Kinescope), and the maximum diameter of the electron stream may be roughly a third that in a conventional cathode-ray tube (because the

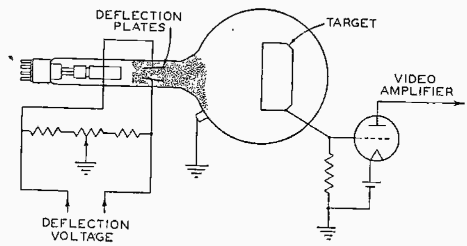


Fig. 5—Circuit for minimizing pickup from electrostatic deflection plates.

beam current can be small). The result is that small and even somewhat nonuniform deflection fields are suitable, though, of course, the wave form of the varying deflection field must be as good as possible. Either electrostatic or magnetic deflection may be used. One requirement, however, not met in reproduction tubes should be observed; the deflection field should be shielded from the target scanned by the electron beam in order to prevent pickup in the amplifier. When electrostatic deflection is used, it is generally sufficient to connect resistors across the deflection plates with an adjustable center tap (as illustrated in Fig. 5). The center tap is then set so that the pickup in the amplifier through capacitance to the deflection plates is minimum. When magnetic deflection is used, the deflection coils should be electrostatically shielded from the amplifier, and in some cases designed so that the stray magnetic field near the light-sensitive target is minimized.

Theory of Operation

Now that methods of generating and deflecting an electron beam have been considered, the question of how to use it for the creation of a television video signal may be discussed. For this purpose, it is only necessary that at the electrode to which the amplifier is connected the current flow at each instant be representative of the illumination of the portion of the picture struck by the electron beam. While the effect of the light may be (1) to control the number of beam electrons which can reach the surface, or (2) to cause variations in the ability of different parts of the target to emit secondary electrons, or (3) to modulate the escape of an otherwise uniform secondary emission, the first of these methods has been used but little in television transmission because of difficulties in controlling low velocity streams of electrons.

The second method of generating a video signal is particularly desirable, since the resulting picture signal may be relatively strong and well defined. Unfortunately, a material which has a considerable ability

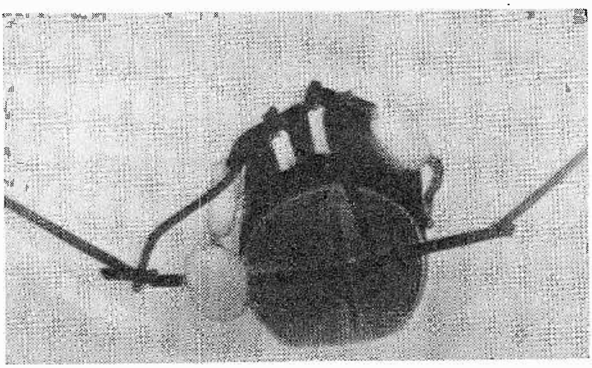


Fig. 6—Television picture of electrode scanned by electron beam.

to change its secondary emission ratio as the result of light is seldom encountered. The possibilities of this type of picture transmission are brought out in the "television picture," Fig. 6, which shows the results of scanning a metal and glass structure with a cathode-ray beam.[6] This picture might be termed an "electron's eye" view of the electrode, for the secondary emission properties of the glass and metal parts are shown in terms of light and shade in the picture. The "electron's eye" has considerable depth of focus, because the scanning beam remains of small cross section throughout the length which is intercepted by the three-dimensional target. (The operation of a television pickup tube in which we believe a change in secondary emission ratio is effected by light will be described later.)

The third method of generating a video signal by cathode-ray beam scanning, namely by controlling the escape of an otherwise uniform secondary emission, is relatively less difficult and more frequently used. A more detailed discussion of this system seems desirable for a more

[6] Other similar photographs are given in a paper by M. Knoll: Aufladepotential und Sekundäremission elektronenbestrahlter Körper, *Zeitsch. für tech. Phys.*, vol. 16, no. 11, pp. 467–475; November, (1935).

complete understanding of its action. The action of a high velocity electron beam has been compared with that of a mechanical contactor which successively touches parts of a light-sensitive target to discern local conducting areas or sources of potential. This concept is one easy to understand, and is satisfactory for some purposes, yet if carried too far, may lead to some erroneous conclusions. In the first place, the beam itself cannot be called the contactor, because its effective resistance is substantially infinite. With most well-known kinds of electron guns in high vacuum tubes the potential of the target can be changed by a thousand volts without altering the current from the end of the gun by a fraction of a microampere; a conducting commutator would not behave in this manner. The thing which may, in some cases and

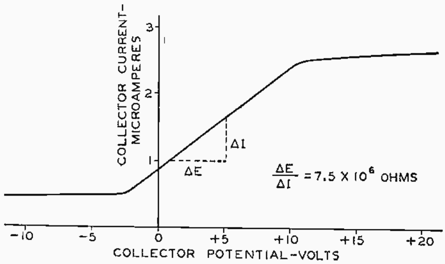
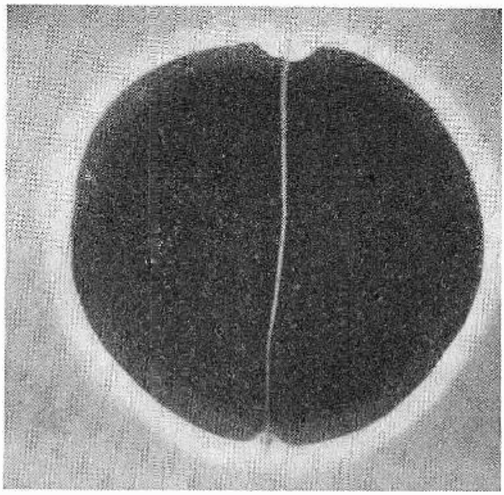


Fig. 7—Curve showing relation between collector voltage and collector current.

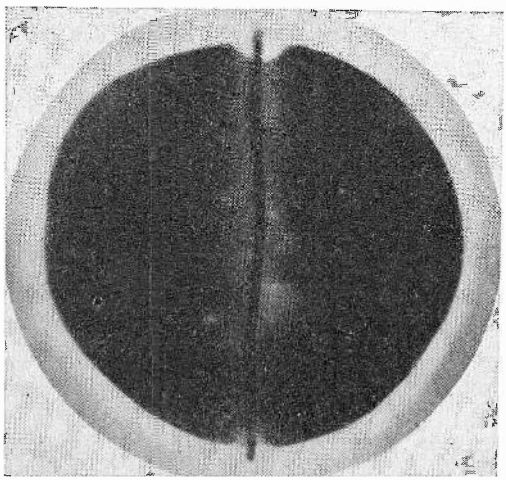
for some purposes, be considered the contactor is the secondary emission released from the scanned surface and collected by some other electrode which may be referred to as a collector. For example, in a tube having the general appearance of the one in Fig. 2, the target was a metal plate covered with caesium on silver oxide. It was found that, when the target was struck by a 1000-volt, 0.7-microampere electron beam and the collector voltage was varied, the secondary emission which reached the collector varied according to the curve of Fig. 7. In this tube, when the operating voltages correspond to the steepest part of the curve, the effective resistance of this contactor may be said to be $\Delta E/\Delta I \doteq$ about 7 megohms.

Thus, the explanation may be given that scanning the target with this electron beam is equivalent to passing over the surface with a conductor having a resistance of 7 megohms in series with a battery to determine the rate of discharge of the surface. This description is useful in that it gives a simplified explanation of the operation, but is unsatisfactory in that it fails to predict the rain of secondary electrons to which the target is usually subjected.

A preferable explanation is that the 1000-volt electron beam (as was used in the work to be described) releases secondary electrons at successive points on the scanned target, and that the light-sensitive



(*a*)



(*b*)

Fig. 8—Television pictures of nickel disk and nickel wire.

target varies the number of secondary electrons from each picture element which leave or reach the electrode to which the amplifier is connected. These variations constitute the video signals transmitted to the television receiver. The variations in collector current as the collector voltage is changed (as shown in Fig. 7) usually result from changes in paths taken by secondary electrons. When the electrostatic field is retarding, the lower velocity secondary electrons are turned back to the target soon after leaving; even when the electrostatic field tends to draw them away, some secondary electrons may have initial directions of motion not directly toward the collector, so that they are deflected back to the target by glass tube walls or other objects. Only when the target is relatively quite negative do all the secondary electrons reach the collector. In this way the potential of a point struck by a stream of electrons determines how much secondary emission will escape, and how much will return to the target near or far from the point of origin.

The darkness or brightness of a certain part of a target, as seen by an observer looking at the Kinescope, may thus be determined by the potential of that particular portion of the surface with respect to other near-by electrodes. This fact is illustrated by Fig. 8, which shows the "picture" received from a plain nickel disk with a nickel wire stretched in front of it. The nickel disk and wire constituting the target were both connected to the amplifier. In Fig. 8(a) the disk and collector were at the same potential, while the wire was two volts positive with respect to the disk. The wire appears as a light line on the dark background of the disk since the secondary emission from the wire to the collector was reduced by a retarding potential of two volts. In Fig. 8(b), the disk and collector were again at the same potential while the wire was two volts negative with respect to the disk. Secondary emission from the wire and most of the disk was drawn to the collector, as indicated by their dark shading. The light area parallel to the wire is a result of the negative grid action of the wire in tending to prevent secondary emission from this area of the disk from reaching the collector.

For the sake of completeness, it should be mentioned that a magnetic field, as well as an electrostatic field, can be used to control a secondary emission current which, without the presence of the magnetic field, would be the same from all parts of a target. In Fig. 9 is shown a photograph of the Kinescope of a television receiver when the electron beam in the pickup tube was scanning a metal target close to which was located one pole of a magnet. The black spot near the center of the picture indicates the position of the magnet.

Of the variety of methods by which a television video signal can be made to result from scanning a target with an electron beam, one of the most desirable is to create at or near the target a distribution of potentials which is similar to the light distribution in the scene to be transmitted. This can be done by focusing the image of the scene upon some material in which light produces an electrical effect, or heat causes some change. Also, an electronic replica of the optical image can be thrown upon an electron-responsive surface. Each of these possibilities will be considered at greater length.

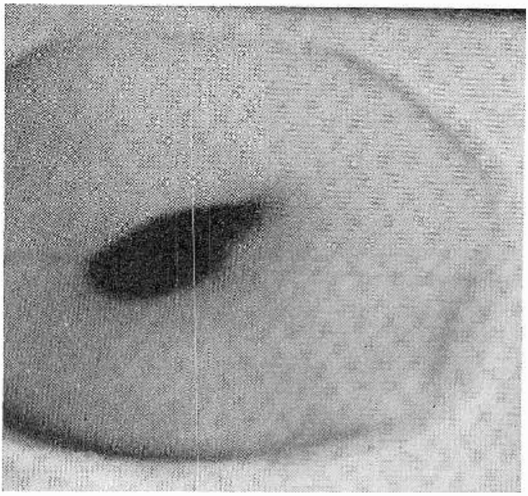


Fig. 9—Television picture showing pattern caused by magnetic field near target.

Light-Sensitive Targets

Materials which exhibit electrical effects when exposed to light have been classified as photoemissive, photovoltaic, or photoconductive, depending upon their behavior. The photoemissive surfaces eject electrons; photovoltaic substances show differences in potential; and photoconductive ones change in resistance. Each of these effects has been tested for its ability to generate a television signal.

Of the photoemissive targets, one of the most effective is composed of a signal plate coated with a multitude of small, insulated, photoemissive particles. Such a television pickup device is already well-known as the Iconoscope.[7] According to the general theory of operation given above, the number of secondary electrons actually emitted from each element of area of the mosaic is the same, but the part of the secondary emission which reaches the collector varies according to potentials established by photoemission. The rest of the secondary elec-

[7] V. K. Zworykin, "The Iconoscope," Proc. I.R.E., vol. 22, pp. 16–32; January, (1934).

trons return partly to the point of origin and partly over the whole mosaic. The polarity of the signal from the target is negative. (It should be understood in this and the following devices that, in reference to the polarity of the picture signal, the amplifier is coupled to the target unless otherwise indicated.)

Another operative photoemissive target is composed of a conducting, silver-plated metal sheet, oxidized, and treated with caesium according to conventional phototube practice. A tube made in this manner is illustrated in Fig. 10. It was found that this target, when illuminated with a very bright image and scanned with an electron beam, was capable of generating the video signals necessary for television reproduction. The polarity of the signal (negative) showed that secondary emission from the lighted places was reduced. Furthermore, the operation was not critically dependent upon beam current, was best when the collector voltage was high enough to collect all of the secondary emission, and was subject to a time lag of about one second. Explanations based upon space-charge interactions or simply upon a high resistance between the base metal and the emitting surface are not very satisfactory. Neither cause should exhibit such a long time lag, nor work well with all the secondary emission collected. The evidence suggests the conclusion that light causes the secondary emission ratio of the surface to change slightly. This case is the first of its kind which has come to our attention.[8]

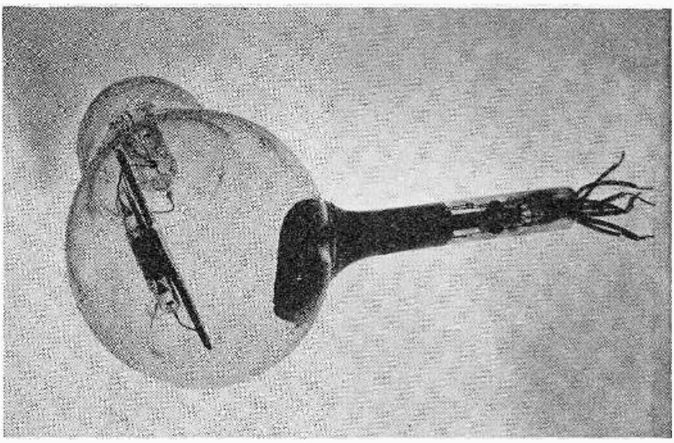


Fig. 10—Pickup tube having silver target sensitized with caesium.

[8] Since this was written V. K. Zworykin has called our attention to unpublished work of G. N. Ogloblinsky (1930), L. E. Flory (1931), and a publication

The photovoltaic properties of cuprous oxide on copper are well known. In some light-sensitive cells a translucent contact is pressed against the surface of the oxide, while in others a film of sputtered silver is used. Since the commercial cells are made with both surfaces covered with conducting material, they cannot be directly adapted for television use. A way of using cuprous oxide in a television tube is to treat the material with one of the alkali metals, such as caesium. For example, one copper target was prepared by baking the metal in air to oxidize it and then removing the black oxide with acid. The copper sheet covered with red oxide was then sealed into the pickup tube and exposed to caesium vapor, after which the tube was baked until practically all the photoemission disappeared.

When the tube was connected as a television pickup device with six volts positive on the collector with respect to the signal plate, it was observed that an optical image projected on the target (scanned by a one-microampere electron beam) produced a picture on the Kinescope at the receiver. The positive polarity of the signal showed that the escape of secondary electrons from the illuminated parts of the target was relatively higher than from the dark parts. Transmission of the video signals apparently started as soon as the optical image was thrown on the target, though under some conditions it required as long as a minute for the picture to die away completely after the light was cut off.

Several photoconductive materials have been found to be suitable for forming a light-sensitive target for the generation of television video signals. Since the operation of this type of tube is somewhat different from that of some of the others, the following explanation may conveniently precede a description of the results obtained.

If an insulated target is bombarded by a beam of electrons and if the secondary emission ratio is greater than unity, then the surface potential of the target will be driven to within a few volts of the collector electrode. At this equilibrium potential the number of secondary electrons arriving at the collector is equal (on the average) to the number of primary electrons striking the target. The secondary emission is unsaturated. If the target, instead of being a good insulator, has appreciable leakage to the signal plate on which it is mounted and if this signal plate is at a lower potential than the collector, then the surface potential of the target will be driven to some potential intermediate between the collector and signal plate. The lower the resistance, and the smaller the secondary emission current, the nearer will the surface

by P. V. Shmakov, "Some photoelectric properties of excited cathodes" (in Russian), *Jour. Tech. Physics* (U.S.S.R.), vol. 6, pp. 1261–1265, (1936).

potential of the target be to the signal-plate potential. Quantitatively, the surface potential of the target will come to equilibrium at such a value that the discharge of the surface by the beam balances the leakage between the surface and the signal plate.

If a target is made up, therefore, of areas all having the same secondary emission ratio but different resistances to the signal plate and and if the signal plate is biased negative with respect to the collector, the secondary emission collected from an electron beam scanning the surface will be greater from the lower resistance areas due to the larger collecting fields existing above these areas. These facts supply the necessary elements for a television pickup device provided a material for the target can be found which is photoconductive and which, in layers penetrable by light, has a sufficiently high resistance. The latter requirement is necessary since, if the light penetrates only a relatively small thickness of the target, the total resistance between the target surface and signal plate will not be sufficiently changed by exposure to light.

Several photoconductive materials have been found to satisfy the requirements mentioned above. Targets were prepared by spraying aluminum oxide (Al_2O_3) or zirconium oxide (ZrO_2) on a metal sheet, treating them with caesium vapor and baking. In certain cases, when there was photoemission as well as photoconductivity, these tubes could be made to work according to either of the two modes of operation; by prolonging the baking the latter effect could be made to predominate.

When scanned with an electron beam of about one microampere, the targets transmitted a positive picture signal with the collector positive with respect to the signal plate, and a negative picture signal with the collector negative with respect to the signal plate. This change of picture polarity is to be expected, since the lighted areas tend to remain near the signal plate potential while the unlighted areas tend to remain near collector potential. Consequently, the collecting field for the unlighted areas tends to remain constant when the potential between collector and signal plate is varied. On the other hand, the collecting field for the lighted areas tends to change sign when the potential difference between the collector and signal plate changes sign. The collector voltage at the transition between positive and negative picture signals was not in general zero (as would be expected from photoconductivity alone), nor was it always the same for different surfaces. The variation is due to the differing photosensitivities of the surfaces and their different resistances to the signal plate. For positive collecting voltages, the photoemissive action and the photoconductive action work in opposite directions. For low positive collecting voltages, therefore, the development of potentials by photoemission was predominant, and the picture signal negative. As the collector voltage was raised, the picture signal became positive, the transition occurring at a higher voltage for thicker layers of ZrO_2. This observation supports the explanation offered for the action of photoconductive materials, since for low collecting voltages the ZrO_2 had enough resistance in both the lighted and unlighted areas to be driven to collector potential and thereby operate by photoemission. It required a larger difference in voltage between collector and signal plate to bring out the spread in potential due to photoconductivity between the lighted and unlighted areas of the target and a still larger difference when the average resistance of the target was higher, as for the thicker layers of ZrO_2.

The positive picture signal obtained with the collector positive could be intensified during the transient of about thirty seconds duration generated by suddenly raising the collector potential about 100 volts. As soon as the transient effects disappeared, the picture faded to its original or even a lower brightness. This transient is due to the beam driving the surface potential of the target up to the new collector potential—several volts per scanning cycle. The unlighted areas rise faster than the lighted areas due to their larger resistance to the signal plate. There is, therefore, a temporarily increased spread in surface potential between the lighted and unlighted areas which is reflected through the increased modulation of secondary emission in a picture of greater contrast.

Lag effects were sometimes observed in the pictures transmitted by these targets. In one case the scanning beam was biased off and a picture was then projected for a few seconds on the target. When the target was again scanned after an interval of two minutes, the picture was still visible. In general, operating conditions could be so chosen that this lag was not objectionable.

Selenium has long been known as a photoconductive material. Probably because of its ease of preparation and sensitivity, it has frequently been proposed for use in various television pickup devices. Some time ago, Campbell Swinton proposed the scanning with an electron beam of a sheet of selenium upon which the optical picture was projected. According to Dauvillier[2] no conclusive results were obtained. In this same paper Dauvillier mentions patents obtained by E. G. Schoultz (1921), Seguin (1924), and Blake and Spooner (1924), which use selenium in a television pickup device.

Although we have succeeded in obtaining pictures from selenium surfaces, they have not, in general, been as good as those obtained from

ZrO_2 and Al_2O_3 sensitized with caesium. The selenium, however, has the advantage of being usable under relatively poor vacuum conditions, and in a demountable vacuum tube. It presents certain difficulties for general use because of its ease of evaporation at the temperature at which the tubes are usually outgassed.

A demountable vacuum system which was used for the tests with selenium is illustrated in Fig. 11. Essentially it consists of a cathode-ray tube with a removable face. The face is a flat glass disk eight inches

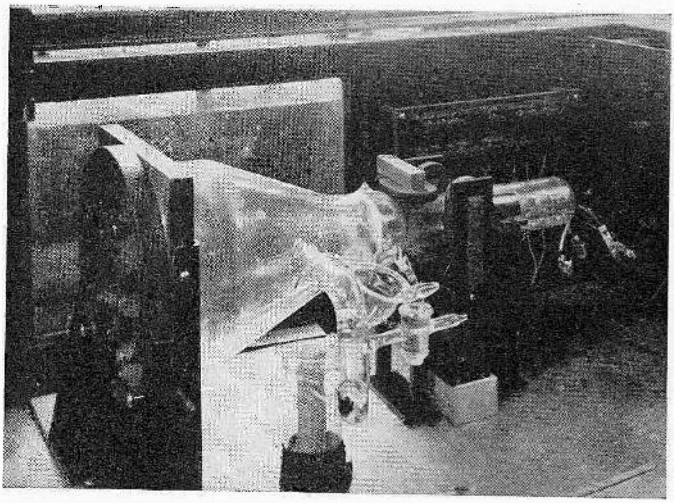


Fig. 11—Demountable cathode-ray tube.

in diameter, sealed to a brass ring by stopcock grease, and held in place by atmospheric pressure. Several bolts were inserted in the holes bored through the disk and sealed in place with Picein. The bolts served to support and make contact with the various targets. The other side of the brass ring has a circular groove in which the rest of the tube is set with Picein. The electron gun is mounted on an assembly which may be removed as a whole for replacing the cathode. The assembly is inserted in a plug bearing the gun leads permanently sealed through the end of the tube. Horizontal deflection is accomplished either by removable electrostatic deflection plates mounted on an insulating ring several inches beyond the end of the gun, or by external iron-core coils, while vertical deflection is obtained by two iron-core coils slipped over the outside of the tube behind the deflection plates. In general, sufficiently good vacuum conditions were obtained by using a Cenco Hyvac pump connected through one-inch glass tubing and through a liquid-air trap to the main tube. (The electron beam may be made visible by gas in the tube when the liquid air is removed.) Power supply terminals are mounted on the inside panels of a safety box.

Selenium-sensitized targets of three different types were found to transmit a picture; the arrangements are illustrated in Fig. 12. In each

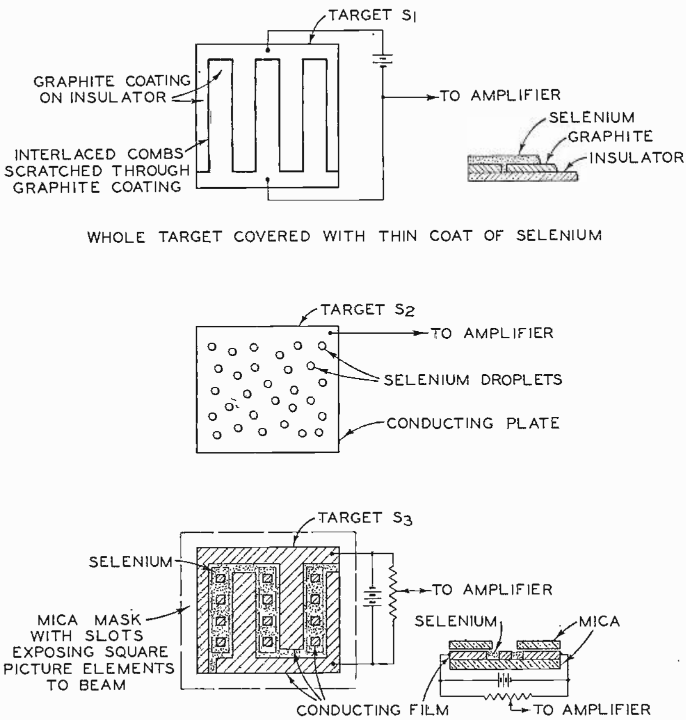


Fig. 12—Various kinds of selenium sensitized targets.

case the mosaic was set up in the demountable vacuum tube shown in Fig. 11. Target S_1 was found to transmit a faint positive picture which tended to fade out when the optical picture was held stationary on the mosaic. The transmitted picture had better definition than would be expected from the coarseness of the comb structure. Target S_2 also transmitted a faint positive picture which tended to fade when held stationary on the mosaic. The definitions in terms of picture elements per unit area was about the same as the number of droplets per unit area. Target S_3 did not show any effect due to light until it was shielded from the electrostatic deflection plates by a grounded coarse mesh metal screen, and until the target was covered with a mica mask which exposed only the separate square picture elements to the beam. Under these conditions light striking the selenium on one edge of a square caused the transmitted picture of the square to become darker, and light striking the selenium on the opposite edge of the square caused its transmitted picture to become lighter. The effect was permanent while the light remained on the selenium, as opposed to the transient fading effects observed in the other two cases. Since the effect of light could be duplicated by shifting the amplifier tap on the potentiometer, which changes the potential of the square elements with respect to the grounded collector, it is reasonable to conclude that the effect of the light was the same.

The results of these and other experiments with selenium-sensitized pickup devices show that a television video signal can be generated, but that much research work would be required in order to produce a commercially useful tube.

Heat-Sensitive Targets

The tubes considered so far are sensitive to visible light, to ultraviolet radiation, or to the near-infrared radiation. For such purposes as navigation in fog, it would be very useful to be able to see far-infrared radiation, say, wave lengths of ten microns or longer (visible radiations lie between 0.4 and 0.8 micron). One means by which radiation of any wave-length may be detected is its ability to heat an absorbing medium. With this in mind, we have conducted a number of tests with heat-sensitive targets.

For the purpose, a target composed of a conducting surface covered with a multitude of thermocouples or thermopiles naturally comes to mind. There is every reason to believe that such a construction would be capable of originating a television signal from invisible radiation, yet the mechanical difficulty of mounting some hundred thousand delicate thermocouples on a metal sheet led to some simpler preliminary tests with thin films of metals evaporated in vacuum upon an insulator. The metals tried were chosen because of peculiarities in their thermoelectric behavior; one of the targets consisted of an opaque film of germanium supported by a sheet of mica less than 0.001 inch thick. (The evaporation of germanium is not easy; it melts at 958 degrees centigrade, but the vapor pressure is so low that the evaporation takes place very slowly. A suitable procedure, as developed by W. H. Hickok of the RCA Manufacturing Company, Inc., is to enclose a small piece of the material in a closely wound tungsten coil sprayed with alumina and to heat it to about 1200 degrees centigrade in a vacuum near the surface which is to be coated. It may require an hour or more to obtain a layer of desired thickness.) A connection was made to the germanium coating by clamping a nickel rim around the mica sheet, and the target was mounted, as shown in Fig. 1, in such a way that the germanium surface was scanned by the electron beam.

When tested, the tube was found capable of transmitting a recognizable positive image. For best operation, the collector voltage was 20 volts positive with respect to ground, the beam current was 0.1 microampere, and the gain of the amplifier was as high as amplifier "noise" would permit. The several seconds required for the image to build up and die away served as confirmation that the operation resulted from heating effects; the polarity of the observed image indicated that the hotter portions of the target were more negative than the cool portions. The sensitivity of this type of target varied over a considerable range, apparently due to heat treatment and impurities

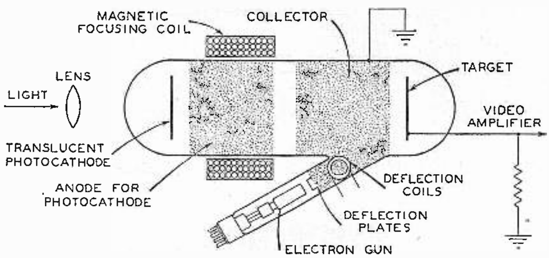


Fig. 13—Pickup tube with electron picture focused upon scanned target.

Electron-Sensitive Targets

So far, the procedure has been to focus the optical image on the target scanned by the electron beam; it is also possible to cast the light upon a photocathode, and to focus the electrons upon the scanned target. Such a general arrangement[9] is indicated in Fig. 13. Suitable means of making the photocathode and of focusing the electronic picture have been described elsewhere,[10,11] so that these need not be considered in detail. The action of the electron-sensitive target, however, is not immediately apparent.

Consider, for example, a target similar to the mosaic of an Iconoscope, consisting of a multitude of small secondary electron emissive

[9] The work of Lubszinski, who has been granted British patent 442, 866, must have been almost coincident with that of the writers, which began on this type of tube in 1933.

[10] F. Coeterier and M. C. Teves, "An apparatus for the transformation of light of long wavelength into light of short wavelength—Part II. Influence of magnetic fields," *Physica*, vol. 3, pp. 968–976; November, (1936).

[11] V. K. Zworykin, and G. A. Morton, "Applied electron optics," *Jour. Opt. Soc. Amer.*, vol. 26, p. 181; April, (1936).

particles scattered over the face of an insulating sheet the opposite side of which bears a metal coating to which the amplifier is connected.

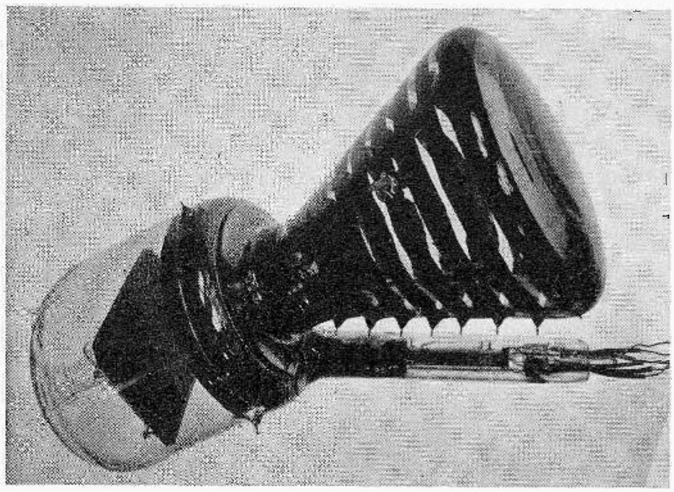


Fig. 14—Pickup tube using electrostatically focused electron picture.

Fig. 15—Television picture transmitted by scanning electron-sensitive target.

After this mosaic has been scanned many times by the electron beam, how can potential variations representing a picture be produced by throwing still more electrons against the target? One answer, of course, is that by choosing different speeds of electrons for scanning and for focusing the electron picture, different secondary emission ratios can be obtained, and thus each group will tend to drive the mosaic to a slightly different potential. Another and usually larger factor is the result of the return of the secondary electrons, emitted at one part of the mosaic to other parts. Even though the scanning beam may at one instant set the potential of an element of the mosaic, returning secondary electrons during the rest of the scanning cycle can be expected to drive

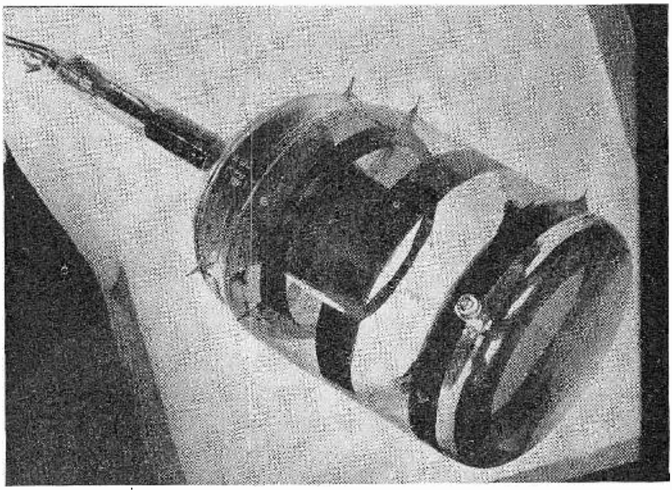


Fig. 16—Pickup tube utilizing magnetically focused electron picture.

the element negative and make possible further potential variations in response to the projected electron picture. A photograph of a television pickup tube designed to work on this principle is given in Fig. 14, while a television picture which this tube transmitted is shown in Fig. 15. This particular tube was, in operation, three times as sensitive as a conventional Iconoscope having equal photosensitivity. Part of the increase in sensitivity is due to secondary emission amplification of the electron picture, although there are other contributing factors.

In another modification, the electron-sensitive target consisted of a high resistance coating on a conducting sheet. The collector was maintained at a voltage positive with respect to the target. A simplified way of explaining the operation of this device is to consider that the flow of current resulting from the projection of the electron image produces a distribution of *IR* drops over the target surface, and that these potential differences cause variations in the escape of secondary emission from the scanning beam. In one developmental tube the target consisted of a sheet of metal coated with a layer of enamel 0.002-inch thick having a specific resistance of 10^{11} ohms-centimeters. The tests showed that such a target is able to initiate a signal of relatively high amplitude, because the interchange of electrons between parts of the mosaic is substantially reduced.

The electron picture need not be focused on the side of the target which is scanned by the electron beam, for there are several ways of transferring electrical effects from one side of a sheet to the other. One way is to use an insulating sheet containing a multitude of conducting plugs, such as may be formed by enameling a wire screen and filling the holes with a metal.[12] A tube designed to operate on this principle is shown in Fig. 16. (The solenoid for focusing the electron picture from the photocathode to the target has been removed to make the tube parts visible.) This general design offers considerable hope for the future, for the operating sensitivity is very high, and the optical arrangement is convenient.

Conclusions

Television pickup tubes of many different types have been found to be operative. Some of them are more sensitive, some give a signal output of greater amplitude, and some respond better to radiation of certain wave lengths than previous devices. While these tubes do not represent final products, in their present forms, they do contribute to the building of a consistent theory of operation for television pickup tubes with cathode-ray beam scanning.

Acknowledgment

The writers wish to acknowledge all the suggestions and assistance given them by laboratory and factory engineers of the RCA Manufacturing Company, Inc., during this developmental work. In particular, the suggestions of Mr. B. J. Thompson and the technical skill of Mr. John H. Fink have been most helpful.

[12] U. S. Patent 2,045,984, issued to L. E. Flory, describes how such a target can be made.

Proceedings of the Institute of Radio Engineers
Volume 25, Number 8 *August, 1937*

THEORY AND PERFORMANCE OF THE ICONOSCOPE*[1]

By

V. K. Zworykin, G. A. Morton, and L. E. Flory

(RCA Manufacturing Company, Inc., RCA Victor Division, Camden, N. J.)

Summary—*Field tests have shown the present standard Iconoscope to be a very satisfactory television pickup device. However, from a theoretical point of view the efficiency of the Iconoscope as a storage system is rather low. The principal factors responsible for the low efficiency are lack of collecting field for photoelectrons, and losses caused by the redistribution of secondary electrons produced by the beam.*

Limits to the sensitivity of the standard Iconoscope are set by the ratio of picture signal to amplifier and coupling resistor noise. Experimental and theoretical determinations indicate that an excellent picture can be transmitted with from two and one-half to six millilumens per square centimeter on the mosaic.

Two methods are considered by which the sensitivity may be increased. The first is by the use of secondary emission signal multipliers and a low capacitance mosaic, while the second makes use of secondary emission image intensification. The sensitivity limits for the two cases are calculated.

EXPERIMENTAL tests on the present standard Iconoscope have shown it to be a very satisfactory television pickup device. These tests include not only laboratory measurements but also extensive field tests by the National Broadcasting Company, at Rockefeller Center, in New York City. A typical studio used in the latter tests is shown in Fig. 1, while Fig. 2 shows a modern Iconoscope camera. The conclusion arrived at from these tests is that the Iconoscope is sufficiently sensitive so that it can be used for outdoor pictures under a wide range of weather conditions, and in the studio without the need of unbearable illumination. However, it would be advantageous for both uses to have somewhat greater sensitivity. The following discussion, as well as dealing with theory of operation of the standard Iconoscope, describes two methods which have resulted in a marked increase in sensitivity—although the tubes described are still in the laboratory stage and not as yet ready for use in a commercial television system.

The principles and construction of the standard Iconoscope, together with its associated equipment, have been described in detail elsewhere,[2,3,4] and a very brief description for the sake of continuity

* Decimal classification: R583. Original manuscript received by the Institute, April 30, 1937. Presented before Silver Anniversary Convention, New York City, May, 12, 1937.

[1] Registered trade-mark, RCA Manufacturing Company, Inc.

[2] V. K. Zworykin, "The Iconoscope—A modern version of the electric eye," Proc. I.R.E., vol. 22, pp. 16–32; January, (1934).

should suffice. The Iconoscope consists of a photosensitive mosaic and an electron gun, assembled in a glass bulb which is highly evacuated. The electron gun is made up of an indirectly heated oxide-coated cathode, a control grid, a cylindrical first anode, and a second anode, also cylindrical but slightly larger in diameter. The gun assembly is shown diagrammatically in Fig. 3. This gun functions as an electron optical system for producing a narrow bundle of electrons which is made to scan the mosaic by means of magnetic deflecting coils.

The mosaic consists of a thin sheet of mica coated with a conducting metal film on one side, and covered on the other with a vast number of tiny, photosensitized silver globules. This mosaic is mounted in the

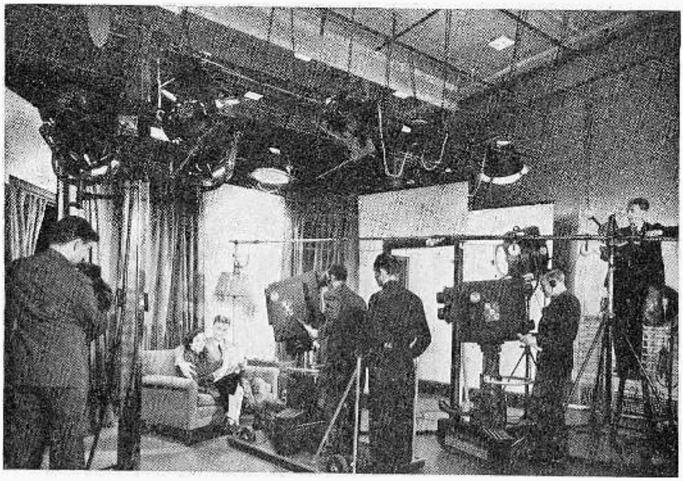


Fig. 1—Scene in N.B.C. television studio.

blank in such a position that the electron beam strikes the photosensitized side at an angle of thirty degrees from the normal and the optical image to be transmitted is projected normal to the surface on the same side. The arrangement of these elements in the tube is shown in Fig. 4, while Figs. (5) and (6) show photographs of two types of the standard Iconoscope.

Briefly, the Iconoscope mosaic may be thought of as a two-dimensional array of tiny photocells, each shunted by a condenser which couples them to a common signal lead. When the mosaic is illuminated

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[3] V. K. Zworykin, "Television," *Jour. Frank. Inst.*, vol. 217, pp. 1–37; January, (1934).

[4] V. K. Zworykin, "Iconoscopes and Kinescopes in television," *RCA Rev.*, vol. 1, pp. 60–84; July, (1936).

these condensers are positively charged with respect to their equilibrium potential due to the emission of photoelectrons from the photosensitive elements. For any particular element, this charging process continues for a time equal to the picture repetition interval, that is, until the beam in the process of scanning returns to the element. When the beam strikes it, it is driven to equilibrium, releasing its charge and inducing a current impulse in the signal lead. The train of impulses thus generated constitute the picture signal output of the Iconoscope. This description serves to illustrate the general principles of the Iconoscope, but is not sufficiently accurate to form the basis of an analysis of its operation.

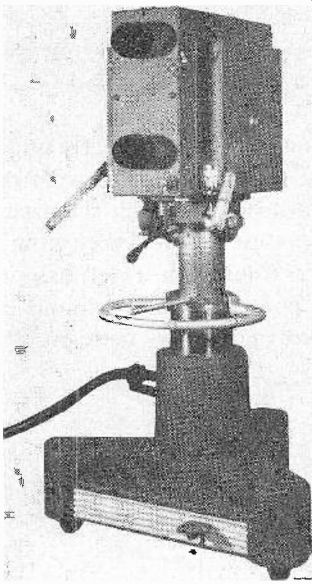

Fig. 2—N.B.C. studio Iconoscope camera.

In considering the operation of the Iconoscope, because of the fact that the silver globules are so small that a great number of them are under the beam at any instant, the mosaic may be treated as a continuous surface which has infinite transverse resistance, and which has both a high secondary emission ratio (in the neighborhood of 5 to 7) and photosensitivity. This surface has a capacitance of about 100 micromicrofarads per square centimeter in the case of a standard tube. Considered in this way, it can be readily seen that the picture element is a purely fictitious concept when applied to the mosaic. Thus, instead of discussing the behavior of discrete photoelectric elements, the mosaic will be dealt with as though it were a two-dimensional continuum.

The average potential of the mosaic under bombardment, while no light is falling upon it, is between zero and one volt negative with respect to the elements which collect the secondary emission from the mosaic, that is, the second anode. However, the potential is not uni-

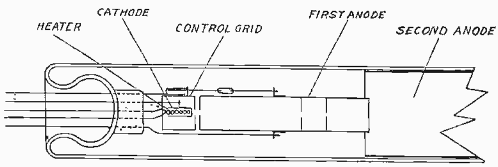

Fig. 3—Diagram of electron gun.

form over the entire surface. The area directly under the scanning beam will be at a potential of plus three volts with respect to the second anode, this being the potential at which the secondary emission ratio from caesiated silver becomes unity. Away from the point under immediate bombardment in the region which has just been traversed by the scanning beam, the potential will be found to decrease until at a distance equal to twenty-five or thirty per cent of the vertical scanning

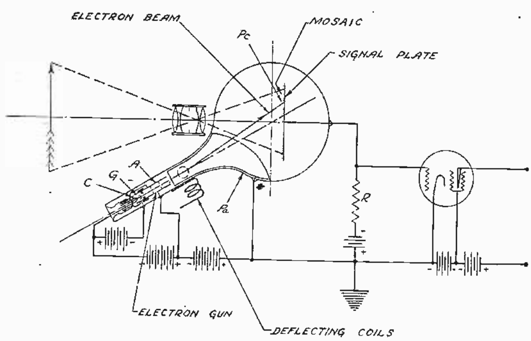

Fig. 4—Diagram of Iconoscope.

distance, the potential reaches about minus one and one-half volts with respect to the second anode. The rest of the mosaic is at this potential. This decrease in potential is caused by electrons which leave the point under bombardment and return to the mosaic as a more or less uniform rain of low velocity electrons. Fig. 7 shows a map of the instantaneous potential distribution over the mosaic.

The scanning beam sweeping over the mosaic acts like a resistive commutator. The resistance in this case is determined by the current-voltage relation of the secondary electrons from the bombarded point. While this resistance is actually nonohmic, it does not introduce appreciable error to assume it ohmic over the small voltage range dealt

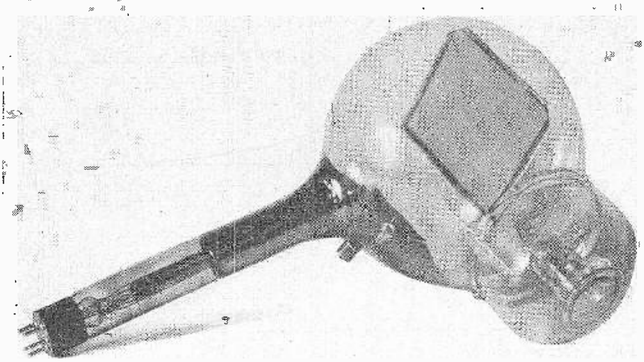

Fig. 5—Iconoscope—Spherical bulb type.

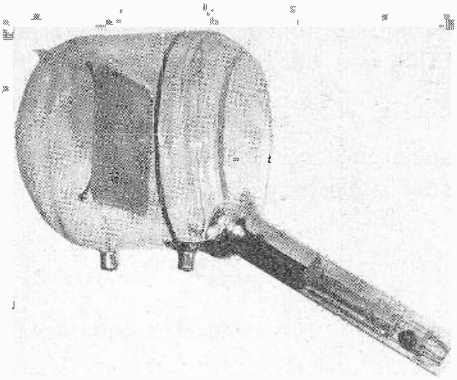

Fig. 6—Iconoscope—Optical flat window type.

with in the case of the Iconoscope. Experimental measurements show this beam impedance, Z, to be given by the relation

$$Z = \frac{Z_0}{i_b}$$

where i_b is the beam current and Z_0, the coefficient of beam impedance, having a value between 1- and 2-ohm amperes.

For purposes of computation, the beam current will be taken as 0.5 microampere, the spot a square of 0.025 centimeter on a side, and the linear spot velocity as 1.6×10^5 centimeters per second.

Any small element of area, ds, of the mosaic when it is swept over by the scanning beam must change its potential from minus one and

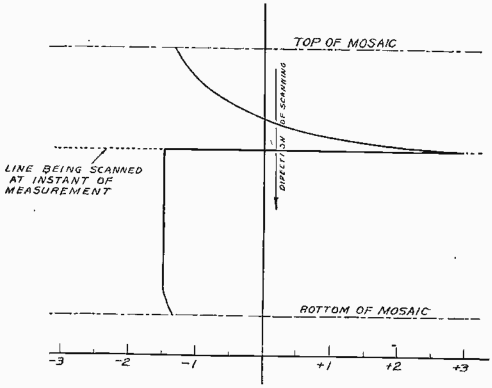

Fig. 7—Instantaneous potential of the mosaic.

one-half volts to its equilibrium of approximately plus three volts. The capacitance of this area will be

$$C = C_0 ds$$

where C_0 is the capacitance per unit area. The impedance through which this capacitance is discharged will be

$$Z = \frac{Z_0}{\rho ds},$$

ρ being the current density of the beam. The equation of the discharge will, therefore, be

$$\begin{aligned} V &= (V_2(xy) - V_1(xy))(1 - e^{(-t/Z_0C_0ds)/\rho ds}) \\ &= (V_2(xy) - V_1(xy))(1 - e^{-t\rho/C_0Z_0}). \end{aligned} \tag{1}$$

In this equation

V = change in potential of ds,
$V_2(xy)$ = equilibrium potential at point xy under beam,
$V_1(xy)$ = potential before bombardment,
t = time.

In order that the elements reach equilibrium, the condition

$$V \cong V_2 - V_1$$

must be fulfilled. For this to be true, the relation

$$\frac{Z_0C_0}{\rho} < t = T$$

T = length of time beam is on the element, ds, or

$T = h/v$ where h is spot diameter and v, the beam velocity, must be satisfied. From the operating conditions we find

$$T = h/v = 1.5 \times 10^{-7} \text{ seconds}$$

and

$$\frac{Z_0C_0}{\rho} = 1.2 \times 10^{-7} \text{ seconds.}$$

Thus, the requirements for establishing equilibrium are fulfilled.

In the above expression both V_1 and V_2 are given as a function of the co-ordinates of the mosaic x and y. This is because both the equilibrium under the beam and away from the beam are not constant over the surface.

The net current leaving the elemental area under these conditions will be

$$di_c = -\left(C_0 \frac{dV}{dt}\right) ds. \qquad (2)$$

Since the beam current reaching the element is $-ds$, the total current from the element is

$$di_t = -\left(\rho + C_0 \frac{dV}{dt}\right) ds.$$

This entire current will not reach the second anode because, on the average, as much current must reach the mosaic as leaves. Let $f(xyV)$ be the fraction of this current which reaches the second anode, then the current to the second anode can be written as

$$di_s = f(xyV)\left(\rho + C_0 \frac{dV}{dt}\right) ds. \qquad (3)$$

The instantaneous current, i_s, reaching the second anode, is given by the integral of the above expression over the area of the scanning beam. Since the current, i_s, carries the picture signal, the solution of (3) would be very desirable. This integration, however, cannot be performed since the function $f(xyV)$ is not known.

It is possible to make certain approximations which will enable the calculation of an average value for the redistribution function. Since the mosaic is an insulator, the average value of this function must be given by

$$\bar{f} = \frac{i_b}{i_T} = \frac{i_b}{i_b + i_e}. \tag{4}$$

In the equation, i_b is known and i_e can be found as follows:

$$i_e = \int C_0 \frac{dV}{dt} ds.$$

But we have

$$V = V_2 - V_1(1 - e^{-t\rho/C_0Z_0})$$

and

$$\frac{dV}{dt} = (V_2 - V_1)\left(\frac{\rho}{C_0Z_0}\right) e^{-t\rho/C_0Z_0}$$

$$ds = hvdt.$$

Therefore, we can write

$$\begin{aligned} i_e &= \frac{hv\rho}{Z_0}(V_2 - V_1)\int_0^T e^{-t\rho/C_0Z_0}dt \\ &\cong hvC_0(V_2 - V_1) \end{aligned}$$

and for

$$\bar{f} = \frac{1}{1 + \dfrac{hvC_0(V_2 - V_1)}{i_b}}. \tag{5}$$

Evaluating this function, using the constants of the Iconoscope, we find

$$\bar{f} \cong 0.25.$$

This means that out of the total charge released by an element when struck by the beam, only about twenty-five per cent will reach the second anode, the remainder being returned to the mosaic. In other words, only about twenty-five per cent of the stored charge is available for producing the picture signal.

As was mentioned above, $V_1(xy)$, $V_2(xy)$, and $f(xyV)$ are not constant over the mosaic, even when it is in darkness. As a consequence, there is a variation in the current reaching the second anode as the mosaic is scanned. This gives rise to a spurious signal which, if not compensated, produces irregular shading over the picture.

The importance of this spurious signal is sufficient to warrant further discussion. It is evident from the nature of the factors upon which it depends that it may be considered as divided into two parts. The first is the stored signal which depends upon $V_1(xy)$, while the second is an instantaneous effect, depending upon the variation of $V_2(xy)$ and $f(xyV)$ over the mosaic.

The instantaneous component can be demonstrated very strikingly if a metal plate is substituted for the mosaic in an Iconoscope. When this plate is scanned in the ordinary way, it being maintained at a potential close to that of the second anode, a spurious signal is produced very similar to that from the mosaic. While the mechanism of generation of this signal is not exactly the same as that in the case of the mosaic, it is quite similar. If the potential of the plate is made negative or positive, with respect to the second anode, the secondary emission will be saturated, or suppressed, and the signal will disappear.

In practice, the spurious signal from the Iconoscope is compensated for by means of an electrical correcting network.

Considerable work has been done and further work is in progress on methods of overcoming the effect of the spurious signal or entirely eliminating it.

When an optical image is projected on the mosaic, the illuminated area emits photoelectrons in proportion to the light falling on it. As a consequence, this area reaches a less negative final potential than an unilluminated area. In this connection, it should be pointed out that although the mosaic receives a continuous redistribution current, this current is very little altered by small changes in potential over small areas. In other words, the impedance shunting any element is very high. As a result of the difference in $V_1(xy)$ for an illuminated and an unilluminated region, there is a change in i_s. This fluctuation constitutes the picture signal.

Besides the inefficiency consequent on the redistribution losses, the photoemission is also inefficient due to the small fields drawing the photoelectrons away from the mosaic. The effective photoemission of the mosaic in the standard Iconoscope is only about twenty to thirty per cent of its saturated value. This means that the over-all efficiency of the Iconoscope is only five or ten per cent. In spite of this inefficiency the very great advantage resulting from the use of the storage principle makes the Iconoscope a very effective pickup tube.

Before leaving the discussion of the mechanism of the operation of the Iconoscope, mention should be made of the phenomenon of line sensitivity which results from the variation in potential over the surface of the mosaic. Referring to Fig. 7, it will be seen that the line on the mosaic just ahead of the scanning beam is subject to a strong positive field, and consequently has high photoelectric efficiency. The line is, in consequence, extremely sensitive. This can be demonstrated very strikingly in the following way.

The image from a continuously run motion picture film (e.g., a picture projected by a moving-picture machine from which the intermittent and shutter has been removed) is projected onto the mosaic of the Iconoscope. The film is run at such a rate that the frame speed is equal to the picture frequency, and in such a direction that the picture moves opposite to the direction of scanning. Under these conditions, the Iconoscope is found to transmit a clear image of two frames of the moving-picture film, although to the eye there appears to be only a blur of light on the mosaic.

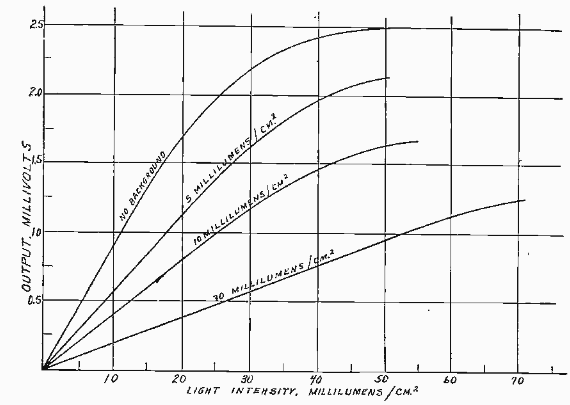

Fig. 8—Variation of output with light for different background illumination.

From the mechanism of the operation of the Iconoscope given above, it is apparent that the efficiency decreases as the light intensity increases. Fig. 8 shows a family of measured curves illustrating this effect. The output is measured in millivolts across a 10,000-ohm coupling resistance and the light input in lumens per square centimeter on the mosaic. The curve showing the greatest response represents the signal output from a small illuminated area when the remainder of the mosaic remains unillumined. The effect of a background illumination over the entire mosaic is shown by the remaining curves of the family.

The color response of an Iconoscope depends upon the activation schedule and the operating conditions involved. Fig. 9 shows the color response measured on the present type of standard Iconoscope.

So far, we have considered only the magnitude of the signal output. If it were possible to amplify the signal output indefinitely without introducing spurious effects, the problem of attaining high sensitivity would merely be one of increasing the amplifier gain. However, the picture amplifier not only amplifies the signal output from the Iconoscope, but also the voltage generated by the thermal agitation in the coupling resistor (or other coupling device). If the voltage generated by the picture signal becomes of the same order as these fluctuations, the picture becomes lost in noise. This sets a definite limit to the sensitivity that can be obtained.

In making any calculations concerning the sensitivity of the Iconoscope, we are faced with the problem of assigning quantitative values to the psychological effect of picture-to-noise ratio. Tests have been made to determine the effect on the observer of various ratios of peak picture signal in an average picture, to root-mean-square noise. It has

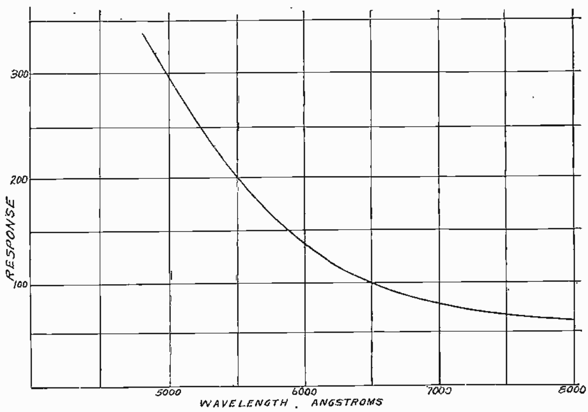

Fig. 9—Color response of standard Iconoscope No. 454.

been found that if the root-mean-square noise is equal to thirty per cent of the picture signal, the picture is still recognizable, but the resolution is decreased and the picture is tiring to watch. In addition, it was found that if the ratio remains constant but the picture amplitude is decreased, the noise becomes less objectionable; however, there is no increase in the effective resolution.

If the ratio of signal to noise is ten to one, a very good picture can be obtained but the noise is still very noticeable. Such a picture is completely usable and has fair entertainment value.

When the noise is reduced to three per cent of the picture, it becomes practically unnoticeable and the picture may be considered as excellent.

Let us base our calculation of sensitivity on an allowable noise-to-signal ratio of ten per cent. While the amount of noise would be greater than should be tolerated if conditions made it possible to avoid such a high noise-to-signal ratio, such a picture would, however, have reasonably good entertainment value and could be broadcast, particularly where program continuity made transmission necessary.

To make these calculations, the following data are necessary:

Area of mosaic	A	128 cm^2
Photosensitivity	p	7 μa/lumen
Over-all efficiency	k	0.05
Coefficient of thermal emf	K_1	1.6×10^{-20}
Coupling resistor	R	10,000 ohms
Frequency band	F	2×10^6 cycles

If the region of maximum illumination receives a light flux L lumens per square centimeter, the signal from the Iconoscope from this point will be

$$I = Lpk\frac{A}{n}\frac{T_0}{T} \tag{6}$$

where,

n = is number of elements,
T_0 = picture (frame) time,
T = time beam is on one picture element, but, since $Tn = T_0$,

$$i_s = LpkA$$

Substituting the values given above, the instantaneous current pulse is

$$I_s = 4.5 \times 10^{-5}L \text{ amperes.}$$

Since this is fed through a 10,000-ohm resistor, the signal voltage is

$$V_s = 0.45L.$$

The coupling resistor alone does not generate the entire noise found in the picture amplifier. Noise generated in the first amplifying tube and first plate resistor, each contribute an appreciable amount, particularly in an amplifier covering as broad a frequency band as is required. In order to take into account these factors, it will be assumed that the noise in the amplifier is equivalent to 30,000 ohms across the input. The noise voltage will, therefore, be

$$\begin{aligned} V_N{}^2 &= K_1FR \\ &= 9.6 \times 10^{-10} \end{aligned}$$

or a root-mean-square noise voltage of

$$\bar{V}_N = 3.1 \times 10^{-5}.$$

The signal-to-noise ratio under these conditions is therefore

$$R = 1.45 \times 10^4 L.$$

Further, if the minimum usable ratio is assumed to be 10, the smallest amount of light falling on the mosaic sufficient to give an adequate picture will be

$$7 \times 10^{-4} \text{ lumens/cm}^2.$$

This corresponds to illumination on the high lights, and is of course somewhat higher than the average illumination of the picture.

On the same basis, the illumination required to produce an excellent picture, i.e., where the noise is only three per cent of the picture signal, would be as follows:

$$R = 1.45 \times 10^4 L = 33$$

$$L = 2.3 \times 10^{-3} \text{ lumens/cm}^2.$$

Actual measurements on an average tube show that an excellent picture can be transmitted from an object having a surface brightness of twenty to fifty candles per square foot using an f 2.7 lens. The illumination on the mosaic under these conditions will be

$$L = \frac{\pi B}{4f^2} = 2\tfrac{1}{2} \text{ to } 6 \text{ millilumens/cm}^2.$$

When allowance is made for reflection losses in the optical system and for the psychological element, the agreement will be seen to be fairly good.

The problem of increasing the sensitivity of the Iconoscope may be approached in three different ways: first, by keeping the signal sensitivity the same and reducing the noise generated; second, by increasing the quantity of charge per unit light flux acquired by the mosaic; and third, by increasing the overall efficiency of the Iconoscope.

The third method has been studied extensively, and laboratory tubes have been made with efficiencies as high as fifty per cent. However, this work is still in the early experimental stage and will not be discussed here.

Let us consider the first method of increasing the sensitivity. This noise reduction is possible because of the fact that the effective circuit carrying the signal from the Iconoscope is completed through the secondary emission from the mosaic. In other words, when the coupling resistor and amplifier are connected to an electrode which collects the secondary emission, a signal can be obtained which is equally as great as that from the signal plate. If these secondary electrons are led into a secondary emission multiplier instead of being collected, it is possible to obtain the signal from the multiplier and thus *completely* eliminate the noise that would be introduced by the conventional coupling resistor and amplifier.

Before taking up the type of multiplier suitable for this purpose, or the methods used to get the electrons from the mosaic into the multiplier, let us consider the sensitivity and noise relations resulting from this scheme.

The signal output will be equal to the signal at the mosaic, times the gain of the multiplier which will be written as B^n, B being the gain per stage and n the number of stages. Hence,

$$I_s = LpkAB^n.$$

On the other hand, the noise will be essentially the shot noise in the secondary emission from the mosaic. More exactly, the noise[5] is

$$I_n^2 = \frac{B^{2n+1}}{B-1} K_2 F 2 i_b$$

K_2 being the shot coefficient. Therefore, the signal-to-noise ratio will be

$$R = \frac{I_s}{I_n} = \frac{kA}{\sqrt{K_2F}}\sqrt{\frac{B-1}{2B}}\, L/\sqrt{i_b}. \tag{7}$$

Evaluating this, we find

$$R \cong 40L/\overline{i_b}.$$

In actual practice the beam current in a standard Iconoscope is about one-half microampere. If R is assumed to be 10, the illumination required will be

$$L \cong 2 \times 10^{-4}\ \text{lumens/cm}^2.$$

This is to be compared with the result where a normal amplifier was used. In this case the illumination was 7×10^{-4} lumens/cm^2; that is, this represents an increase in sensitivity of about three times.

However, the interesting point about this multiplier Iconoscope is that the sensitivity depends upon the beam current; therefore, if we can reduce the beam current without decreasing the efficiency, the Iconoscope becomes more effective.

It is not possible, in a multiplier Iconoscope using a standard mosaic, to reduce the beam current without loss in efficiency due to

[5] V. K. Zworykin, G. A. Morton, and L. Malter, "The secondary emission multiplier—A new electronic device," Proc. I.R.E., vol. 24, pp. 351–375; March, (1936).

the increase of discharge time of the elements. When this condition occurs, the efficiency falls off, and, furthermore, moving objects blur. In order to decrease the time constant so that the beam current can be decreased, it is necessary to reduce the element capacitance. The simplest method of accomplishing this is by using a thicker insulating layer for the mosaic. Assuming that the time constant is fixed, the beam current should be inversely proportional to the capacitance; in other words, approximately to the mosaic thickness. It is interesting to carry the calculation down to the limiting case and to see what is the maximum sensitivity obtainable by this method. Obviously, the beam current cannot be reduced beyond the point where it becomes equal to the photocurrent. Under these conditions, we can calculate the sensitivity as follows:

$$i_{\text{phot.}} = k'Lpah$$

where a and h are the length and height of the region considered, and k' the fraction of photocurrent leaving the mosaic. The instantaneous beam equivalent must therefore be

$$i_0 = k'Lpah \frac{To}{Ta} = LpAk'$$

$$I_s = LpkA.$$

Hence, the signal-to-noise ratio will be

$$R = \frac{I_s}{I_n} = \frac{pkA}{\sqrt{K_2F}}\sqrt{\frac{B-1}{B}}\frac{L}{\sqrt{2LpAk'}}$$

$$= \sqrt{\frac{pk^2A(B-1)}{2k'K_2FB}}\sqrt{L}. \tag{8}$$

Assuming, as before, that R must be at least 10, the minimum light that can be used will be

$$L = 5 \times 10^{-6} \text{ lumens/cm}^2.$$

This would be the smallest amount of light that would suffice to transmit a satisfactory picture when noise suppression of this type is used. The value for sensitivity just given must be considered purely as a theoretical estimate. In practice, no tube has yet been made based on this principle with a sensitivity greater than ten to twenty times that of the standard Iconoscope.

Having arrived at certain theoretical conclusions as to the ultimate sensitivity that can be attained, let us now consider the practical details of construction.

The multiplier suitable for this purpose is preferably one which does not involve the use of a magnetic field, must be capable of multiplying a comparatively broad beam of electrons rather than a sharply defined spot, and must have a high gain per stage. It has been found that the T type[6] multiplier, whose construction is shown in Fig. 10, serves very adequately. There are, however, a number of possible multipliers that might be used. In order to get the electrons away from the mosaic, a disk, run at from 25 to 100 volts positive with respect to the second anode, is placed at the entrance of the protuberance containing the multiplier. This disk is perforated with an aperture behind which is mounted a small truncated cone at a high positive potential, carrying the electrons through the aperture and into the multiplier.

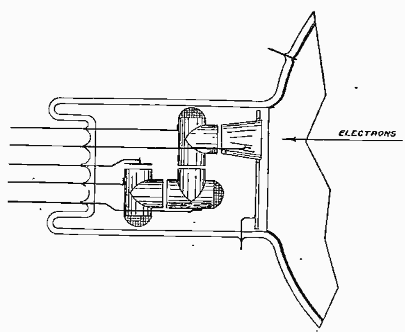

Fig. 10—Diagram of T type multiplier.

The disk, because of its area, determines to a great extent the field close to the mosaic, while the cone governs the shape of the field close to the disk.

Several tubes were made to determine the most suitable location for the multipliers, with the following conclusions:

Position	*Percentage Electrons Collected*
Behind mosaic	10 per cent
Side of mosaic	50 per cent
30 per cent to normal	80 per cent
Front	100 per cent

Because of optical reasons, it is a difficult problem to locate the multiplier directly in front of the mosaic. However, it was found that two multipliers located at thirty degrees on either side of the normal to the mosaic, collected all of the electrons leaving the mosaic. This type

[6] G. A. Morton and E. G. Ramberg, "Electron optics of an image tube." *Physics*, vol. 7, pp. 451–459; December, (1936).

of Iconoscope is shown in Figs. 11 and 12. While work is still being done on this development, very satisfactory pictures under conditions of low illumination have been obtained from this type of tube. The

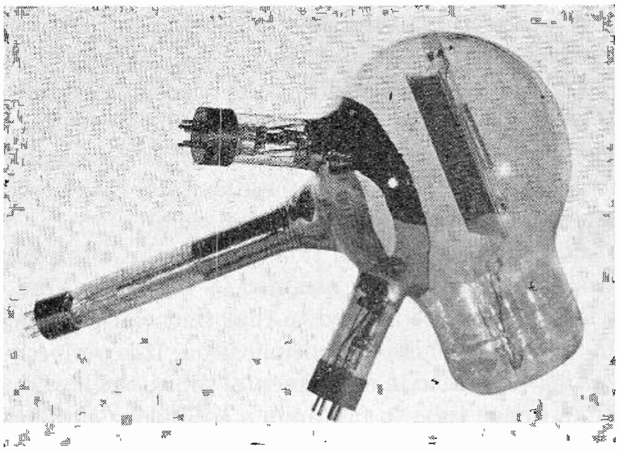

Fig. 11—Signal multiplier Iconoscope.

principal problems yet to be dealt with are those of activating the multipliers and mosaic simultaneously, and of obtaining a uniform distribution of the picture.

The second method of approach is by the use of secondary emission

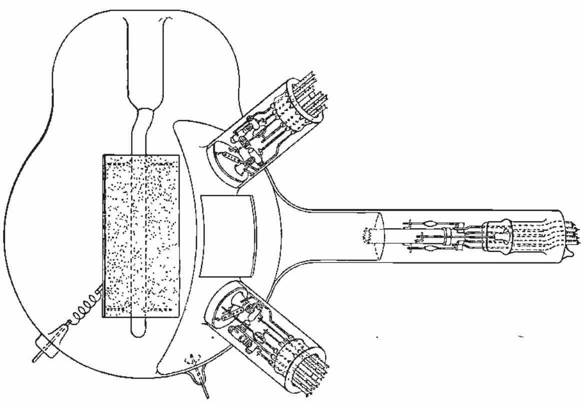

Fig. 12—Diagram of signal multiplier Iconoscope.

image intensification. This can be accomplished by allowing the electron image produced in some form of image tube to fall on a mosaic constructed in such a way that the elements extend through the mosaic. The elements on the side of the mosaic on which the electron image is projected are made secondary emissive so that for every electron striking the mosaic, six to eight are emitted. Thus, the stored signal will be several times that that would be due to the original photoelectric current. The scanning beam sweeps across the back of the mosaic, removing the stored picture in the same way that the picture is removed from the ordinary, one-sided mosaic. The gain in sensitivity will be proportional to the intensification at the mosaic. Furthermore, it is possible to produce semitransparent photocathodes of the type used in the image tube with more than twice the photosensitivity of the ordinary mosaic. Considering both these factors, it is possible to increase the sensitivity by from ten to fifteen times.

Before taking up the details of this type of tube, let us consider the limiting sensitivity that can be attained in this way. First, the gain obtainable is not of course limited to that that can be obtained from one stage of secondary emission multiplication. It is perfectly possible, and has been accomplished in experimental tubes, to allow the electron image from an image tube to fall upon a secondary emitting surface, and with a second electron optical system to refocus this enhanced image. Let us assume that this process can be repeated as many times as is desired, and the multiplied image be projected on a two-sided mosaic. In this way, the charge image stored on the mosaic may be made as large as is desired.

However, as was the case with the low capacitance tube, there are definite limits to the sensitivity that can be attained. The limit in this case is due to the statistical fluctuation in the photocurrent emitted from the photosensitive cathode upon which the image is initially projected.

In order to estimate the ultimate sensitivity, let us assume that the gain of each stage of the secondary emission multiplier is sufficiently great that the "picture-to-noise" ratio at the cathode is not appreciably greater than it is at the mosaic. This is equivalent to assuming that the fraction $(B-1)/B$, used above in multiplier calculations, is equal to unity, which is amply justified when gains of 7 or 8 per stage can be obtained.

It can be shown that if q is the photoelectric charge emitted by one picture element during one frame time, the mean-square fluctuation will be

$$\bar{q}_N{}^2 = eq.$$

If, as before, we assume that the root-mean-square fluctuation should be ten per cent of the total charge, we have

$$R = q/\bar{q}_N = q/\sqrt{eq} = i_pT_0/\sqrt{ei_pT_0}$$

but,

$$i_p = Lap = \frac{LAp}{n}$$

where i_p is the photoemission from one element and a the area of an element. Thus, we have

$$R = \sqrt{\frac{LAp\ To}{en}}.$$

It can be demonstrated, by means of a Fourier transformation, that $To/n = 1/2\,F$ so we may write

$$R = \sqrt{\frac{LAp}{2eF}}.$$

Actually, the signal-to-noise ratio should have been written

$$R = \sqrt{\frac{LAp}{2eF(1 + k'')}}$$

where the factor, k'', takes into consideration the fluctuations in the entire group of multiplied photoelectrons which strike the mosaic and induce noise directly on the signal plate. The value of k'' depends on a great many variables. Its value cannot be less than unity, and for the purpose of calculation will be assumed to be in the neighborhood of 10.

On this basis, the limiting amount of light which will produce a picture signal ten times the root-mean-square noise will be

$$L = \frac{2eF(1 + k'')R^2}{Ap}$$
$$= 7 \times 10^{-7} \text{ lumens/cm}^2. \qquad (9)$$

For the case just considered it would require an image multiplication of 500 to 1000 to reach the limiting sensitivity. It is interesting to note that this limit is about the same order of magnitude as for the case of the low capacitance Iconoscope. In general, it is possible to show that the limiting light sufficient to give a signal-to-noise ratio of R for an ideal storage television system (where the conversion efficiency is 100 per cent) will be

$$L = \frac{2eFR^2}{Ap}. \qquad (10)$$

While experimental tubes have been made with more than one stage of image multiplication, this technique has not been developed to a sufficient extent to be applicable to a commercial Iconoscope in use in the television field test.

Very successful one-stage image multiplier Iconoscopes have been built. Fig. 13 shows a photograph of such a tube. This tube consists, essentially, of an electron image tube[7] which projects onto a secondary emissive mosaic, an electron reproduction of an optical image formed

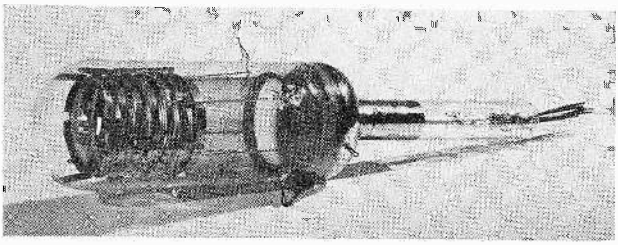

Fig. 13—Image multiplier Iconoscope.

on the photocathode. The mosaic in this instance differs from that in the standard Iconoscope in that the mosaic elements extend through the insulating matrix in such a way that the electron image can be formed on one side while the mosaic is scanned on the other. If the mosaic is scanned while the photocathode is in darkness, the potential of each element will be nearly the same as that of the second anode, due to the action of the beam and the redistribution of electrons.

When light is projected on the photocathode, electrons will be emitted. These electrons are accelerated by the electron optical system and refocused on the mosaic. Each element thus bombarded will emit secondary electrons which will be drawn to the anode cylinder, since the latter is at a positive potential with respect to the mosaic. If the secondary emission ratio of an element is, for example, B, the net current to it will be $B-1$ times the primary current incident upon it. It should be pointed out, however, that the average amplification of the mosaic will not be $(B-1)$ due to the fact that the elements do not cover the entire surface under the electron image. Let C be the fraction of the surface covered by the elements, then the effective gain will be $C(B-1)$.

The electron optical part of this Iconoscope is identical with the electron image tube, for which purpose the latter was developed. It consists of a semitransparent photocathode, a cathode cylinder composed of five rings, each at a successively higher positive potential,

[7] V. K. Zworykin and G. A. Morton, "Applied electron optics," *Jour. Opt. Soc. Amer.*, vol. 26, pp. 181–189; April, (1936).

and an anode cylinder which is carried at approximately 1000 volts positive. The lens of this system may be considered as being located between the cathode and anode cylinder, though actually it is a thick lens occupying a considerable portion of the total length of the system. The magnification of such a system can be shown to be

$$m = v/2u$$

where u and v are object and image distance from the lens. For the type of tube illustrated where unity magnification of the image is used, the cathode cylinder is half the length of the anode cylinder.

The cathode is curved with a radius equal to the lens diameter. This curvature corrects not only for image distortion and curvature of the image field but also reduces the astigmatism to such an extent that it no longer limits the resolution in any part of the field.

The semitransparent photoelectric surface used is caesium on oxidized silver. It is formed by evaporating a thin layer of silver onto the cathode disk from a filament located directly behind the aperture forming the electron lens. This silver is then oxidized by means of an electric discharge in oxygen at a low pressure, until the layer becomes almost completely transparent. Caesium is admitted and the tube is baked exactly as is done in activation of a photoelectric cell. As a final step, additional silver is evaporated onto the surface and the tube is again baked. This final silver sensitization not only increases the photosensitivity and conductivity of the film, but also adds to its stability. This type of surface will have a photosensitivity of 20 to 25 microamperes per lumen and a color response very similar to that of a caesium photocell.

The most difficult item of construction in the image multiplier Iconoscope is the mosaic. One method by which a suitable mosaic can be built is as follows: A fine mesh, electrodeposited, nickel screen forms the base. It is coated with a thin layer of special vitreous enamel, in such a way that its entire surface is completely insulated. The interstices in the screen are then filled with silver oxide made into a paste with an appropriate binder. The screen is then heated to a temperature just under the melting point of the enamel in order to drive off the binder and to reduce the silver oxide to metallic silver.

The arrangement of the elements just described and the actual construction of this type of tube will be clear from Fig. 14, which shows diagrammatically the completed tube.

Actual tests on this type of Iconoscope show that its sensitivity is about ten times greater than that of a standard Iconoscope. This added sensitivity is caused, in part, by the secondary emission multiplication and, in part, by the greater photosensitivity of the light-sensitive surface. For the present, this type of tube must be considered as a purely experimental device because of the difficulties of producing, commercially, screens free from blemishes due to irregular electrical leakage between the mosaic elements and base screen. However, there is every reason to believe that this type of tube can be made commercially available in the near future.

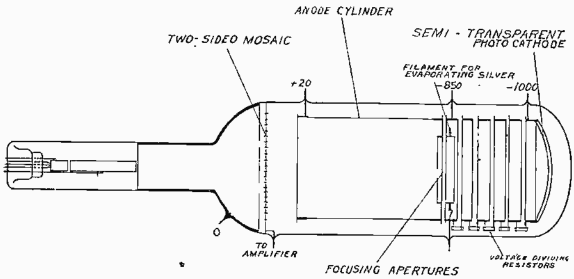

Fig. 14—Diagram of image multiplier Iconoscope.

In conclusion it may be said that the Iconoscope has, in actual field test, proved itself to be a very practical pickup device in spite of its low theoretical efficiency. The tube has been accepted as the sole pickup equipment in several extensive television broadcast projects, both in the United States and abroad, and has been rapidly gaining general recognition.

It would, nevertheless, be very desirable to increase the sensitivity of the Iconoscope. This paper describes several methods by which this may be accomplished. Before these principles can be incorporated in tubes to be used for broadcast purposes, a great deal of research and development work must be done. Eventually, however, it will be possible to produce a tube which will operate at even lower light levels than at present.

Acknowledgment

The work described has been possible only through the co-operation of the members of the research staffs of both the Victor and Radiotron Divisions of the RCA Manufacturing Company. Particular mention should be made of the work of Messrs. G. N. Ogloblinsky, deceased; H. Iams, and A. W. Vance, who have contributed so materially to these developments.

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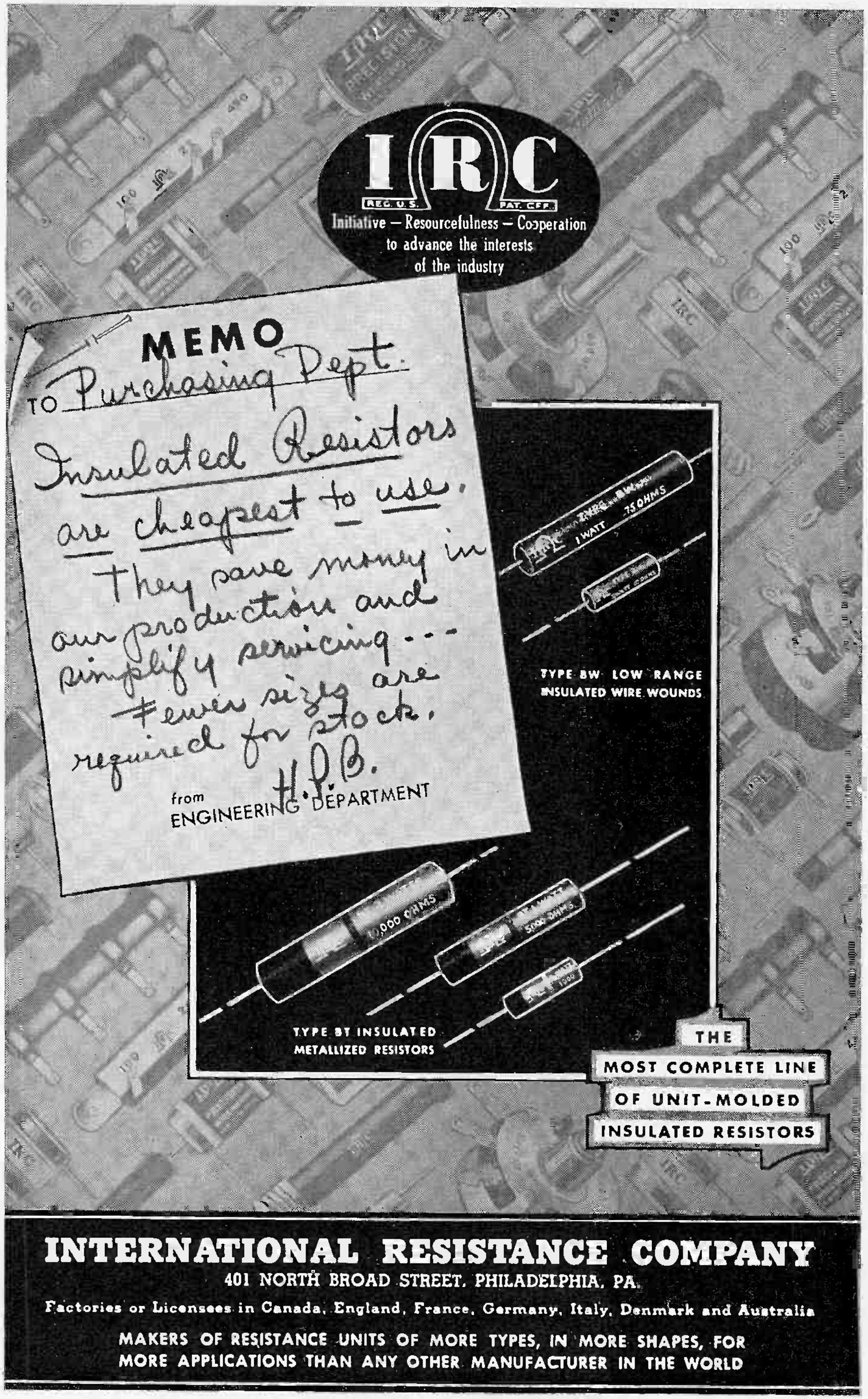
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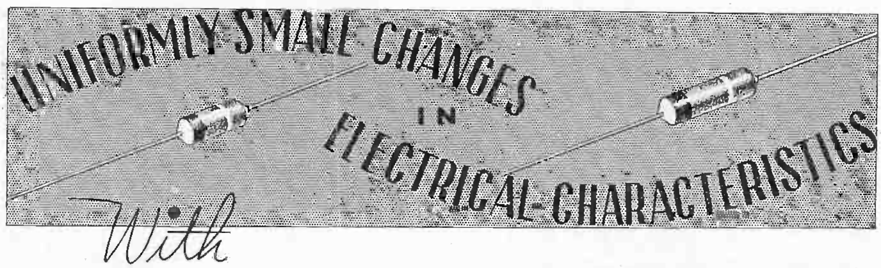

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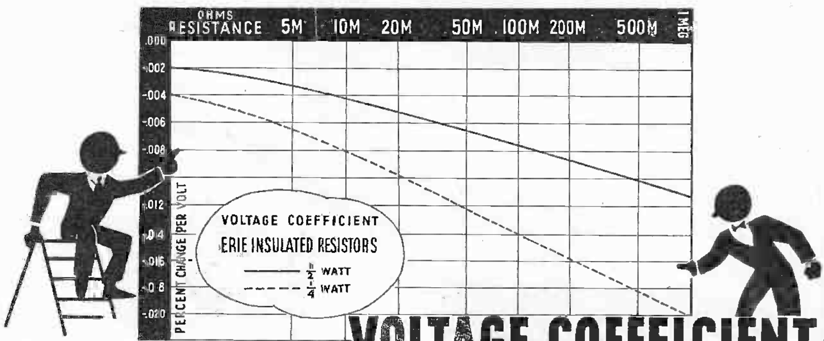

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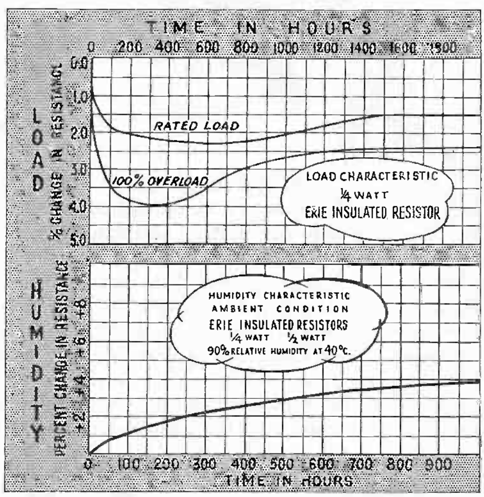

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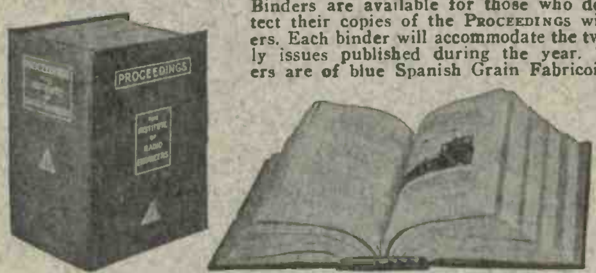

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