TELEVISION

The Future of the New Art
And Its Recent
Technical Developments

Volume II

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TELEVISION

Collected Addresses
and Papers on the Future of the
New Art and Its Recent Technical
Developments

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FOREWORD

SINCE the publication of "Television", Volume I, in July 1936, the research work and field tests conducted by the Radio Corporation of America in the development of television have continued. Engineering papers and various statements have been published describing this work. This book, Volume II, is a collection of these papers and statements, and of a few papers not heretofore published elsewhere.

Acknowledgment and thanks is given to all those engineering societies and other organizations who have granted permission to republish herein papers originally published by them.

WHAT OF TELEVISION?

BY

DAVID SARNOFF
President, Radio Corporation of America

FIRST, let me emphasize that television bears no relation to the present system of sound broadcasting, which provides a continuous source of audible entertainment to the home. While television promises to supplement the present service of broadcasting by adding sight to sound, it will not supplant nor diminish the importance and usefulness of broadcasting by sound.

In the sense that the laboratory has supplied us with the basic means of lifting the curtain of space from scenes and activities at a distance, it may be said that television is here. But as a system of sight transmission and reception, comparable in coverage and service to the present nation-wide system of sound broadcasting, television is not here, nor around the corner. The all important step that must now be taken is to bring the research results of the scientists and engineers out of the laboratory and into the field.

Television service requires the creation of a system, not merely the commercial development of apparatus. The Radio Corporation of America, with its coordinated units engaged in related phases of radio communication services, is outstandingly equipped to supply the experience, research and technique for the pioneering work which is necessary for the ultimate creation of a complete television system. Because of the technical and commercial problems which the art faces, this system must be built in progressive and evolutionary stages.

RCA's research and technical progress may be judged by the fact that upon a laboratory basis we have produced a 343-line picture, as against the crude 30-line television picture of several years ago. The picture frequency of the earlier system was about 12 per second. This has now been raised to the equivalent of 60 per second. These advances enable the reception, over

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limited distances, of relatively clear images whose size has been increased without loss of definition.

From the practical standpoint, the character of service possible in the present status of the art, is somewhat comparable in its limitations to what one sees of a parade from the window of an office building, or of a world series baseball game from a nearby roof, or of a championship prize fight from the outermost seats of a great arena.

Television is a highly complicated system of transmitting and receiving elements with thousands of interlocking parts, each of which must not only function correctly within its own sphere of activity, but must also synchronize with every other part of the system. In broadcasting of sight, transmitter and receiver must fit as lock and key.

On the other hand, broadcasting of sound permits a large variety of receiver devices to work acceptably with any standard transmitter. Notwithstanding the great progress that has been made in sound broadcast transmission, a receiver set made ten years ago can still be used, although with great sacrifice of quality. This is not true in television, in which every major improvement in the art would render the receiver inoperative unless equivalent changes were made in both transmitters and receivers.

Important as it is from the standpoint of public policy to develop a system of television communication whereby a single event, program or pronouncement of national interest may be broadcast by sight and sound to the country as a whole, premature standardization would freeze the art. It would prevent the free play of technical development and retard the day when television could become a member in full standing of the radio family. Clearly, the first stage of television is field demonstration by which the basis may be set for technical standards.

Side by side with televison, although in many respects nearer to final achievement, there is emerging from the field of radio experimentation high speed facsimile communication. By means of this new development, written, printed, photographic and other visual matter can be sent by radio over long distances and reproduced at the receiving end with amazing exactness. It is difficult to imagine limits of the use of such an invention. It should ultimately make the dot-and-dash system of telegraphy as outmoded as the pony express. Pictures, sketches, handwriting, typewriting and every other form of visual communication, will be transmitted as easily as words are now sent over a telegraph wire. Even in its earlier stages facsimile ill be a medium for the instant dissemination of information of a hundred different types, from weather maps to statistics, from educational data to comic strips. Far from displacing the existing media of information—and particularly the newspapers—facsimile should contribute to their progress providing them with swifter and more effective facilities.

In this new facsimile service we have also reached an advanced stage. R.C.A. Communications, Inc., has built an experimental facsimile circuit between New York City and Philadelphia, demonstrated publicly for the first time recently. It uses ultra-high frequencies linked into instantaneous transmission by automatic relays. This circuit will demonstrate the possibilities inherent in facsimile transmission and should also contribute to solving the difficult problems of relaying television programs on these ultra-high frequencies.

One of the triumphs of this demonstration circuit has been its success in combining, for the first time in radio history, the simultaneous transmission of visual matter with automatic typewriter telegraph operation on the same radio channels. This ability to carry separate services simultaneously on a single frequency is of great importance.

It is the mastery of the ultra-high frequencies which is bringing television and facsimile within the area of practical use. We are steadily pushing farther into the higher regions of the spectrum which only yesterday constituted a "radio desert," now being made fruitful.

When television broadcasting reaches the stage of commercial service, advertising will have a new medium, perhaps the most effective ever put at its command. It will bring a new challenge to advertising ingenuity and a stimulus to advertising talent.

The new medium will not supplant nor detract from the importance of present day broadcasting. Rather, it will supplement this older medium of sound and add a new force to the advertisers' armament of salesmanship. Television will add little to the enjoyment of the symphony concert as it now comes by radio to your living room. Sound broadcasting will remain the basic service for the programs particularly adapted to its purposes. On the other hand, television will bring into the home much visual material—news events, drama, paintings, personalities—which sound can bring only partially or not at all.

Broadcasting has won its high place in the United States because—unlike European listeners—American set owners receive their broadcasting services free. Despite the greater cost of television programs, I believe that owners of televison receivers in the United States will not be required to pay a fee for television programs. That is an aspect of the television problem in which the advertising fraternity will doubtless cooperate in finding the commercial solution.

Whoever the sponsor may be, or whatever his interests or purposes, he will be under the compulsion to provide programs that will bring pleasure, enlightenment and service to the American public. That compulsion operates today and must continue to operate if we are to retain the American system of radio broadcasting. The public, through its inalienable right to shut off the receiver or to turn the dial to another program will continue to make the rules. In television as in sound broadcasting the owner of a set will always be able to shut it off. In other words, the ultimate censorship of television, as well as of sound broadcasting, will remain between the thumb and forefinger of the individual American.

RCA DEVELOPMENTS IN TELEVISION

BY

R. R. BEAL
Supervisor of Research, Radio Corporation of America,

Summary.—*A brief review is given of the studies made of the several characteristics of television images and other factors that have been effective in establishing standards, in determining satisfactory performance, and in guiding the step-by-step development of the RCA electronic system of high-definition television.*

The system employs the "Iconoscope," a cathode-ray tube for translating the visual image into electrical impulses, and the "Kinescope" for transforming the electrical impulses back into the variations of light-intensity to reproduce the image. The sensitivity and characteristics of the "Iconoscope" as a pick-up device are discussed.

The fundamentals of the RCA high-definition television system now under experimental field test in the New York area and the standards presently employed are reviewed. Photographs of the studios and other parts of the field-test facilities are included. A brief review is given to indicate the progress made and the results attained up to the present time in these field tests.

The technic of formulating and presenting television programs is peculiar to the requirements of television. The development of the technic is presently related to programs employing artists in studios, outside pick-ups, and motion picture film. The requirements of program technic are discussed.

TELEVISION and motion pictures have in common the objective of reproducing on a viewing screen images that appear to the eye to have uninterrupted motion. While some of the fundamentals through which this objective is attained in the two arts may be closely related, others are widely different. Objectively and to some extent technically, the problems parallel in the illumination of the subject, in creating the illusion of motion, in realizing an acceptable standard of definition, and in obtaining appropriate brightness and size of reproduced image on the viewing screen. An outstanding difference appears in the system by which the reflected light from the subject is transmitted to the viewing screen.

In motion pictures, the reflected light from the subject is converted into a film record, and transmission from the film record to the viewing screen is effected through the agency of light. In

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Reprinted from *Journal of the Society of Motion Picture Engineers.*

television, transmission is effected through the agency of electricity. Reflected light from the subject is converted into electrical impulses. These may be transmitted by radio or by special cables from the point at which the subject is located to a point far removed from that locality, and then reconverted into light-images upon the viewing screen. The reproduced image may originate from a subject or from a film record of a subject.

The development of a television system by which images of high definition may be transmitted electrically and reproduced on a viewing screen has required intensive research by RCA for a period of more than ten years. This research has passed through many stages, beginning wth early mechanical arrangements and advancing to the present all-electronic system now under field test in the New York City area.

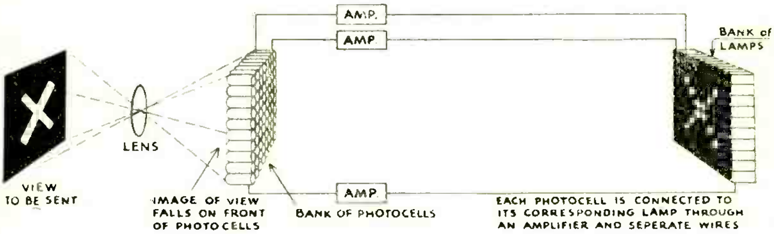


Fig. 1—Elements of the Carey system.

Some of the requirements of a high-definition system may be indicated by a brief description of a system patterned after a suggestion made by Carey about 1875. The elements of this system are illustrated in Fig. 1. A pick-up area is constructed of a bank of photoelectric cells and a viewing screen of a like number of incandescent lamps. Each photocell in the bank is connected by an electrical circuit through an amplifier to the correspondingly positioned lamp in the viewing screen. When the light-image to be transmitted is focused upon the bank of photocells, electric current then will flow through the circuits connecting those of the photocells that receive light to the corresponding lamps in the viewing screen, and a reproduction of the subject will appear as an illuminated picture.

In this system, the amount of detail that can be transmitted is limited by the physical dimensions of the individual photocells in the pick-up area. Each photocell represents an element of picture area, and the detail in any area of the picture smaller than the area of the photocell cannot be transmitted. An electrical circuit is required to transmit information concerning the brightness of each element of picture area. As the amount of detail increases, the number of electrical circuits increases. Such a multiple-circuit method is not practicable for transmitting images electrically over long distances. A single channel must be employed for this purpose. This requires methods that involve dividing the light into elements, converting the illumination on each element into electrical impulses, transmitting these impulses in orderly sequence, and reconverting them into appropriately positioned light upon the viewing screen.

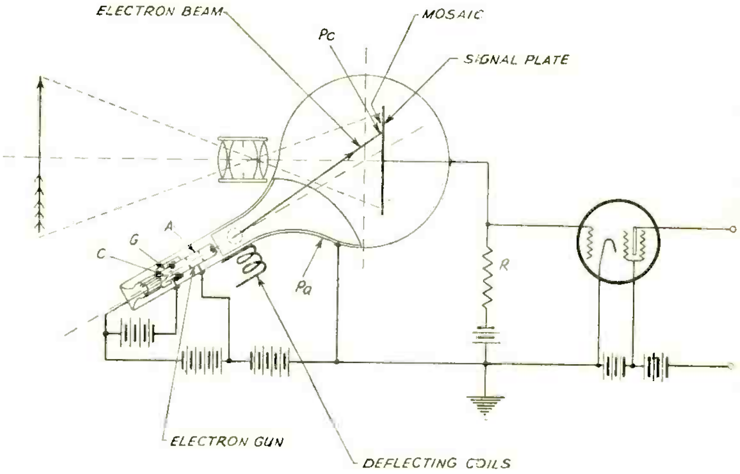


Fig. 2—Schematic arrangement of the Iconoscope.

In the RCA high-definition television system, the first step in this process occurs in the Iconoscope,* which converts the light-image into electrical impulses, and the final step takes place in the Kinescope,* which transforms the electrical impulses into a light-image upon the viewing screen.

The Iconoscope, illustrated in Fig. 2, consists of an electron gun and a photosensitive mosaic in a highly evacuated glass envelope. The electron gun produces a fine pencil or beam of electrons, which is focused to a spot on the mosaic. This beam

* Registered trade-marks of Radio Corporation of America.

is moved horizontally and vertically, and so caused to scan the mosaic. The motion of the scanning beam is produced by appropriately applied electromagnetic fields.

The mosaic consists of a vast number of tiny electrically isolated photosensitized silver globules. These cover one side of a thin sheet of mica. The other side of the mica is covered with a conducting film, and this film is connected to a signal lead. The mosaic may be thought of as a very large number of minute photocells, each of them shunted by an electrical condenser which couples it to a common signal lead. When the mosaic is illuminated, these condensers are charged positively with respect to their equilibrium potential, due to the emission of photoelectrons. This positive charge is proportional to the quantity of light received. The electron beam, as it scans the mosaic from left to right, drives to equilibrium the elements over which it passes, and thus releases the charges and induces current impulses in the signal lead. The train of current impulses thus generated constitutes the picture signal output of the Iconoscope. These current impulses will appear in orderly sequence, as the electron beam scans the area of the mosaic one horizontal line at a time from top to bottom. It is in this order that the current impulses are transmitted as television signals. Fig. 3 is a photograph of a representative Iconoscope.

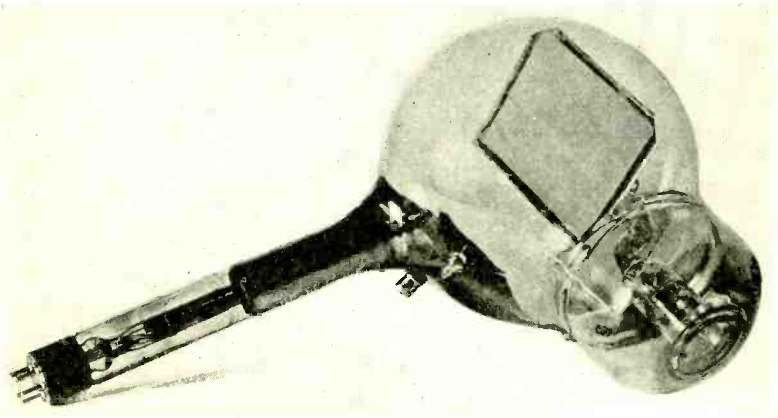
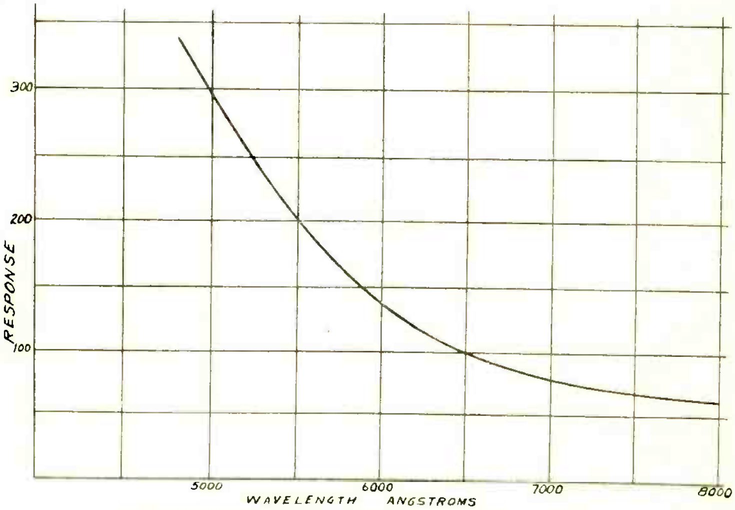


Fig. 3—The Iconoscope.

In the Iconoscope the charging process in any specific element of the mosaic continues for a time equal to the picture repetition interval; that is, until the beam, in the process of scanning, returns to that element. The electrical charge stored in the condenser increases with this passage of time. The greater the electrical charge, the greater will be the current impulse induced in the signal lead. This storage principle makes the Iconoscope a very effective pick-up device for television.

The sensitivity of the Iconoscope is of great importance in picking up a wide variety of scenes, both indoors and out, under practical lighting conditions. This sensitivity at the present stage of development is about the same as that of ordinary negative film. Research in progress is disclosing methods by which it may be possible greatly to increase the sensitivity.



COLOR RESPONSE OF STANDARD ICONOSCOPE NO 454

Fig. 4—Color-response characteristic of the Iconoscope.

The color-response of an Iconoscope depends upon the activation schedule used in producing the mosaic and upon the composition of the photosensitive material. The color-response characteristic may be varied over a range comparable with that covered by photographic emulsions available from motion picture work. The color-response characteristic of a representative Iconoscope is shown in Fig. 4.

The Iconoscope and its associated optical parts correspond in the RCA television system to the camera in motion pictures. This unit of equipment is called the Iconoscope camera. Iconoscope cameras having the same elements but differing in physical form are used for direct pick-up of indoor and outdoor scenes and for the transmission of motion picture film material.

A photograph of an Iconoscope camera for use in indoor studios is shown as Fig. 5. The camera may be moved about the studio during a performance; it is raised and lowered by a motor-driven mechanism; the usual provisions are made for following the motion and action of the scene; it is silent in operation. The Iconoscope mosaic is about 4 by 5 inches, or about six times as large as one 35-mm. motion picture frame. Therefore the Iconoscope camera lenses are of greater focal length than those employed in motion picture cameras. Present Iconoscope cameras are equipped with lenses of 6.5- or 18-inch focal length. Fig. 6 shows this camera, with the housing raised. The picture signals and the necessary power-supply currents are carried by a cable connecting the camera to the system. A wide-band preamplifier for amplifying the picture signal produced by the Iconoscope is included in the camera.

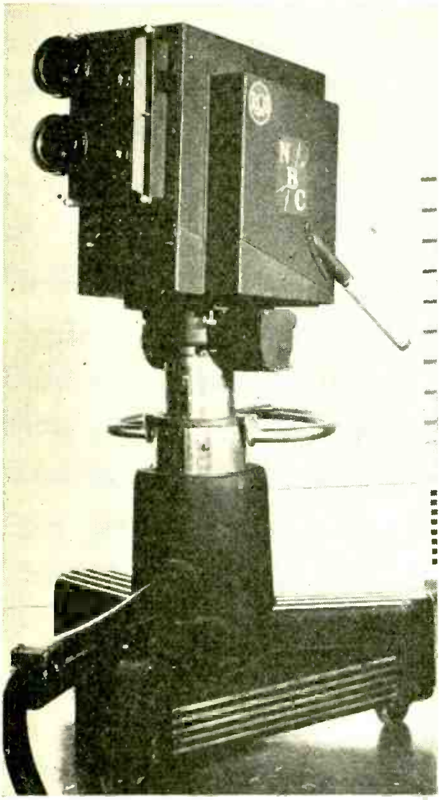


Fig. 5—Iconoscope camera.

The picture signals generated by the Iconoscope in the camera are amplified and delivered to the radio transmitter. These signals are caused to modulate the carrier-wave of the transmitter in a manner analogous to that employed in sound broadcasting. The radio signal thus produced is picked up at the distant point by the receiving antenna and delivered to the television receiver. Here it is restored to its original form as a train of impulses. These impulses are fed through amplifiers to the Kinescope, which transforms them into a light-image upon the viewing screen.

The Kinescope is an evacuated glass envelope containing as the essential elements an electron gun and a luminescent screen.

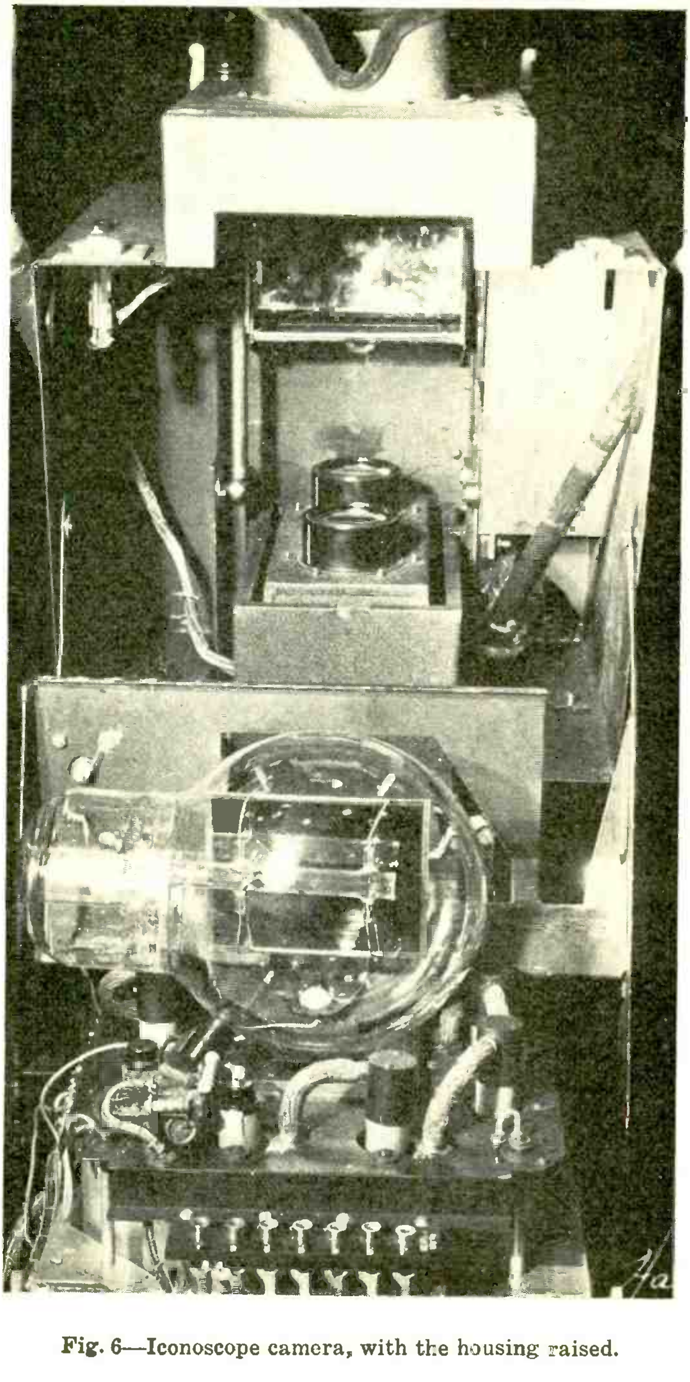
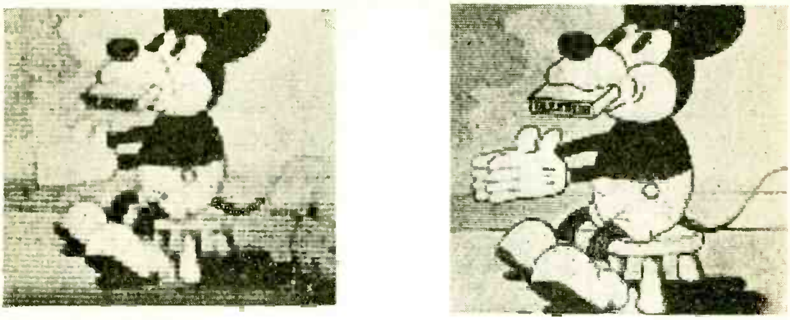


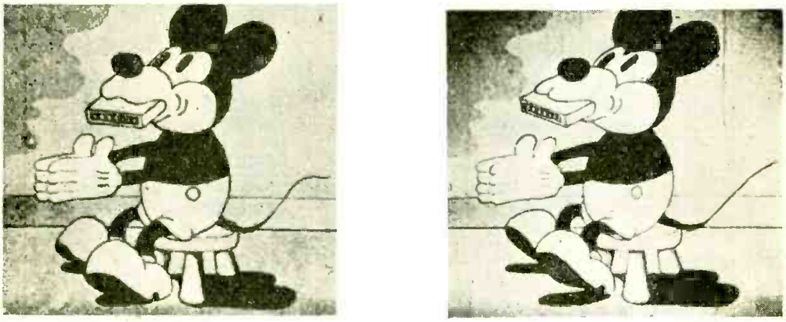
Fig. 6—Iconoscope camera, with the housing raised.

The electron gun produces an electron beam similar to, but of greater current-carrying capacity, than the gun in the Icono-



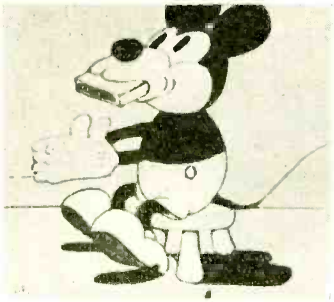
60 lines

120 lines



180 lines

240 lines



Enlargement

Fig. 7—Showing the improvement in detail with increasing numbers of scanning lines.

scope. Light is produced when the electron beam bombards the luminescent screen. The amount of light thus produced is proportional to the current in the beam. The electron beam is caused to scan the viewing screen by appropriately applied electromagnetic fields.

The scanning beams in the Iconoscope and the Kinescope are accurately synchronized. The two beams are at corresponding points of the mosaic of the Iconoscope and of the luminescent screen of the Kinescope at any instant. The brightness of a point on the luminescent screen is proportional to the current in the bombarding beam. This current is produced by voltages related to the picture signals generated by the Iconoscope. These picture signals represent, by electrical impulses, information concerning the brightness of each picture element. Since the electron beams in the Iconoscope and Kinescope are in exact synchronism, the brightness of any point on the Kinescope screen will be a function of the brightness of the corresponding point on the mosaic of the Iconoscope. Thus the image projected upon the mosaic of the Iconoscope will be reproduced with exactness upon the viewing screen of the Kinescope.

The electron beams in the Iconoscope and the Kinescope are synchronized by transmitting synchronizing impulses at the end of each scanning line and at the end of each picture or frame. A synchronizing amplifier in the receiver separates the synchronizing signals from the composite signal by amplitude selection, separates horizontal and vertical synchronizing signals from each other by frequency selection, and delivers the impulses to the respective deflecting oscillators in proper amplitude and polarity for synchronization. The requirement of accurate synchronization between the scanning beams at the transmitting and receiving ends of the circuit is one of the important factors necessitating a uniform standard for all television systems to be used in broadcasting services in this country.

As in motion pictures, the degree of technical perfection of the reproduced image may be measured in part by the detail it contains. To produce a system that will transmit and reproduce pictures of acceptable detail has presented one of the most severe problems in television. The solution was found in the all-electronic system.

The amount of detail that can be transmitted by a television system depends upon the number of picture elements resulting from the scanning process. The number of picture elements depends upon the number of lines by which a complete picture is scanned. A picture element has a height equal to the distance between the centers of adjacent scanning lines; that is, the scanning-line pitch, and a length 56 per cent greater than its height, for equal horizontal and vertical resolution in the picture. The number of picture elements, and hence the amount of detail, increases with the number of scanning lines. In a system that employs the Iconoscope and other electronic devices, the number of scanning lines, hence the picture detail, may be greatly increased over that obtainable by earlier devices and methods. The Iconoscope mosaic does not limit the detail because many tiny photosensitive elements in the mosaic contribute to a single picture element.

The detail that may be obtained by different numbers of scanning lines is indicated in Fig. 7. These are synthetic representations developed in the course of the studies of the subject. Pictures of less than 60 lines were used in early experimental systems. The electronic system, embodying the Iconoscope and other electronic devices, produces pictures of satisfactory detail with 441 scanning lines. This amount of detail corresponds approximately to that obtained with 16-mm. motion picture film. A photograph of an actual 441-line television picture is shown in Fig. 8. This is a photograph of an image on the viewing screen of the Kinescope. The picture was transmitted by the RCA system now under test in the New York City area.

Fig. 8—Photograph of a 441-line television picture on the viewing screen of the Kinescope.

In television, as in motion pictures, two considerations are involved in determining the rate at which the scanning operation must be repeated. The rate of repetition must be great enough to give the appearance of reasonably continuous and natural motion in the reproduced scene, and must be great enough to minimize unsteadiness or flicker in the reproduced picture. Continuity of motion is maintained with a repetition rate of 16 pictures or frames per second. At least 48 frames per second are required, however, to minimize flicker unless some artifice be employed. Motion pictures are projected at the rate of 24 frames per second, and the artifice to reduce flicker takes the form of an additional blade upon the shutter that interrupts the light while the film is being pulled down from one frame to the next. Thus, as far as flicker is concerned, the projection is, in effect, at the rate of 48 frames per second.

Such an artifice is not applicable in television. Some other method must be devised. Interlaced scanning is employed in the RCA system. This provides satisfactory freedom from flicker. In interlaced scanning, instead of scanning the picture in adjacent lines from top to bottom, alternate lines covering the entire area of the picture are first scanned, and then the beam returns and scans the omitted lines. The entire picture is scanned 30 times per second, but the picture area is covered in alternate lines 60 times per second.

Another requirement for consideration in television is the relation that should exist between the frequency of the power supply to the transmitter and receiver and the repetition rate. It is desirable that the repetition rate be an integral divisor of the power-line frequency. This is necessary to minimize certain synchronous interference effects, which otherwise might be detrimental to the picture. The television transmitter and receivers of the RCA field test system operate on a 60-cycle power supply. Hence a repetition rate of 30 frames per second fulfills the requirements.

It should be noted that although the scanning beams of the Iconoscope and the Kinescope must be in exact synchronism, it is not necessary that the frequencies of the power supplies to the transmitter and the receiver be synchronous, that is, interconnected, provided they have the same nominal frequency and both systems are regulated in frequency accurately enough for the operation of electric clocks.

The transmission electrically of high-definition images over a single channel requires very wide frequency band apparatus and circuits. This is occasioned by the rate at which information must be transmitted concerning the brightness of a very large number of picture elements. A 441-line picture with an aspect ratio of 4 to 3, as transmitted by the RCA system, will contain 165,957 picture elements, for equal resolution horizontally and vertically. This is derived from the product of the square of the number of scanning lines and the aspect ratio divided by 1.56, the dimension of the picture element in terms of the scanning line pitch.

When 30 pictures per second are scanned information must be transmitted concerning the brightness of 30 times 165,957, or 4,987,710 picture elements each second. One cycle of the picture signal provides such information for two picture elements; hence the total frequency band required for transmitting a picture as above described is about 2,500,000 cycles.

This is the width of the frequency band that must be amplified and carried by the apparatus and circuits in the system. It is the frequency band by which the carrier-wave of the radio transmitter must be modulated. The total radio transmitting channel will be 5,000,000 cps. when the carrier is modulated by the picture signal. This is equal to the combined widths of 500 sound broadcasting channels of 10,000 cycles each.

Channels of such great width are not available in the frequency spectrum now used for radio services. For this and other reasons related to technical requirements, the ultra-high frequencies, or ultra-short waves, are used for television. Frequencies above 30 megacycles ($\lambda < 10$ meters) are employed. Ultra-short waves have quasi-optical properties in propagation. The range over which satisfactory high-definition television pictures may be reliably transmitted by ultra-short waves is limited practically to the distance of the horizon from the height at which the transmitting antenna is placed. Under some abnormal conditions, pictures may be received over greater distances for periods of very short duration, but primarily television stations will serve local areas. The signals from the stations in these local areas will be stable and will have about the same intensity during the day and night hours, and during the seasons of the year.

Television networks for the simultaneous distribution of programs orginating at one point will consist of interconnected local stations. The circuits interconnecting these stations must be capable of transmitting the very wide frequency band required for high-definition television. Existing circuits, either wire or radio, cannot fulfill this requirement. New facilities must be provided; and while wide frequency band circuits, either cable or radio, are feasible technically, to provide them for extensive, nation-wide networks become an economic problem of magnitude.

The development of a high-definition television system has required technical advances over a broad front. Fundamental research in an unexplored portion of the radio-frequency spectrum was required to determine the laws of propagation of ultra-short waves and to produce methods and devices by which they may be applied. Entirely new methods and apparatus had to be produced for picking up images and converting them into electrical impulses for transmission. New methods and devices were required for amplifying, transmitting, and receiving the very wide frequency bands on ultra-short waves. The fundamental character of the work and its extensiveness constitute practically the development of a new art.

The technical advances made through a step-by-step program of research in the laboratory, and through practical tests in the field, have been incorporated in the television system RCA now has under experimental test in the New York City area.

The equipment provided for this field test is installed under conditions that closely correspond to the requirements of a television broadcasting service. The field tests are comprehensive in scope. They embrace studies of the functioning of the equipment under field conditions; the collecting of engineering information and data related to signal and noise levels within the service area; experiments to develop program technic; and observations on receivers in the field by technical personnel.

This system is now using standards of which the essentials are 441-lines per frame, a frame frequency of 30 per second, a field frequency of 60 per second (interlaced), negative polarity of transmission, and a video-audio (picture-sound) carrier-frequency spacing of 3.25 megacycles. The picture signals are transmitted on a frequency of 49.5, and the sound at a frequency of 52.75 megacycles.

The studios in which artists perform and from which motion picture film is transmitted are located in the RCA Building, Radio City (New York). The radio transmitting equipment is installed in the Empire State Building, and the transmitting antenna on top of the building. The picture signals from the Radio City studios are sent to the radio transmitter in the

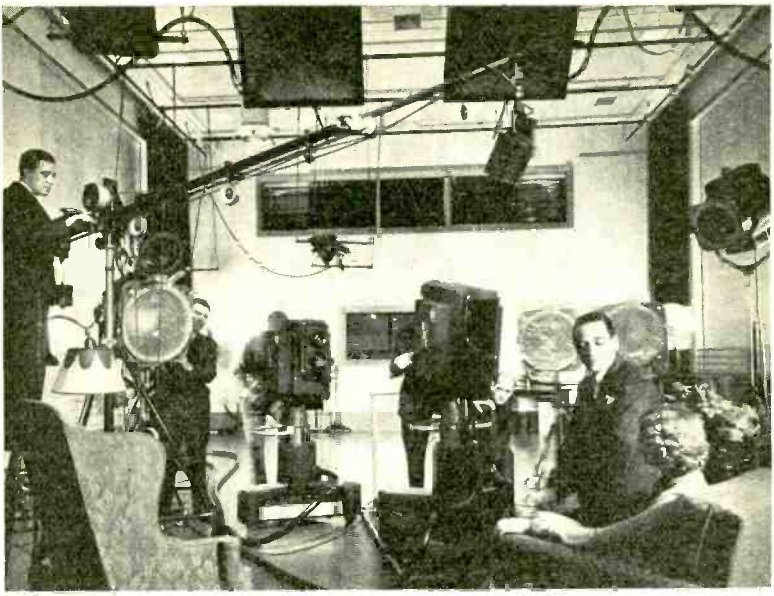


Fig. 9—Radio City television studio.

Fig. 10—Studio control room.

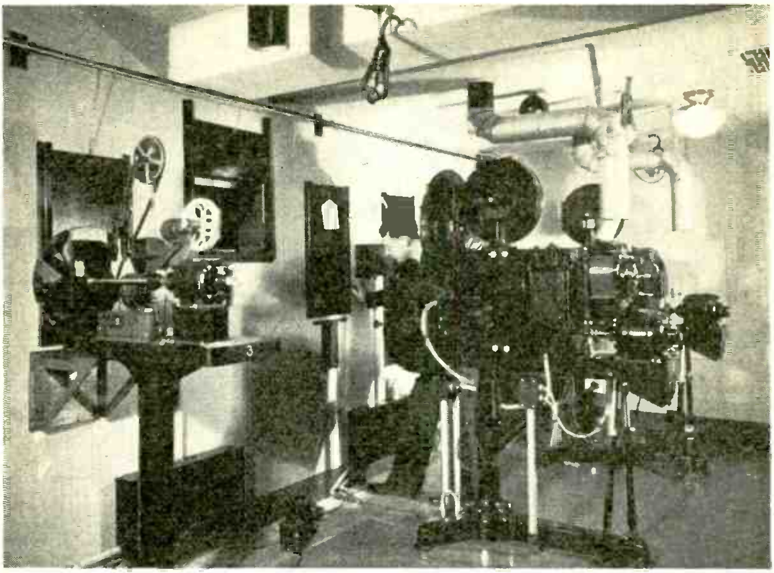


Fig. 11—Film projector equipment.

Empire State Building either by coaxial cable or by ultra-short-wave radio relay. The accompanying high-fidelity sound is carried over special cable circuits.

The terminal equipment at Radio City includes three Icono-

Fig. 12—Film studio control room.

scope cameras for direct pick-up in the artists' studio and two motion picture film projectors of special design, each with its Iconoscope camera. This equipment includes the video, or picture signal, amplifiers, and the deflecting and control apparatus for each Iconoscope camera, the Kinescope monitors, the synchronizing generators, the line amplifiers, and other associated apparatus.

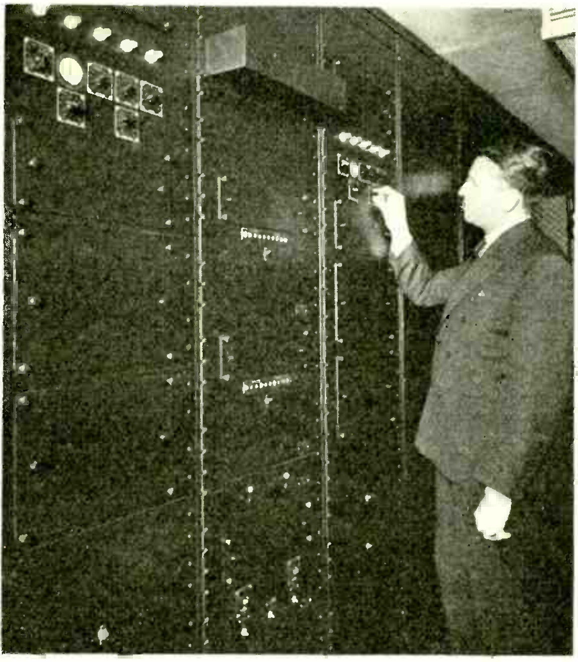


Fig. 13—Synchronizing generator and video line amplifier panels.

Television Studio.—The equipment in the Radio City television studio is shown in Fig. 9 as it is used for a program transmission. In the scene shown in the photograph, the Iconoscope cameras are employed to pick up scenes to be transmitted in sequence by switching from one camera to the other. The switching operation takes place in the studio control room, which is located in an elevated position at one end of the studio. The sound that accompanies the picture is picked up by a standard velocity microphone equipped with a windshield and attached to a boom.

The studio is about 30 by 50 feet, with a ceiling height of about 18 feet. It is an NBC studio formerly used for sound broadcasting. The studio is equipped with incandescent lamps of various types, having a total power consumption of more than 50 kw. The lighting equipment is flexible, to enable comprehensive studies of a variety of effects in experimental programs. Rifles, floods, and focusing spots, with ratings between 2 and 5 kw. each, are most numerous, although there are several large units of special design. Key lighting and back-lighting units are suspended from the ceiling; modelling lights are operated on the studio floor. The present sensitivity of the Iconoscope requires an incident light-intensity upon a set of about 1000 to 2000 foot-candles.

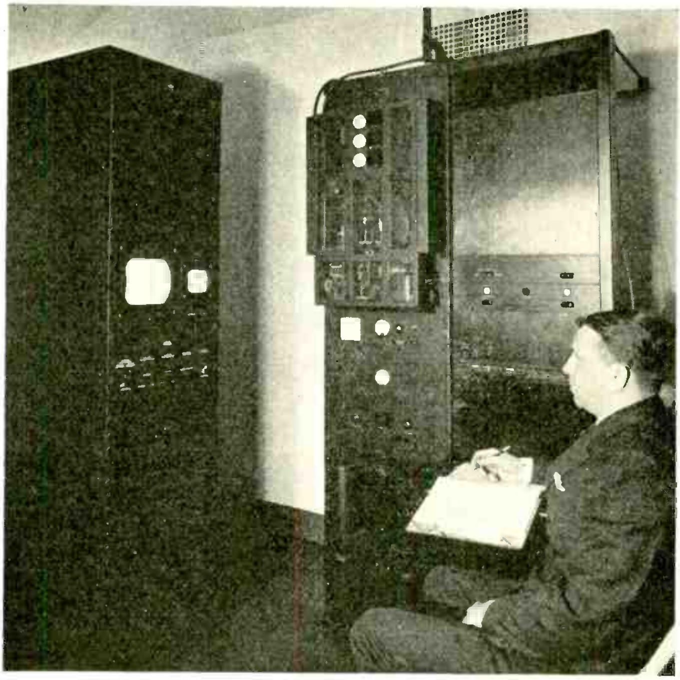


Fig. 14—Inter-building ultra-short-wave radio relay transmitter.

Studio Control Room.—Adjoining the studio and at such an elevation that the operating engineers have a clear view of the studio scene, is the studio control room. This control room is shown in Fig. 10. The sound and video signals from the studio are monitored in this room. The scenes are picked up by the Iconoscope camera and reproduced on the two monitoring

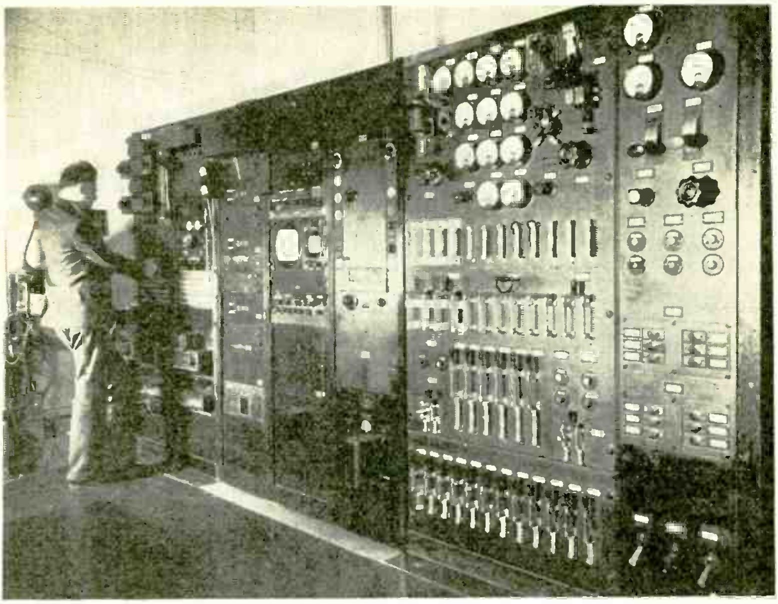


Fig. 15—Empire State Building control panel.

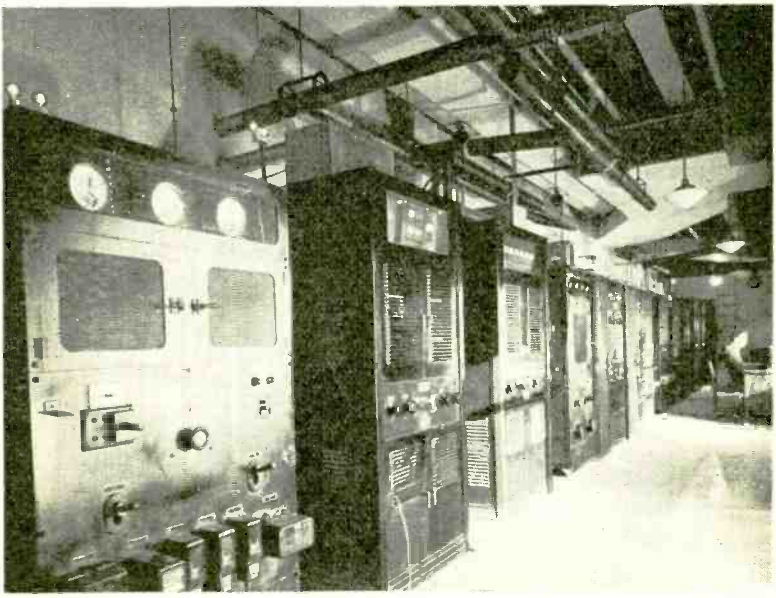


Fig. 16—Empire State Building video and audio transmitters.

Kinescopes shown at the left of the photograph. One monitor shows the scene being transmitted, and the other the scene picked up by the second Iconoscope camera preparatory to transmission. The operating position in the foreground of the photograph controls the sound from the studio. The video controls are at the opposite end of the control board. The racks of equipment behind the engineers include the video amplifiers and the synchronizing and control equipment associated with each Iconoscope camera.

Film Studio.—Motion picture film material originates in a film studio in another part of the National Broadcasting Company plant. This studio consists of two rooms, in one of which are installed two special 35-mm. motion picture projectors and other supplementary equipment, and in the other two Iconoscope cameras with video and monitoring and control apparatus. The projectors are so designed that standard 24-frame motion picture film is used to produce television pictures at 30 frames per second. In these projectors a changing rate of intermittent drive is used for the picture portion of the film and a constant 24-frame rate of feed for the sound portion. Pictures from the projectors are focused on the mosaics of the Iconoscope cameras located in the same control room beyond the partition separating the two rooms. The film projector equipment is shown in Fig. 11.

Film Studio Control Room.—A control room is associated with the film projection room. A view of this room is shown in Fig. 12. The equipment in the film studio control room includes two Iconoscope cameras with their video voltage amplifiers and associated synchronizing and control equipment, and audio equipment for the control of the sound from the film. The two Iconoscope cameras are so mounted that they may be shifted from side to side for use with either of the film projectors in the adjacent room.

Synchronizing Generator and Line Amplifier Equipment.—The panels containing the electronic synchronizing generator equipment, and the video line amplifiers that feed the video signal to the Empire State Building are shown in Fig. 13. This equipment is installed in the main equipment room of the National Broadcasting Company plant.

Inter-Building Transmission.—The inter-building ultra-short-wave radio relay transmitter (Fig. 14) is installed on the 10th floor of the RCA Building. It operates on a frequency of 177 megacycles, and has a channel width adequate to carry the full video frequency band. Equipment is provided for monitoring the signal at this point. The transmission distance between the two buildings is approximately 0.9 mile. The signal obtained at the Empire State Building is free from noise, and pictures transferred by radio relay are as satisfactory as those for which the coaxial cable is used.

Empire State Building Control Panel.—The coaxial cable and radio relay channels, and the channel for the sound accompanying the picture from the studios in Radio City terminate at the Empire State Building control board (Fig. 15). From left to right, the control board consists of the sound channel panel, a video monitoring panel, the radio relay receiver panel and battery and switching panels. The video monitor may be switched either to the radio relay or the coaxial cable channel.

Transmitters.—The video and audio transmitters installed in the Empire State Building are shown in Fig. 16. The video and audio transmitters are entirely separate, and are specially designed for high-power operation on ultra-high frequencies. The modulator of the video transmitter is capable of handling the wide side-bands required for the video frequencies. Both transmitters are coupled to a common transmission line connected to the single antenna on top of the building.

Antenna.—This antenna produces a horizontally polarized field with a pattern essentially circular in the horizontal plane. The antenna has a power gain in the horizontal plane of about 2.1, or 3.2 db., as measured with reference to a vertical dipole. The Empire State Building, having a height of the order of 1250 feet, provides a location from which a maximum transmitting range may be obtained. The distance from the antenna to the horizon is approximately 43 miles. Fig. 17 shows a view of the Empire State Building transmitting antenna.

Experimental Field Test Receivers.—The experimental field test receivers resemble in appearance a console broadcast receiver. Fig. 18 is a photograph of the type of receiver now in use. This receiver is of the superheterodyne type, and has a tuning range of 40 to 84 megacycles. It receives the picture and the sound. The Kinescope is mounted vertically and the television image is viewed in the mirror mounted inside the cover of the cabinet. Tuning is accomplished by a single knob controlling the radio-frequency circuit and the single oscillator which heterodynes both carriers to produce two intermediate frequencies.

Of the seven knobs on the front of the receiver the center knob tunes the picture and the accompanying sound. The three knobs on the right, from top to bottom, are the sound volume control, the treble tone control, and the bass tone control. The three knobs on the left, from top to bottom, are the picture contrast control, the detail control, and the background brightness control. These receivers operate on the ordinary 110-volt, 60-cycle power supply, and draw about 350 watts of power.

These receivers have been used to produce two sizes of pictures. For the first few months of the tests, the picture size was 5¼ by 7½ inches. At the present time most of the receivers have Kinescopes that produce pictures 7½ by 10 inches in size. Fig. 18 shows a 9-inch Kinescope that produces a 5¼ by 7½-inch picture. A Kinescope about 12½ inches in diameter is required to produce a 7½ by 10-inch picture. The shape of the picture, defined by the aspect ratio 4 to 3, is the same as that used in motion picture practice.

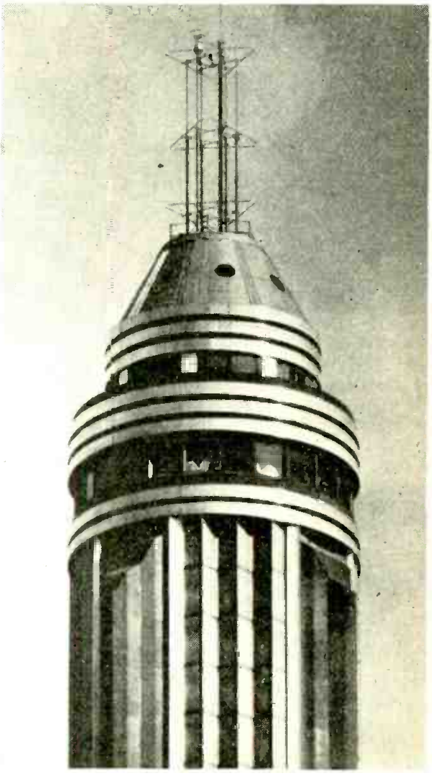


Fig. 17—Transmitting antenna on tower of Empire State Building.

The brightness of the reproduced picture is such that it can be viewed in a moderately lighted room. The color of the Kinescope screen depends upon the composition of the fluorescent materials. Many screen colors have been produced. At the present time a slightly greenish yellow screen and a more nearly white screen are being used. The present yellow screen used for the 7½ by 10-inch picture has a brightness in the highlights of about 4 foot-lamberts. This may be compared with the tentatively proposed standards of 7 to 14 foot-lamberts for the brightness of motion picture theater screens.

The optimal viewing distance for a 441-line picture of the 7½ by 10-inch size is of the order of three to four feet. At this distance the line structure is not resolved by the eye. The screen angle or the angle subtended by the picture at the eye is about 20 degrees. At a viewing distance of 12 feet, the screen angle is about 5 degrees, which, in general, is of the order of magnitude of the minimal acceptable screen angle for motion pictures. The size and brightness of the 7½ by 10-inch picture of 441 lines appears to satisfy reasonably the requirements for pictures to be viewed in the home by the average family group.

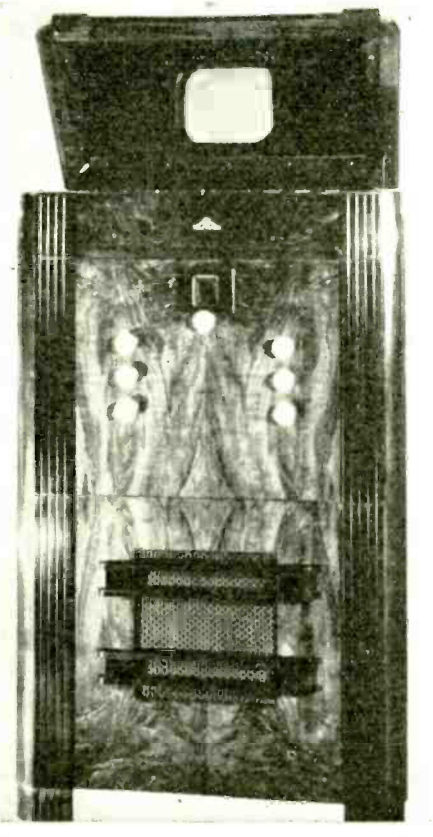


Fig. 18—Experimental field test receiver.

In connection with television program technic, it is too early to predict accurately the technic that ultimately will develop in television programming. It is clear to those who are closely associated in the development of a system that although some parts of the program technic may parallel the technics of the stage, motion pictures, and sound broadcasting, it will be distinct from any of these. In effect, a new art form must be created.

In general, television program material may fall under three principal classifications. These are direct pick-ups from indoor studios and other points, outdoor pick-ups, and motion picture film. Spontaneity eventually may be an important element in television programming. The televising of outdoor events as they occur is entirely feasible under the light conditions that prevail during fair weather. Studio programs and motion picture film probably will find liberal use in television programming, but here again the requirements peculiar to television will affect the nature and composition of the material.

The field tests in the New York City area are contributing to further technical advances. Pictures of 441-scanning lines have been transmitted and satisfactorily received within a service area having a radius of 30 miles or more from the Empire State Building. Good pictures are regularly received at one observing point in a suburban home over a distance of 45 miles.

Much remains to be done. When it will be completed can not be accurately predicted. The engineering information and data collected and the experience gained from operating the system under field conditions are pointing the way toward the realization ultimately of a high-definition television broadcasting service.

This new service, just as have many new services in the past, will supplement and not supplant the existing services or agencies representing the older arts. The telephone did not supplant the telegraph; it supplemented it. Sound broadcasting did not supplant the theater and the motion picture. On the contrary, it increased public interest and appeal in them, and thereby contributed to their advancement and financial profit. And so it will be with television. When it is successfully accomplished, we shall have added another service to the continually growing list. There will be some things that television can do that previous arts can not do; a few things that it can do better than they; but there will be many things that they will continue to do that television can not do. We may therefore welcome the advent of a great new public service, which will come not to displace but to augment our agencies of entertainment and information, thereby making the world a more interesting place in which to live.

RCA TELEVISION FIELD TESTS

By

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FOR more than ten years RCA has been conducting research work directed toward application of television. This research has passed through many stages, beginning with early mechanical arrangements and developing to the present electronic system. In this step-by-step program, many new devices has been evolved—among them, the "Iconoscope"* and the "Kinescope."* Effort has been directed toward performance having lasting value and this has required studies of image characteristics, program possibilities and apparatus considerations. Execution of such a program on a logical, coordinated basis requires adequate practical tests from time to time. RCA has conducted several field tests to determine status and to indicate the course for further development, and is now beginning experimental operation of a system for another field test.

1931-32 Field Test

During the early part of 1931 it was decided to make practical tests on a cathode-ray television system of the type being developed by the research organization of RCA. This project was entirely experimental in nature, but was so directed as to obtain operating conditions as nearly as possible in keeping with probable television broadcast service. The location chosen for these tests was the metropolitan area of New York. The studio and transmitter equipment was located in the Empire State Building with the antenna structures at the very top. Apparatus for this project was completed and installed during the second half of the year. Operation tests followed, continuing through the first half of 1932.

The equipment used for these experimental field tests was in keeping with the status of television development at that time. Two radio transmitters were used, one for picture and the other

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for sound. These were operated in the experimental television band, 40 to 80 megacycles. The picture and sound transmitters were widely separated in frequency to simplify the apparatus requirements. One hundred and twenty-line progressive scanning was used. The limit of 120 lines was established mostly by the signal-to-noise ratio for direct studio pick-up. The frame frequency was 24 per second. This was chosen so as to provide adequate continuity of action for objects in motion for studio programs, and to enable the use of standard motion picture film for film subject material. Synchronization was automatically maintained at the receiver by transmitted synchronizing impulses, one impulse for each line and one impulse for each picture frame. The line and frame impulses differed in character. "Mechanical" scanning equipment was used in the transmitter for both studio and film subjects.

The television receiver consisted essentially of two channels, one a receiver for picture with its cathode-ray tube and associated circuits, and the other a receiver for sound with its usual loud speaker. Independent tuning arrangements were provided for each channel. The cathode-ray tube was mounted in a vertical position and the reproduced images viewed in a mirror mounted on the inside of an adjustable top lid of the cabinet.

After the apparatus had been installed and placed in operating condition, practical tests followed. These tests were varied in nature and were intended to be as comprehensive as possible. A propagation study was made in the metropolitan area of New York. An analysis was made of electrical "noise" disturbances, sources of this "noise," and the resulting effect on television performance. Experience was obtained in the use of the terminal and radio transmitter apparatus which indicated existing limitations and conditions to permit greatest usefulness. Receivers were placed in many locations and the installation and operating problems were studied. Reactions of many observers were obtained.

Much valuable engineering information was obtained as a result of this project. An opportunity was available to design and construct apparatus for a complete experimental television system. Indications were obtained regarding the possibilities and limitations of the apparatus. Extensive operating data were accumulated. The project provided further insight and it broadened the perspective on that rather intangible factor "satisfactory television performance." An analysis of the experience and engineering information provided concrete objectives for continued research on television.

Some of the major findings and conclusions are of general interest. The frequency range of 40 to 80 megacycles was found well suited to television transmission. The greatest source of interference was from ignition systems of automobiles and airplanes, electrical commutators and contactors, etc. It was sometimes necessary to locate a favorable spot for the receiving antenna with regard to signal and sources of interference. For an image of 120 lines the motion picture scanner gave satisfactory performance. The studio scanner was adequate for only small areas of coverage. In general the studio scanner was the item which limited the program material most seriously. Study indicated that an image of 120 lines was not adequate unless the subject material from film and especially that from studio was carefully prepared and limited in accordance with the image resolution and pick-up performance of the system. To be satisfactory, a television system should provide an image of more than 120 lines. The operating tests indicated that the fundamentals of the method of synchronizing used were satisfactory. The superiority of the cathode-ray tube for image reproduction was definitely indicated. With the levels of useful illumination possible through the use of the cathode-ray tube, the image flicker was considered objectionable with a repetition frequency of 24 per second. The receiver performance and operating characteristics were in keeping with the design objectives.

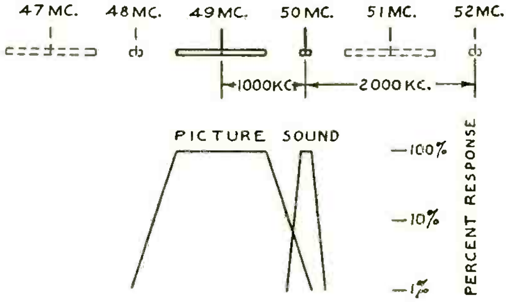
1933 Field Test

The previous field tests indicated many of the objectives for continued research in the laboratory. In order to make practical tests on the next stage of television research, a complete system was built in Camden and operated during the first several months of 1933.

In the New York tests the major limitation to adequate television performance was the studio scanning apparatus. This consisted of a mechanical disk, flying-spot type, for an image of 120 lines. Even for small areas of coverage and for 120 lines, the resulting signal amplitude was unsatisfactory. In the Camden system, an "Iconoscope" was used as the pick-up device. The use of the "Iconoscope" permitted transmission of greater detail, outdoor pickup, and wider areas of coverage in the studio. Experience indicated that it provided a new degree of flexibility in pickup performance, thereby removing one of the major technical obstacles to television.

The picture characteristics for this experimental television system included 240-line progressive scanning, 24 frames per second. The choice of 240 lines was not considered optimum, but all that could be satisfactorily handled in view of the status of development.

In the earlier New York tests the picture and sound transmitters were widely separated in frequency to simplify apparatus requirements. In our analysis of television systems, it had been judged desirable that there be two transmitter carriers, one for picture and one for sound. It had further been concluded that the picture carrier should include the *video* signal, synchronizing impulses, etc. On this basis, the problem of television reproduction requires the reception and utilization of two transmitted carriers with their respective modulations (one for *video* and control signals and the other for sound), without interference from each other and without interference from other television stations. These considerations plus a study of station allocation in a national system, receiver design and tuning problems, and other related factors, indicated that the two carriers for one station should be adjacent, with their spacing being dependent upon image detail, and transmitter and receiver selectivity characteristics. For these tests it was assumed that a television channel for picture and sound should be 2,000 kilocycles wide and that the picture carrier and sound carriers should be spaced by 1,000 kilocycles. This particular channel width and



OVER-ALL TRANSMITTER AND RECEIVER SELECTIVITY CHARACTERISTICS

Fig. 1

carrier spacing were not decided as optimum, but rather as practical limitations for the tests. The picture carrier was at 49,000 kilocycles and the sound carrier, 50,000 kilocycles. Diagrammatically, a television channel of this type is shown in Fig. 1.

Since the tests were essentially for the purpose of obtaining experience with the system fundamentals and with the terminal apparatus, the picture and sound transmitters had nominal outputs. The two transmitters were located in one of the RCA buildings in Camden and the antennas on masts above the building. The studio and control apparatus were located in another building about 1,000 feet direct-line distance from the building housing the transmitters. Most of the receiving tests were made at a point four miles from the transmitter.

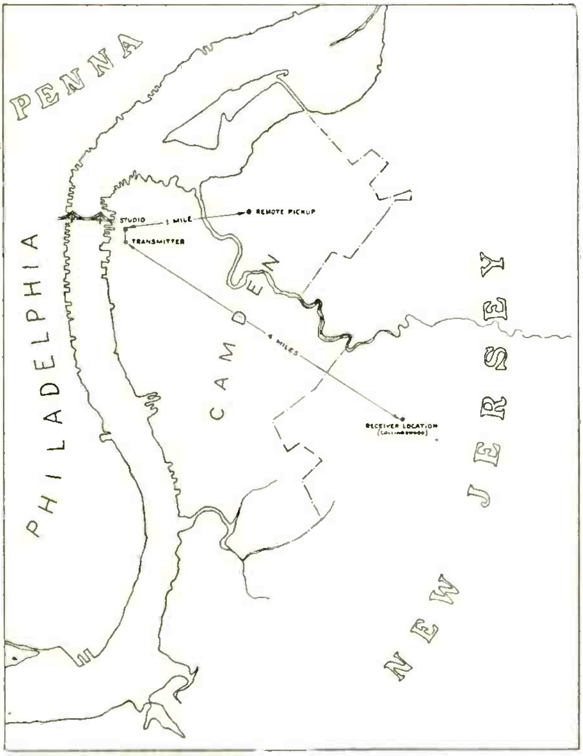


Fig. 2

One of the problems in television is to provide facilities for program pick-up at points remote from the studio and transmitter. In this experimental system a pick-up point was located approximately one mile from the studio. Here an outdoor program was televised and relayed by radio to the main studio and transmitter. Figure 2 illustrates the Camden system.

Another problem in television is to tie groups of stations together for network service. The interconnecting link might be either a special land wire or radio. In this experimental system, tests were made on radio relaying of television programs between New York and Camden. A program originating in the Empire State Building studio was transmitted by radio, relayed at an intermediate point, received and broadcast in Camden. For these tests 120-line scanning was used, since this was the standard for the New York equipment. Figure 3 illustrates the complete system.

The increase of image detail (from the New York tests—120 to 240 lines) widened very considerably the scope of the material that could be used satisfactorily for programs. Experience with this system indicated that even with 240 lines, more image detail was desired for much of the program material. The desire was for both a greater number of lines and a better utilization of the detail capabilities of the system and lines chosen for the tests. The "Iconoscope" type pick-up permitted a freedom in subject material and conditions roughly equivalent to motion picture camera requirements.

As in the New York tests, much valuable experience was obtained in constructing and placing in operation a complete television system having standards of performance abreast of research status. Estimates of useful field strengths were formulated. The need for a high power television transmitter was indicated. Further studies were made of interference caused by automobile and airplane ignition systems. Consideration was given to receiver antenna problems. Technical and lay opinion was obtained on receiver operation, image characteristics, and entertainment possibilities. Some work was done on program, studio, and pick-up technique. Again the tests indicated directly, or as a result of analysis, the objectives for further research.

1934 Field Test

In order to make field tests on further advances as worked out in the laboratory, an improved system was set up in operation in Camden during 1934. Since the major items under test related to terminal apparatus, low power transmitters were used. Scanning lines per frame increase to 343. Previous field tests and laboratory work had indicated the seriousness of flicker at frame frequencies in the order of 24 per second. For these field tests interlaced scanning was used—a frame frequency of 30 per second and a field frequency of 60 per second. Former systems tested made use of a mechanical-optical synchronizing generator. With the increase in number of scanning lines, with the requirement of extreme accuracy and with the need for fairly complicated waveshapes, an electronic synchronizing generator was developed and used. This removed the last mechanical element from the system.

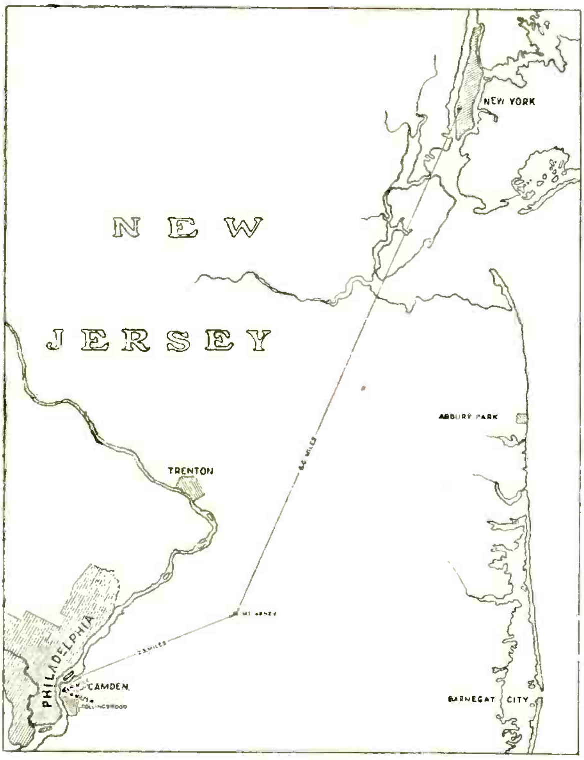


Fig. 3

The tests that followed gave further evidence of the desirability of an all-electronic system. The effectiveness of interlacing as a solution to the problem of flicker was conclusively demonstrated. The increased number of scanning lines permitted further flexibility in program possibilities.

As the next step a development program was undertaken on relatively high power transmitters. The outstanding technical characteristic of television is the very wide range of modulation frequencies. This development of higher powered transmitters resulted in the design used in the field test about to be undertaken.

1936 FIELD TEST

During the early part of 1935 RCA explored the possibilities of a further field test so that subsequent steps might be based on additional experience. It was decided to make additional field tests. Operating standards were chosen which were in keeping with apparatus considerations and which were adequate for the field test determinations. The essential items are:

(1)	Number of Lines	343
(2)	Frame Frequency	30 per second
	Field Frequency	60 per sec. (interlaced)
(3)	Aspect Ratio	4:3
(4)	Picture Carrier	49,750 kc
	Sound Carrier	52,000 kc
(5)	Channel Width	4,000 kc
(6)	Polarity of Transmission	Negative

A brief description of the system follows. Provision is made for studio and motion picture film programs. An NBC sound studio at Radio City has been adapted for television. Three studio cameras using "Iconoscopes" have been provided together with three *video* channels and the necessary control and monitoring facilities. Apparatus flexibility has been included so as to permit varied experimentation with programs and lighting.

Two special motion picture projectors and "Iconoscope" cameras for use with these projectors provide for continuous programs from 35 mm. film.

A common generator of synchronizing impulses supplies the entire system. The composite *video* and synchronizing signals are made suitable for transmission by line amplifiers and control units. There are two means of sending these signals to the transmitter, one by cable and the other by radio relay. The radio relay operates at a frequency between 150 and 200 megacycles. The relay transmitter and receiver antennas are directive arrangements and are so positioned as to have an unobstructed transmission path.

The picture and sound transmitters are located on one of the top floors of the Empire State Building. Provision is made for supplying the *video* transmitter with signals from the cable and the radio relay. The transmitters have outputs of approximately 7.5 kilowatts, the picture transmitter operating at 49.75 megacycles and the sound transmitter at 52 megacycles. The two transmitter outputs feed through coupling filters to a single transmission line which runs to the top of the building. A single radiating structure is used having a power gain of approximately two through concentration in the vertical plane. This structure provides a circular pattern in the horizontal plane having horizontal polarization.

The receivers used in this field test are superheterodynes having a tuning range of 42 to 84 megacycles, capable of receiving both sound and picture simultaneously.

The head-end circuits are broad enough to accept both carriers and one picture side band. A single oscillator heterodynes both carriers. The intermediate frequencies thus produced are therefore separated in frequency by the same number of kilocycles as the transmitted carriers were separated, namely 2,250 kilocycles.

Separation of the sound and picture signals is accomplished in the intermediate amplifiers. The sound intermediate amplifier is relatively sharp and the picture intermediate amplifier relatively broad to pass the picture carrier and one sideband, and their pass bands are so spaced that when the sound is properly tuned the picture is also properly tuned.

The sound side of the receiver is more or less conventional. The intermediate amplifier is broader than is customary for a simple sound receiver. Following the sound intermediate amplifier are the audio detector, automatic volume control and audio amplifier, all designed to give high fidelity reproduction.

Following the picture intermediate amplifier are the detector and automatic volume control (which is independent of the sound AVC). From the detector the *video* signal is impressed on two amplifiers, one for the *video* signal to the "Kinescope" grid and the other to the synchronizing separating circuits for separating out the synchronizing impulses and impressing them on their respective scanning oscillators.

The *video* amplifier is designed to pass the *video* frequencies in the required range of approximately 60 to 1,500,000 cycles, with proper regard to amplitude, phase shift, transient response and signal polarity. This amplifier contains the contrast (or volume), detail and automatic background controls and circuits.

The synchronizing amplifier separates the synchronizing signals from the composite *video* signal by means of amplitude selection, separates horizontal and vertical synchronizing signals from each other by means of frequency selection, and delivers the impulses to the respective deflecting oscillators in proper amplitude and polarity for synchronization.

Each of the deflecting circuits consists of a blocking oscillator for generating synchronous impulses of large amplitude, a discharge tube circuit for generating the saw-tooth scanning voltage, and output amplifier tubes for supplying the saw-tooth current wave to the deflecting coils. Deflection, vertically and horizontally, is electromagnetic.

The television image is formed on the luminescent screen of a "Kinescope" 9″ in diameter, with an image size approximately 5½″ x 7¼″.

The receiver operates from the usual 110-volt 60-cycle line. One rectifier system supplies voltage to all tubes in the receiver except the "Kinescope," whose anode voltages are supplied by separate rectifiers. The receiver uses 33 tubes including the "Kinescope."

It is intended that these receivers will be used with an antenna which is a horizontal dipole.

EQUIPMENT USED IN THE CURRENT RCA TELEVISION FIELD TESTS

By

R. R. Beal

Research Supervisor, Radio Corporation of America

THE development of the RCA high definition television system has been advanced by a step-by-step program of research in the laboratory and tests in the field over a period of more than ten years. These developments have passed through many stages during which effort has been continually directed toward producing a system to provide a standard of performance of lasting value. Many new devices and methods have been evolved. Mechanical arrangements used in the early phases of the work have been entirely replaced by electronic methods through which much higher standards may be achieved. The RCA all-electronic system employs the "Iconoscope"* as the device which converts the light image into electrical impulses for transmission as radio signals, and the "Kinescope"* for transforming these signals back into visible images.

This system is now undergoing experimental tests in the field in furtherance of its development by progressive and evolutionary steps. These tests are being conducted in the New York City area. They are comprehensive in scope and embrace studies of the functioning of the equipment under field conditions; propagation studies to determine the service area; studies to determine the source of and corrective measures for interference; measurements to determine the necessary signal levels in Metropolitan New York and the surrounding suburban localities; experiments in program technique; studies related to receiver installation and operation; and observations on receivers in the field by technical personnel for determinations of standards for an acceptable and satisfactory system. These field tests began on June 29, 1936 and will continue for several months.

The equipment provided for the field tests is installed substantially as it would be employed in a radio broadcasting service. Studios for programs in which artists perform and for motion picture film programs are located in the RCA Building, Radio City. The transmitting

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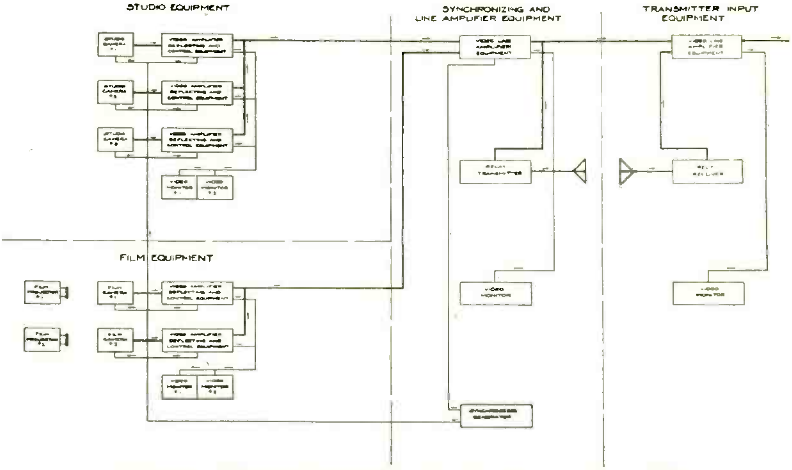
equipment is installed in the Empire State Building and the transmitting antenna is on top of the building. Ultra short waves are used for transmitting the "video" or picture signals and the accompanying sound. The picture signals are transmitted on a frequency of 49.75 megacycles and the sound on a frequency of 52 megacycles.

The system is now using standards of which the essential elements are 343 lines per frame, a frame frequency of 30 per second, a field frequency of 60 per second (interlaced), negative polarity of transmission, and a video-audio (picture-sound) carrier spacing of 2,250 kc. In cooperation with the radio industry, RCA has recommended the adoption of standards which include images of 441 lines and a video-audio carrier spacing of approximately 3,250 kc. The RCA field test system will be changed to conform to these standards at a time convenient in the experimental program.



TELEVISION TERMINAL EQUIPMENT FOR RCA FIELD TEST SYSTEM

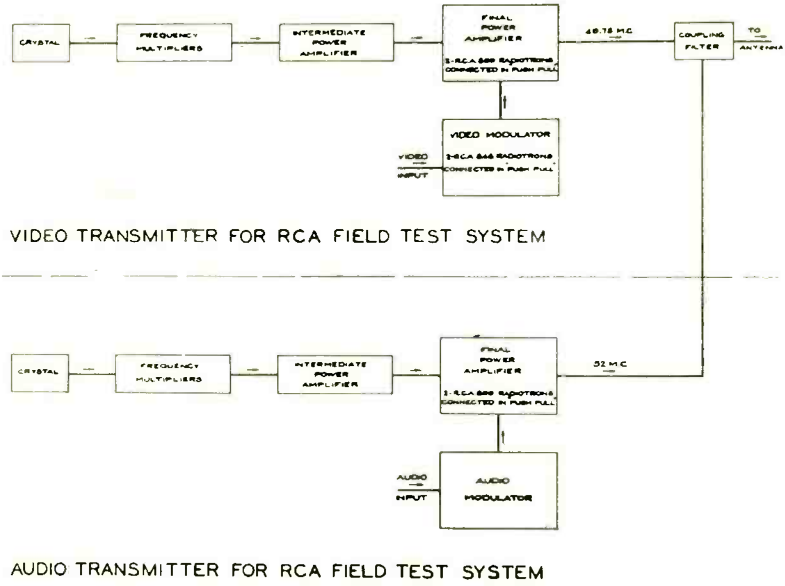
Fig. 1

The principal groups of equipment and the continuity of the system are shown diagrammatically in Figures 1 and 2. Figure 1 shows the terminal equipment installed in Radio City, and Figure 2 the video and audio transmitters in the Empire State Building.

The terminal equipment at Radio City, Figure 1, includes three "Iconoscope" cameras for direct pickup in the artists studio and their video amplifier, deflecting and control apparatus. Each of these "Iconoscope" cameras includes a preamplifier for amplifying the video output of the "Iconoscope". This output is delivered by cable to amplifying and control equipment from which it is fed to a video line amplifier for transmission to the Empire State Building.

In the film studio, two film projectors of special design are provided. Two "Iconoscope" cameras are furnished and, as in the direct pickup studio cameras, these include preamplifiers for amplifying the video output of the "Iconoscope". The camera output is delivered to the video amplifier and control equipment, after which the picture signals are fed to a video line amplifier for transmission to the Empire State Building.

The picture signals may be transmitted to the Empire State Building either by a radio relay channel or by an experimental coaxial cable. The radio relay transmitter and the common generator of synchronizing impulses which supplies the entire system, are located at Radio City.



VIDEO TRANSMITTER FOR RCA FIELD TEST SYSTEM

AUDIO TRANSMITTER FOR RCA FIELD TEST SYSTEM

Fig. 2

The video and audio transmitters installed in the Empire State Building, are shown diagrammatically in Figure 2. The frequency control of both transmitters is provided through conventional temperature controlled crystals. Frequency multipliers are employed to produce the carrier frequencies. The outputs of both transmitters are passed into a coupling filter which permits delivering both signals to a common transmission line and antenna without reacting on each other in the power amplifiers.

TELEVISION STUDIO

The equipment in the Radio City television studio is shown in Figure 3 as it is used for picking up programs for transmission. A light image of the scene to be transmitted is focused through a lens system on a mosaic composed of a large number of separate photosensitive elements in the "Iconoscope" in the camera. An electron beam produced in the "Iconoscope" scans the mosaic and converts the light image into a train of electrical impulses with amplitudes representing the various intensities of light as it is distributed from point to point over the image. These electrical impulses are the picture signals.

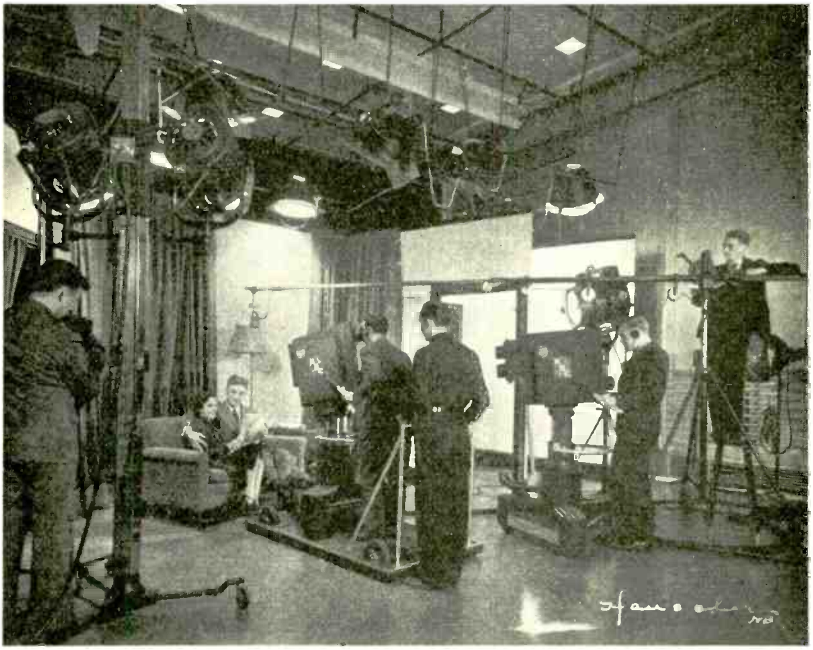


Fig. 3—Television studio equipment at Radio City

In the scene shown in the photograph, two "Iconoscope" cameras are employed for picking up close-up and distant views to be transmitted in sequence by switching from one camera to the other. The cameras are movable as units, adjustable with respect to height, and the upper section containing the "Iconoscope" is movable horizontally and vertically for "panning" or following the action. The camera attendants are equipped with telephone receivers and microphones for receiving and acknowledging instructions from the studio control room.

The lighting equipment is flexible to enable comprehensive studies of a variety of effects in experimental programs. Incandescent lamps are used in the equipment shown in the photograph. Studies of light intensities in relation to the subject to be picked up and of various types of lights constitute one phase of the engineering work related to program experimentation. Other phases of the work involve studies of program technique and research and engineering on methods of expanding the program capabilities of the system.

Fig. 4—Television studio control room

The sound which accompanies the television scene is picked up with a boom type of microphone and delivered to the studio control room after which it is fed to the Empire State Building over high quality telephone circuits.

STUDIO CONTROL ROOM

The studio control room, Figure 4, is at one end of the studio and at such an elevation that the engineers have a clear view of the floor on which the pickup is made. The control console position in the foreground of the photograph controls the sound from the studio. The video circuit controls are at the opposite end of the console. Two video monitors are mounted on the wall in front of the video control position. One monitor shows the scene that is being transmitted and the other, the scene picked up by the second "Iconoscope" camera preparatory to transmission. The engineer at the video control position performs the operation of switching from one camera to the other.

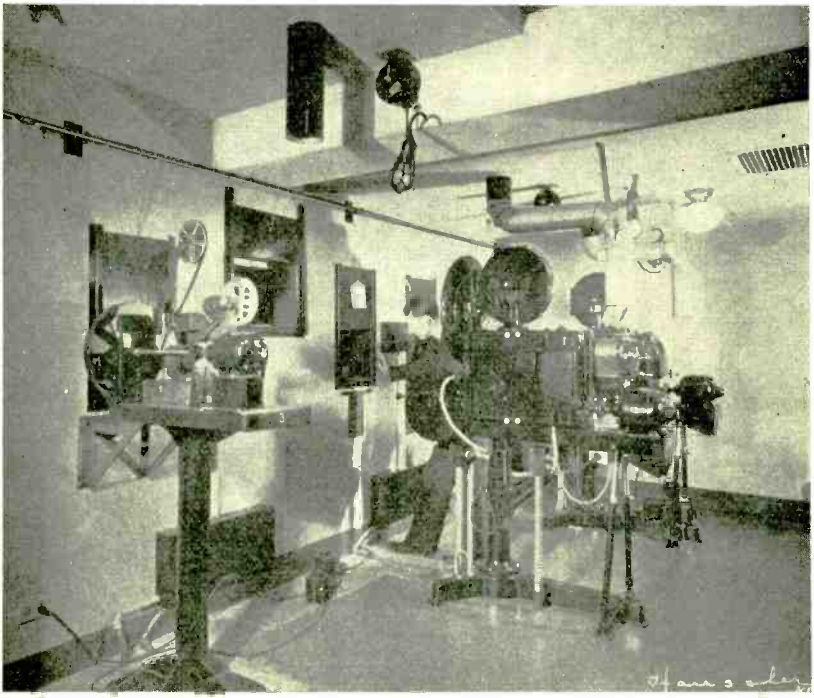


Fig. 5—Film studio equipment

The racks of equipment behind the engineers include the video amplifiers and the synchronizing and control equipment associated with each of the "Iconoscope" cameras.

FILM STUDIO

The film studio equipment, Figure 5, consists of two motion picture projectors of special design to permit the use of standard 24 frame motion picture film to produce television pictures at 30 frames per second. In these projectors a changing rate of intermittent drive is used for the picture portion of the film and a constant 24 frame rate of feed for the sound portion. Pictures from the projectors are focused on the mosaics of the "Iconoscope" cameras located in the control room beyond the partition separating the two rooms.

FILM STUDIO CONTROL ROOM

The equipment in the film studio control room, Figure 6, includes two "Iconoscope" cameras with their video voltage amplifiers and associated synchronizing and control equipment and audio equipment, and controls for the sound from the film. The two "Iconoscope" cameras are so mounted that they may be shifted from side to side for use with either of the film projectors.

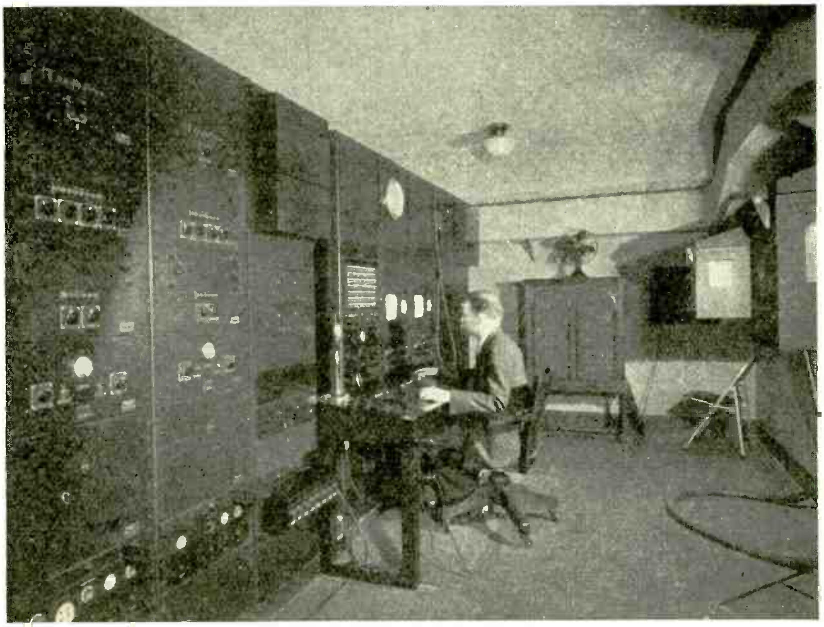


Fig. 6—Film studio control room

Adjustments of signal levels and switching are accomplished by the engineer at the control console. Two video monitors are furnished, one for each film projector channel, to provide for continuous transmission from film.

SYNCHRONIZING GENERATOR AND TIME AMPLIFIER EQUIPMENT

The panels containing the electronic synchronizing generator equipment and the video line amplifiers which feed the video signal to the

Empire State Building are shown in Figure 7. Synchronization at the receiver is obtained by transmitted impulses. The horizontal and vertical impulses have the same amplitude and wave shape selection is employed.

INTERBUILDING RADIO RELAY

The ultra short wave radio relay transmitter, Figure 8, is installed on the 10th floor of the RCA Building. It operates on a frequency of 177 mc. The circuit has a channel width of 3 mc. to carry the video frequencies up to 1.5 mc. with double side band transmission. Video signals from the studio are delivered to this transmitter by coaxial cable. Video monitoring equipment is provided for the signal at this point.

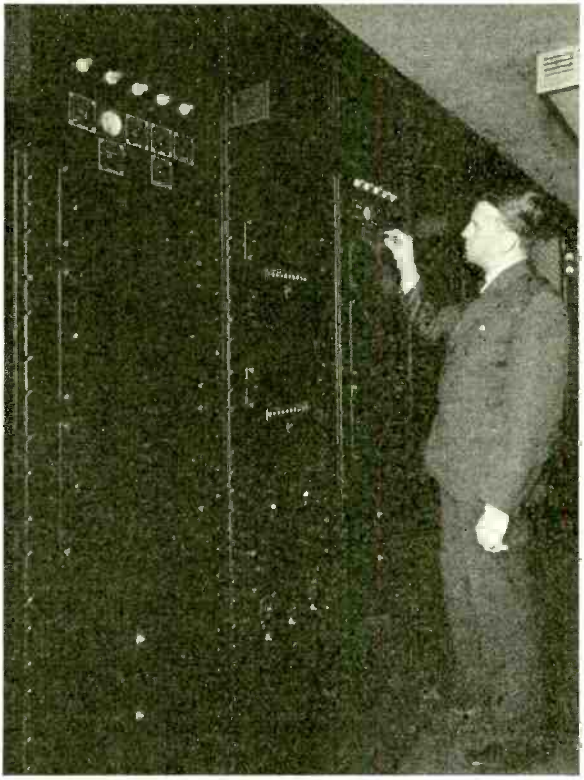


Fig. 7—Synchronizing and video line amplifier panels

The radio link transmitting antenna is located at about the 14th floor level on the south side of the RCA Building to provide an unobstructed transmission path to the receiving antenna placed at the

85th floor of the Empire State Building. The receiver for the radio relay circuit is installed in the Empire State Building transmitter control room. The air-line distance between the two buildings is about .87 mile.

The overall frequency characteristic of the radio relay circuit is substantially flat over the range from 20 cycles to 1500 kc. This circuit is practically free of noise and the picture quality over it is equal to that obtained over the coaxial cable.

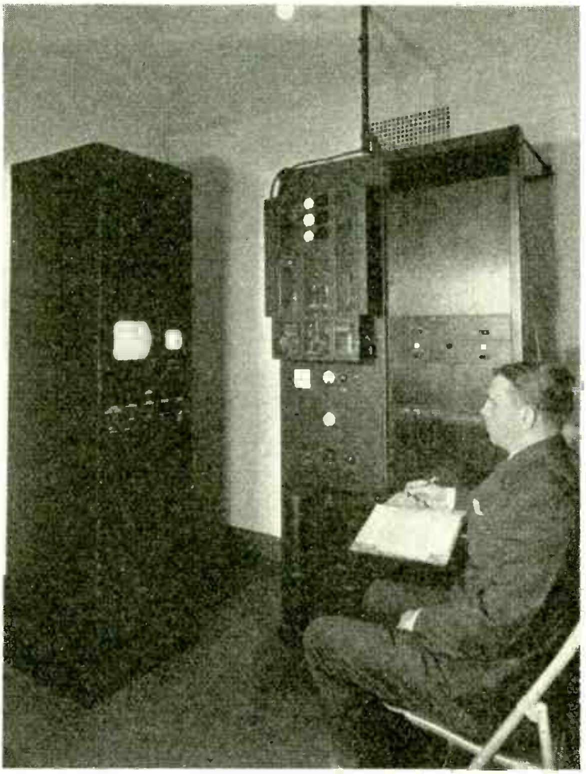


Fig. 8—Ultra short wave radio relay transmitter

EMPIRE STATE BUILDING CONTROL BOARD

The coaxial cable and radio relay channels and the channel for the sound accompanying the picture from the studios in Radio City, terminate at the Empire State Building control board (Figure 9). From left to right, the control board consists of the sound channel panels, a video monitoring panel, the radio relay receiver panel and battery and switching panels. The video monitor may be switched either to the radio relay or the coaxial cable channel. The video signals are delivered to the transmitter by coaxial cable.

EMPIRE STATE BUILDING TRANSMITTERS

The video and audio transmitters installed in the Empire State Building are shown in Figure 10. The tubes used in the final power amplifier of these transmitters are especially suited for the frequencies employed. Their plate dissipation rating is 30 kw. per tube. The filament power is sufficient to produce an electron emission of 18 amperes per tube which permits of a video carrier power of 8 kw. with a tank circuit loading to pass the 1.5 mc. sidebands.

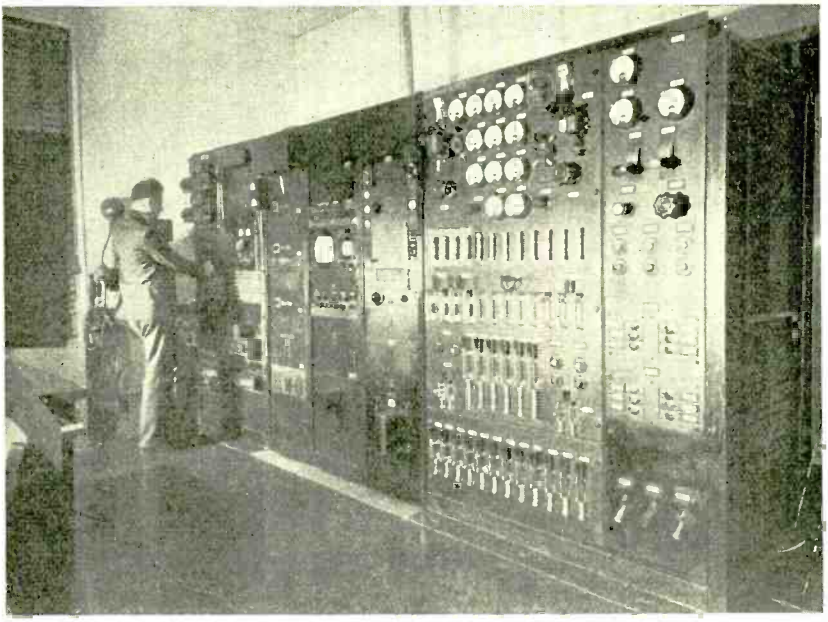


Fig. 9—Left to right, sound channel panels, video monitoring panel, relay receiver, battery and switching panels

The audio carrier final power amplifier is plate modulated in the conventional manner. In the video carrier final power amplifier, grid modulation is employed to reduce the video voltage that must be developed. The complete video modulator is impedance coupled.

EMPIRE STATE BUILDING ANTENNA

A single antenna structure is employed to radiate both the audio and video signals. In this antenna, the fundamental radiator unit consists of three dipoles arranged in the face of an equilateral triangle. Three of these units are so positioned vertically as to increase the concentration of radiation in the horizontal plane. A horizontally polarized field is produced with an essentially circular pattern in the horizontal plane. The power gain in the horizontal plane is about 2.1 to 1 or 3.2 db. as measured with reference to a vertical dipole.

The frequency band of the antenna is practically flat over the upper side band of the video transmitter, namely 49.75 to 51.25 megacycles, and its flat characteristic includes both side bands of the audio transmitter, 52 megacycles plus and minus 10,000 cycles.

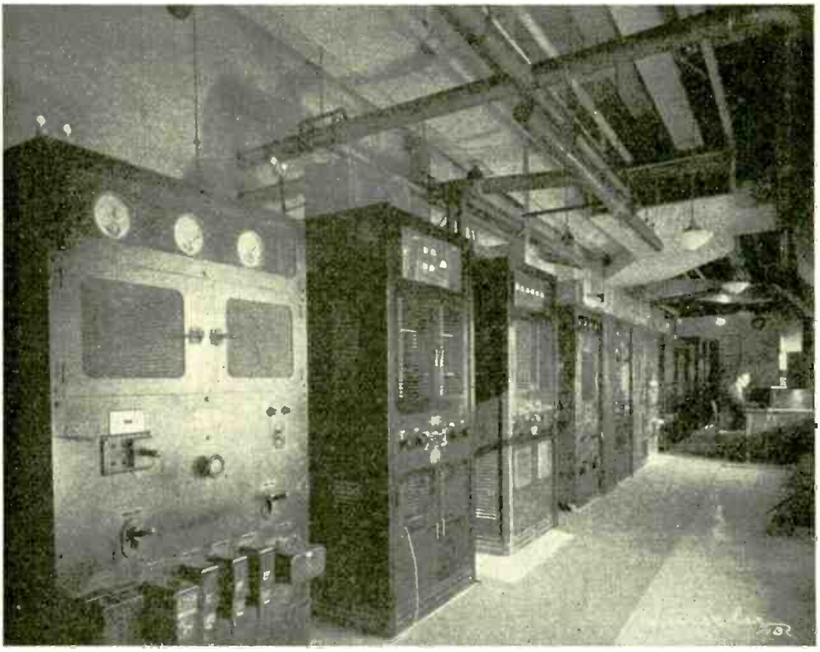


Fig. 10—Video and audio transmitters

Due to the quasi optical properties of the ultra short waves employed in television the transmitting range increases with the height at which the transmitting antenna is placed. The Empire State Building, having a height in the order of 1250 feet, provides a location from which a maximum transmitting range may be obtained.

EXPERIMENTAL FIELD TEST RECEIVERS

The field test receivers are of the superheterodyne type and have a tuning range of 42 to 84 megacycles. They receive both sound and picture simultaneously. The head end circuits accept both carriers and one picture side band. Tuning is accomplished by a single knob controlling the radio frequency circuit and the single oscillator which heterodynes both carriers to produce the intermediate frequencies. These are separated by the spacing of the transmitted carriers, namely, 2,250 kc.

Figure 11 shows a photograph of the television field test receiver

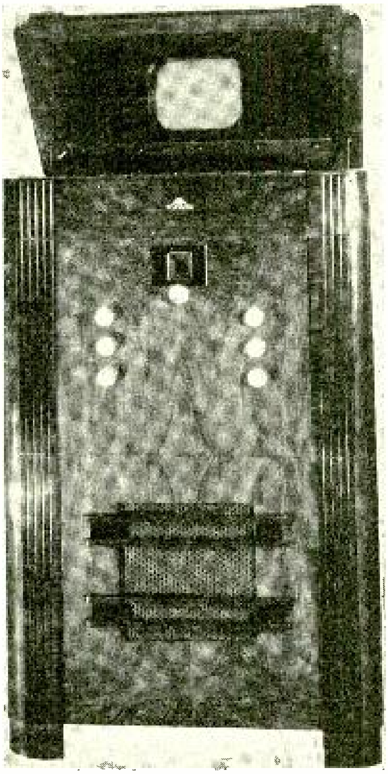


Fig. 11—Television receiver used in tests

with the cover raised to the viewing position. The television image is produced on the luminescent screen of a "Kinescope" 9″ in diameter which provides a picture size of approximately 5½″ x 7¼″. The "Kinescope" is mounted vertically and the picture is viewed in the chromium plated steel mirror mounted inside of the cover of the cabinet.

Of the seven knobs on the front of the receiver, the center knob tunes both the picture and the accompanying sound. The three knobs on the right from top to bottom are the sound volume control, the treble tone control and the bass tone control. The three knobs on the left are the picture contrast control, the detail control and the background control.

The receiver operates from the usual 110-volt, 60-cycle power supply and draws about 350 watts of power. Since the synchronization is controlled entirely by impulses sent from the transmitter, it is not necessary that the power supply frequency of the receiver be synchronized with that of the transmitter, although it should have the same nominal frequency.

The experimental receivers have 33 tubes including the "Kinescope". Horizontal dipole receiving antennas are used in the field installations.

As the field tests have advanced the soundness of the technical fundamentals of the system have been confirmed. Engineering studies related to program technique are broadening the program capabilities of the system. Good progress has been made in adapting the system to practical operating conditions in the field. Live talent and motion picture programs have been satisfactorily transmitted and received over distances of 25 miles from the Empire State Building at typical apartment house and suburban home locations. The height of the transmitting antenna has made possible consistently good reception at one favorably located suburban home over a distance of 45 miles.

Measurements of signal field strength and noise intensity are in progress to determine the requirements for service in the area under test. Electrical interference on the frequencies employed consists almost entirely of man-made noise originating in automobile ignition systems, diathermic apparatus and other electrical devices. Propagation studies and measurements are under way to obtain data on the interference range of the ultra short wave signals used for television. The tests of the system are incomplete, but as they progress the engineering and technical data, and the experience obtained by operating the system under field conditions, are expanding its capabilities and pointing the way toward realization ultimately of a satisfactory high definition television system for broadcasting service.

TELEVISION AMONG THE VISUAL ARTS

By

Dr. Alfred N. Goldsmith

Consulting Industrial Engineer

THE NEW field of television is under rapid technical development and program study. It is reasonable to expect that it will soon be one of the major visual arts, with a technique of its own and with broad applications of great public interest and commercial significance. Accordingly it seems appropriate to attempt to classify television among the visual arts, to study its relative advantages and disadvantages, and to attempt to judge some of its specified capabilities and limitations.

The other major visual arts are, of course, direct ocular vision, as accomplished by all of us through our eyes, and the arts of still-picture and motion-picture photography. We need not here consider still pictures. It is necessary for our purposes to compare television only with human vision and with motion picture processes.

It seems that television is a curious and rather unexpected blend of direct vision and motion-picture photography. It lies between these two older fields, borrowing from each and perhaps adding its own contribution to each of them. It seems worth while to compare these arts more specifically in various basic respects.

The first element meriting consideration is *duration* of the envisioned picture. In the case of direct vision, the image is completely transient. If we humans were not equipped with memory, our eyes would be of little use, since it is not the eye, but the brain that remembers. While it is a convenience to be able to shift our vision from one subject to another, yet it also places us under the handicap of having to retain a vast store of mental images or visual memories. The motion picture, on the other hand, is a recorded and practically permanent pictorial record. Subject only to the limited factor of physical life of film, a motion picture can be viewed at any time in the future in its original form. The silver image in the emulsion on the film is, in fact, nothing more than the stored memory of previous happenings. Television, oddly enough, is either transient and permanent depending on its mode of use and the extent to which it utilizes its allies, the motion picture or alternatively the electrical record. If we have a direct television pick-up instantly transmitted to the usual cathode-ray receiver in the home, television is as transient as direct vision. But suppose that at the transmitting station or the receiving station we record the pictures. This can be done either by the usual motion picture process or, theoretically at least, we might record the electrical variations at transmitter or receiver which correspond to the video modulation and the picture controls (such as synchronizing and background currents). In this way we can have either a film record or an electrical record of a television presentation and thus provide a "television memory".

Considering next the element of *color*, direct vision is of course color vision (except for the unfortunately color-blind individuals). Motion pictures similarly can be either monochromatic or in full color, though the latter process is not too readily accomplished. Television, in theory at least, can also be either monochromatic or in color. Nevertheless, color television at this time presents a most forbidding aspect to the already sufficiently harassed television experimenter and designer.

As regards the *sensitivity* of the various processes, direct vision has an extremely high sensitiveness to light and is limited only, so far as we know, by the sensitiveness of the electrochemical effects occurring at the retina of the eye. Where the sensitivity of the eye is uncomfortably low, we either increase illumination or perhaps use such auxiliary light-gathering devices as the telescope (and ultimately perhaps, the electron telescope with its capabilities of amplifying light). So far as motion pictures are concerned, the process starts with the formation of a latent image, and again is limited by the sensitiveness of an electro-chemical process. Film may be specially sensitized, illumination may be increased, or some other equivalent measures used if ordinary film sensitivity is found to be inadequate. Television is also limited by an electrical characteristic in its sensitivity, namely, by the sensitivity of the photoelectric effect. It is possible greatly to amplify the output of the original photo-electric pick-up device in television by such means as the secondary-emission amplifier. It is also possible, within limits, to increase the brightness of illumination of some subjects for television. However, considering the electrical background of each of the three visual methods of pick-up, it is not astonishing that their sensitivities are of the same general order of magnitude.

The *range* of transmission or viewing is quite different in the three cases in question. So far as direct vision is concerned, this extends optically to the nearest opaque obstacle, which may be anything from the walls of a room or the horizon to the furthest regions of the universe. Visual range is readily extended by telescopic devices. So far as the motion picture is concerned, it has, strictly speaking, no range. If a motion-picture film and a projector were to be carried to a remote planet, the reproduction would presumably be unchanged. Television in its most usual form of direct pick-up and reception has a range which extends to the nearest electromagnetically opaque obstacle, except insofar as reflection, refraction or diffraction may extend this range under favorable but somewhat erratic conditions. If, however, the television program is photographically or electrically recorded, the range becomes theoretically unlimited. Then again, if individual television stations are connected by radio or wire links, the range of television again becomes theoretically unbounded.

Another factor of interest is the ultimate *definition*, the degree of fineness of structure of the image which can be obtained by each of the visual arts. So far as direct vision is concerned, the limitation in general arises from the structure of the retina which structure is well known not to be continuous. The finite wave length of light imposes a further limit on the definition of images but, in every-day life at least, this is not the limiting factor. In the case of the motion picture, the grain structure of the developed image is one of the limiting factors. The accuracy of registration of each of the successive projected images on the viewing screen can never be absolute, and this imposes a further degradation of quality or loss of definition on the motion picture image. In addition, the usual optical limitations, resulting from the measurable wave length of light, exist in this case as well. However, motion pictures have been found to be adequately defined under practical working conditions when using modern photographic emulsions of fine grain and suitably limited enlargement. The television image encounters limitations in definition from several sources. In the pick-up device, the granular structure of the receiving photo-electric screen may limit definition. Alternatively, or in addition, the size of the beam aperture used for the scanning process or for the formation of a "picture element" is another and generally more serious limitation. This limitation exists as well at the receiving end in connection with the fluorescent screen. Not only beam cross-section, but spreading and persistence of image reduce definition at the receiving end. And, all along the line from original pick-up to final reproduction, we encounter electrically disturbing elements which tend to "degrade" or reduce the fidelity of the reproduced image. In the present state of the television art, the definition obtainable is only a minor fraction of that of direct vision or of motion pictures, but it is nevertheless adequate for many purposes, including certain types of mass entertainment and education.

Another element of interest is the necessary *delay*, measured between the time of original pick-up and the time of final viewing by the looker. In the case of vision, there is no delay, the pick-up process and the actual vision by the looker coinciding (except for a brief lag in the brain paths). In the case of motion pictures there is always an appreciable delay. The most speedy viewing of film after exposure appearing in the literature is that of the so-called intermediate-film process applied to television reception with large-screen projection. Here the film is used to record the incoming television pictures and is developed extremely rapidly, fixed, and projected (a positive being produced immediately by deliberately arranging for the reception of a negative—which is a mere matter of phasing). It has been claimed that from a few seconds to say thirty seconds elapse in this case between reception of the television picture and projection of the corresponding motion picture film. However, about the most rapid commercial procedure involving the making of a number of positive prints from an original negative is that of the newsreels, and this process may take anywhere from one to three hours. Where haste is not so essential, as in the case of feature films and short subjects used for motion-picture entertainment, the delay may run from weeks or months to years! Thus the motion picture in its more evolved forms pays a fairly high price for the permanence of its records in the form of a delay in their production and reproduction. Television can adapt itself to either the visual or the motion picture limitations and possibilities in this respect. Ordinarily television is instantaneous where a direct pickup is used. If film is used for television transmission, the delay is that inherent in the filming process and is as brief or as prolonged as corresponds to the particular photographic and film-processing methods which may be employed.

A factor of considerable practical importance is the *dependence of transmission* on the instant of *occurrence* of an event. So far as ocular vision is concerned, a real event can be seen only at the instant of occurrence (leaving out of consideration such relativistic questions as the actual time of viewing a star explosion in a distant part of the universe). Accordingly all the historical past is lost so far as direct vision by human beings is concerned. The motion picture suffers from no such limitation. It is true that there must be light with which to photograph the event and that the film support and the image carrier and constituents must be of suitably permanent nature. However, granted these reasonable requirements, the motion picture may be made at any time and shown at any later time. In fact, the motion picture has one curious characteristic. It can show things that never happened, as in the case of animated cartoons and trick photography. The nearest approach to this in direct vision is the deliberate distortion of a view by means of colored glasses, distorting lenses or reflectors, or the like. These means for modifying an actual view are relatively limited in their scope as compared to the possibilities of imaginative picturization accomplished by the motion-picture film. Television with direct pick-up of an actual event is just as dependent on its time of occurrence as is the eye. However, if the pick-up is by motion picture and the transmission is by television, or alternatively if the pick-up is by direct television and the received images are recorded on film, we again have independence of the time of reproduction relative to the time of occurrence of the original event. Thus television is happily able to borrow the techique of either the eye or the camera and thus to expand its own capabilities in accordance with the needs of the situation. This will obviously be a great convenience since the pick-up of a football game, for example, may be at a time of reduced available television audience, thus making it desirable to repeat the television transmission of the game from a film record at a later time.

A practical factor of considerable importance is the possibility of *time transpositions*. With natural vision, we are compelled to observe things in the order in which they occur. In fact, we can only observe that instant which is the present and which forever merges into the immediate future and departs from the near past. The motion picture is entirely unhampered in this respect. A number of pictures can be made in any desired sequence, and can then be rearranged and assembled in any other new sequence. The familiar "flash back" of the motion picture is a striking instance. Here action, presumably in the present, is interrupted by scenes from the past, after which the picture continues again in the present or even takes an imaginary trip into the future. This possibility of time transpositions has always been a great asset for the motion-picture producer. The scenes of a play can be photographed in any desired order, but can be cut, edited, or re-arranged in such a way that they are presented to the audience in quite a different order which may be artistically more attractive and dramatically more striking. This also leads to economy in production since all scenes taking place in given surroundings can be photographed in one sequence regardless of their apparent time of occurrence in the finished film. Television with direct studio pick-up is rather handicapped in this respect, just as is direct vision (or, for that matter, a particular act in the usual leisurely legitimate-theater production). It is only when television enlists the aid of the motion-picture film, either for background projection, in the production of composite pictures, or for the entire presentation, that it partly or entirely acquires the great advantages which result from the possibility of time transpositions. Since, however, there is no scientific reason why television should not use motion pictures whenever desirable, the motion-picture technique of time transpositions could, to a considerable extent, be effectively utilized by television.

All of the foregoing leaves little doubt that television is so flexible, convenient, and eclectic a method of visual reproduction that it will have general human appeal and wide-spread application. Carrying within itself for the first time all the possibilities of both the eye and the camera, it seems destined to be one of the great instruments of universal human enlightenment and progress.

TELEVISION PROBLEMS — A DESCRIPTION FOR LAYMEN

BY

ARTHUR VAN DYCK
Manager, RCA License Laboratory

RADIO has attained its present position of important widespread use so rapidly that it has not been possible for people generally to gain clear understanding of it, to the degree they do understand many other technical devices, such as the automobile for example. When radio's new service of television arrives, there will be even more intimate contact and impact between radio and the home. Many people realize this and an interest in "how television works" is frequently expressed to radio engineers. This article is an attempted answer to those questions.

The idea of being able to observe far-away events as they take place has always fascinated the human mind. Realization of the idea has been the dream of inventors for centuries, but the problem has been so difficult that many new and different tools were required, and we have had to wait through past centuries until all of them are provided. The discovery of electricity and the development of electrical communication were the first steps of course. The first devices needed particularly for television were discovered about sixty-five years ago, and experimenters have been improving and refining them, and adding new ones, ever since. The Radio Corporation laboratories have been engaged in this research for over ten years, and today we have all the scientific tools needed, and television is at long last, a technical possibility.

The first point of interest is that everyone has heard of television, that public interest in it is widespread—although it has not yet reached even the first beginnings of commercial or public service. That is unusual in scientific developments, and an understanding of why it is so, will explain much about television. Most developments come to public attention with the starting of public service in some form, and the laboratory

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Reprinted from lecture given before the Brooklyn Institute of Arts and Sciences (February 1937).

stage passes by unknown and unsung. The sound motion picture, even sound broadcasting, are recent examples of new arts bursting upon the public stage full grown and ready to act.

But television has been different. For ten years it has been written about in public print, everyone has heard of it and conjectured about it, all without a commercial practice or a public service. Why has this been? American business has not suddenly changed its outstanding characteristic of rapid utilization of new developments and become laggard in making new services available. On the contrary, it is much to the credit of American industry that the introduction of television has been delayed until it could be accomplished with safety and satisfaction to the public. Television service might have been started a few years ago, receivers might have been sold, but the performance would have been poor, the receivers would be obsolete and useless now, and the whole investment made worthless. I think that we can be grateful and pleased that the development has been sensible and orderly, the introduction not premature, and the serious problems solved in a few laboratories rather than in thousands of homes.

We need to see why the television art is so complex as to require this careful treatment. Why is it so different from sound broadcasting? We have seen sound receivers develop from the simplest crystal headphone type to the complex instruments of today, with no troubles from obsolescence—we have seen transmitters grow from tiny power to fifty thousand and even five hundred thousand watts—wherein is the difference in television?

The difference is not one merely of degree of complexity of apparatus. A totally new element is present in television, and not in sound broadcasting, namely the factor of time, and infinitesimal divisions of time at that. At the transmitter we have in effect to take pictures and send out descriptions of these pictures, bit by bit, and at the receiver we must put these bits together in the right places, as in a jig-saw puzzle, and at the right time. In other words, there are various actions at the transmitter and at the receiver which must be coordinated accurately. This means that the process involves a *system*—that transmission and reception can not be designed or conducted independently, and each is vitally dependent upon the other.

Before we discuss these characteristics, which are responsible for the peculiar engineering problems of television, it will probably be helpful to review briefly the principles upon which the simpler forms of radio communication operate, as this will assist toward clearer understanding of television, the most complex form.

We may note at the outset that there is nothing wireless about wireless apparatus. The wireless part is entirely in the medium between transmitter and receiver. The transmitter and receiver themselves are electrical apparatus fundamentally, like motors, lamps, telephones, and so on. Of course, radio uses some forms of electricity which these other devices do not, but basically it involves electrical apparatus using voltages, currents, power, under the same electrical laws as govern the others.

The function of the radio transmitter is to excite the medium between stations, by means of electric currents which in some way represent the intelligence to be transmitted. The function of the receiver is to detect these disturbances in space, translate them back to electric currents like the ones at the transmitter, and then to convert the currents to the form of intelligence which they were made to represent at the transmitter.

The fundamental parts of the transmitter are the generator, the modulator, and the antenna. The generator generates the particular form of electric currents needed, the modulator controls those currents to represent the intelligence to be transmitted, and the antenna radiates the modulated currents, or their effects, into space. Considering the generator for a moment, we can note that the only vital difference between it and the generator we use for electric light and power, is that its frequency is higher. Where light and power currents have a frequency of sixty cycles per second, that is have sixty pulses of flow in each direction per second, the currents used in an antenna have a frequency of thousands and millions per second. When we say that station WEAF has a frequency of 660 Kilocycles, or 660,000 cycles, it signifies that the currents in the WEAF antenna are flowing back and forth from the station generator that many times per second. These high frequencies are used because they radiate from the antenna more efficiently. The highest frequency used for standard sound broadcast stations is about one and one-half million cycles per second. Later we shall see that television stations use still higher frequencies, of the order of fifty million. And radio laboratories are experimenting with frequencies of over one billion cycles per second!

The modulator is the part which controls the high frequency alternating currents in the antenna, and modifies them to represent intelligence. If we are concerned with telegraphy, we find that the modulator simply starts and stops the current, in short and long bursts representing dots and dashes of the telegraph code. Therefore the antenna radiates a series of disturbances through space exactly representing the letters by dots and dashes.

If we desire telephony, the process is somewhat more complex. Here the high frequency alternating current is fed to the antenna continuously, without ever stopping, but is varied in strength to accord with the sounds to be transmitted. Here the microphone is used, because its ability is to convert air sound waves which strike it into electric currents which vary in exact representation of the sounds. These microphone currents are then used to control, or modulate, the high frequency currents going into the antenna from the generator, thus causing the antenna currents to be representative of the originating sounds. To complete the story, we may note that the receiving antenna has currents generated in it when struck by the traveling and varying strength space waves, and these currents are caused to actuate a loudspeaker, which is a device to convert electric currents to sound waves.

Note that in both telephony and telegraphy, we have transmitted intelligence by modulating the flow of high frequency current in an antenna to represent what we wanted to transmit, whether that was words of a message, letter by letter, with a dot-dash code, or whether it was sound occurring in front of a microphone. Now suppose that the form of intelligence to be transmitted is a picture, a drawing, a visual scene of any kind. We must arrange to modulate the same antenna high frequency current in some way which can represent the picture to be transmitted. And right here we come up against the enormous difference between sight and sound. In sound, we have to transmit only one thing, one bit of intelligence, one sound, at a time, with others in sequence. A symphony concert, or a Jack Benny program, consists merely of one sound at a time. True, each sound may be a complex one, with various tones composing it, but it is only one sound, and can be represented by one current. An instant later, another sound can be represented by another current, and our signals radio transmitter can follow the progression of single instantaneous sounds faithfully. But a picture, even one instantaneous flash, is not a single thing of any sort, and can not be described or represented by *one* electric current or one anything else. It is composed of many little elements, one for each area of that size which the eye can distinguish. For example, if we look at a scene whose dimensions are ten feet square from a distance where the eye can distinguish objects one inch in diameter, there are about fifteen thousand small, one inch areas which must be described individually to convey the whole picture. If the scene to be transmitted is a stationary one, and we are permitted to take any amount of time to describe the scene, we could do so successfully by an ordinary telegraph system and a simple code. We might divide our scene up into imaginary squares, one hundred each way, and number them in sequence beginning with the upper left corner, going across the top row, then beginning the second row at the left, and so on until the lower right small square would be number ten thousand. We will then arrange an understanding with our correspondent that we will telegraph him a message containing ten thousand numbers and that the numbers will be the digits one, two, or three. One will mean white, two will mean gray, and three will mean black. Our telegram may then read 1113221233331123111 et cetera for ten thousand digits. If our correspondent then takes a sheet of paper ruled with one hundred squares each way, and fills in the squares by the information we have sent him, he will have the complete picture—when he finishes.

Obviously this procedure is an exceedingly slow one, impossibly so if we desire to transmit pictures of moving objects. But it is satisfactory, with only moderate change, for the transmission of still pictures, or the art known as facsimile transmission. If for example, instead of transmitting numbers by telegraph code, we arrange the transmitter to send out an impulse once each second, let us say—one impulse for each of the little squares in sequence, and the strength of each impulse to correspond to the degree of light in the square it represents, we can send out a description of the picture in ten thousand seconds, or two and one-half hours. At the receiving end we will arrange a printing device to record each impulse in the same order and location which they had at the transmitter, and with an ink intensity corresponding to the current intensity of each impulse. Our chief problem will be that of synchronization between transmitter and receiver, that is the receiver must make its mark in square number one when the transmitter is describing number one, and so on coincidentally throughout the picture. This is the facsimile system, as used on wire and radio, and now in commercial service in various applications. In these services, the performance has been speeded up by several impulses each second, so that only ten minutes or so is required to transmit a picture, rather than two and a half hours mentioned in the simplified illustration.

We can notice, from this requirement of transmitting a simple still picture bit by bit until the whole scene has been covered, that the problem is very different from sound radio where only one thing, one sound, has to be transmitted. The facsimile art, that of transmitting single still pictures, has been developed extensively and well, so that very excellent pictures can be transmitted. Note, however, that a time of several minutes is required to accomplish the transmission of *one* picture.

Now, television, the transmission of moving scenes, really requires transmission of many pictures each second, enough so that, just as in motion pictures, the eye will be deceived by the succession of still pictures, into believing it sees a continuous scene.

The motion picture of today shows twenty-four different lantern slides each second, and that is what we have to accomplish in television, namely, transmit at least two dozen different pictures each second. In other words, we have to send out information about each little element of each picture, repeating the process many times each second. Remembering that the facsimile system takes ten minutes to send one picture, if we need say thirty pictures per second for television, we shall have to speed up the process of facsimile by eighteen thousand times to accomplish television.

There, in a nutshell, we have the primary cause of practically all the television engineering problems. It may be described as a requirement for transmitting an enormous amount of information very accurately in a very short space of time. Let us proceed to examine how it may be accomplished.

Of course we have only light to start with. Any object or scene is visible because of the light waves which reflect from it to the eye. We desire to catch these light beams in a device which will convert them into electric currents which we can use, in turn, to modulate or control the radio currents being fed into the transmitting antenna from a generator. Several ways are known by which to convert the light images to electricity. Two or three different ways were used in early television systems, but the modern system utilizes a device of outstanding superiority, and it is necessary to consider that one only. This device is called the "Iconoscope",* from the Greek meaning

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* Trade Mark Registered U. S. Patent Office.

"image observer". The "Iconoscope" in television corresponds to the microphone in sound transmission. Where the latter converts sound waves to electricity, the former converts light waves to electricity. The "Iconoscope" has two main parts. One is a plate upon which is focussed by ordinary optical means, the scene to be televised. This part corresponds exactly to the plate or film in a photographic camera. Its surface is covered, not with photographic emulsion, but with light-responsive, or photoelectric, cells. These cells are microscopic in size, but each is separate from the others, and each generates electric voltage when light strikes it, with the voltage being proportional to the strength of the light.

Therefore when a picture is focussed on this plate, with various parts of the picture at various degrees of brightness, those tiny cells having no light upon them generate no voltage, those with strong light generate strong voltage, and those with intermediate light generate intermediate values of voltage. It remains to collect these various voltages off of the plate in order to use them. To do this we might have a tiny wire brushing against the plate and sweeping with uniform strokes all over it, thus contacting the whole area bit by bit. But since we must sweep the plate so fast, and so many times per second, it is impossible to devise any mechanical system light enough to be so moved. So the "Iconoscope" utilizes a brush which has no material weight, namely a beam of electrons. The second main element of the "Iconoscope" is an arrangement for generating this small beam and directing it so that it falls upon the plate in one tiny spot. Other electric arrangements cause this spot to move all over the plate, in regular fashion, line by line. The present standard television system is designed to have 441 of these lines to cover the whole picture from top to bottom. The first systems had only 24 lines. It is clear that the picture will be more accurately reproduced, more capable of showing small details, the greater the number of lines. Also of course, the more lines there are, the more information about the picture must be transmitted in the same length of time, and this is more difficult. It has been a most important problem to determine the best number of lines to use, and in general to find the best compromise between the opposing factors of picture quality and apparatus difficulty. The value of 441 has been chosen after very careful study and experiment covering several years' time, and will be the standard value in this country.

Part I

The little electron "searchlight" beam, sweeping across the plate with its 441 regular brush strokes, acts just as a wire brush would, and collects electricity from the cells on the plate as it passes over them. It is interesting and import~~ing~~ to notice at this point that the scene being televised is focussed on the plate continuously, and therefore the cells receiving light are storing up electric charges continuously. The electron beam sweeping across the plate contacts with only one little spot of the plate at a time, which incidentally is smaller than a pinhead. After the beam has completed its travel all over the plate, that is after it has traversed all the 441 lines, it comes again to the same spot on the plate. Each time it comes to a spot, it collects the electricity which has been storing up there while the beam was travelling over the rest of the plate collecting from all the other spots.

So the electron beam is a collector, travelling over the plate in a regular pattern of lines, picking up electricity wherever there is any present, as there will be in places where light is present.

Now this electron beam originates in a simple part of the "Iconoscope" which is called the electron gun or cathode. The cathode is covered with certain chemical compounds which give off electrons when heated, and the cathode may be heated readily by current, just as is a lamp filament. Therefore the cathode is a part of the electron beam and if we connect the cathode and the plate to external apparatus, we can obtain the electricity which the beam collects from the plate having the light image upon it.

The electric currents which are obtained from the image plate by the electron beam are of course very small. But they can be fed into vacuum tube amplifiers and be amplified to useful proportions. When this is done, we will have currents carrying intelligence representing the light pictures, and these we will use to control the transmitter antenna current.

Now let us examine this scanning process again with an overall viewpoint. The scene to be televised is focussed upon the "Iconoscope" plate. The plate is continuously being explored by an electron beam, about the size of a pin, which sweeps across it in regular lines, taking 441 lines to cover the picture from top to bottom. The time required to sweep the whole picture is made such that the process can be repeated thirty times per second. In other words, every spot of the picture is visited by the collecting beam, thirty times per second. And there are about a quarter of a million spots on the picture to be thus visited! Undoubtedly the busiest thing in the world is this electron beam as it scans the picture, flying back and forth at a speed of several miles per second, and collecting the current, so to speak, at each tiny spot of its path.

In short, we have a system which is operating to pick up scenes a spot at a time, but covering spots so quickly, and the whole scene over and over so many times a second, that if we arrange a reproducing system to act in reverse fashion to that described, and to deliver light images corresponding to the spot currents, our very slow human senses will not follow the details of the process, and will perceive only the average total result, which is the complete picture.

We have now "scanned" the process of television transmission, perhaps almost as rapidly as the "Iconoscope" scans a picture, and of course we have lightly passed over many engineering problems. It will be of interest to list at least some of them.

First the "Iconoscope" must have sufficient sensitivity, that is, it must be able to generate electric currents from small light intensites falling upon it. The latest forms have developed sensitivity to equal that of the photographic camera and film, so that any scene which can be photographed by snapshot, can be televised.

Also, the "Iconoscope" must be free from color-blindness. Present "Iconoscopes" are sensitive to all colors, and in fact to the invisible parts of the light spectrum as well as the visible. As a result, interesting applications are possible for purposes other than television, and utilizing ultra-violet and infra-red rays.

We have referred repeatedly to movements of the electron beam over the image plate. Of course its travel sideways and up and down is not inherent, or voluntary, and must be caused and controlled. To do this, coils are located outside the tube, and magnetic fields from these coils move the beam as desired because the beam responds to magnetic forces. The nature of the currents in the coils and the physical location of the coils determine how the beam will move. The proper kinds of currents are provided from oscillating vacuum tubes and so-called deflection circuits. These currents, which are at the transmitter, will also be used to control a similar beam at the receiver, as we shall see later.

An interesting problem in the "Iconoscope" is that which may be described crudely as that of cleaning away the electrons in the electron beam after they have been used. The electron beam is playing upon the plate like a fire-hose, and some of the electrons are splashing off into the space in front of the plate, where they may gather in clouds. They must be cleared away for each fresh scanning of the plate, or the picture will be clouded or blurred.

The electric currents mentioned so frequently are alternating currents, flowing back and forth millions of times per second. Many of the most difficult problems of television result from the fact that such rapid reversals, or such high frequency currents, have to be used. Ordinarily we think of electricity as being instantaneous. Actually it is not, but has a finite speed of about 186,000 miles per second. So that when we call upon a current to travel even a few feet only, but to turn around and reverse itself, and repeat this millions of times per second, we begin to encounter limitations even in the speed of electricity. This situation is so real that a copper rod four or five feet long, which is a practically perfect conductor for current at low frequencies, under some conditions acts like an insulator when the current is at frequencies of millions per second. Since we have to make and connect up our television apparatus with wires hundreds of feet long, it is obvious that expedients and special conditions must be provided to enable the currents to behave as we want them to.

These tremendously high frequencies are forced upon us because we are trying to crowd so much information into each interval of time, much more than we need to with sound broadcasting, or telegraphy, or even facsimile.

The unusually high frequencies give rise to new problems in the really wireless part of the system, that is the medium between the transmitting and receiving stations. Everyone is familiar with the conditions existing in sound broadcasting and knows that the quality of service received depends upon the power of the transmitter, the distance between transmitter and receiver, and the degree of static or other interfering noise present in the receiving neighborhood. With the higher frequencies used for television, the same factors are present, but in different ways and degrees. The television frequencies are so high that the waves approach in behavior that of light waves. It will be remembered, of course, that there is no difference in character between light waves, heat waves, ultra violet rays, X-rays, radio waves, except that of frequency. All are disturbances in space of the same character, and differ only in frequency. We are accustomed to ordinary radio waves going around the curvature of the earth, over and behind mountains, through buildings and so on. But radio waves at television frequencies, behaving more like light, act somewhat as does a powerful searchlight. They do not follow the earth's curvature very well, or go behind a mountain, or through a building. Therefore they are more limited by obstacles on the earth's surface, and conversely, the transmission will be more effective, the higher the antennas are located. It is for this reason that the Radio Corporation has located its New York experimental transmitting antenna on top of the Empire State Building. Similarly, better reception is had by locating the receiving antenna as high as possible, and when television does come to the home, it will be found advantageous in most cases, to put a good antenna on the roof, rather than a wire on the base board in the living room.

Very fortunately, there is little natural static on television frequencies. Unfortunately, there is considerable disturbance from certain man-made devices, especially automobiles (from their ignition systems) and certain electro-medical devices. This can be eliminated readily, however, and no doubt will be eliminated when necessary.

The propagation characteristics of the medium and the interferences existent, chiefly determine the distances over which reception may be effected. The tests now being carried on by the Radio Corporation indicate that with an antenna as high as the Empire State Building, satisfactory reception can be had to distances somewhere between twenty-five and fifty miles. Of course, there will be some locations at less than twenty-five miles, having especially bad conditions, where reception may not be good, and there may be a few high locations more than fifty miles away which will be able to receive. But, in general, it may be observed that the service area of a television station is limited, in comparison with the areas of sound broadcasting stations as we now have them.

This condition results in a television engineering problem of the greatest magnitude, and one with profound economic influence on the television problem as a whole. The service area of a station is small because the frequencies required for television are extremely high. Just as it is difficult to make these high frequencies travel far through space, so is it difficult to make them travel far over wires. Consequently the television studio must be located close to the television transmitter and antenna. This means that we cannot utilize the simple effective method used in sound broadcasting of conducting a single studio performance in one city, and radiating its program from scores of radio stations scattered over the country, all connected to the studio by wire telephone circuits. At present, a television program is confined to the area around the orginating studio, and its audience can be only that within that area.

Obviously the expense of providing programs to the nation is vastly greater. In sound broadcasting, one performance on a nation-wide network of stations, reaches the whole country. To cover the country with a television program, with present technique, would require repetition of the program a thousand times, from a thousand studios.

Of course, a great deal of work has been done on this vital problem, and good reason exists for hopes of speedy solution. Wires of special kind which will be capable of carrying the high television frequencies are being developed. Radio circuits to carry them long distances by means of short distance relays are also being developed. Undoubtedly one method or the other, or both, will eventually be perfected so that a performance in one city can be transmitted to other cities, just as sound is now.

While on the subject of program expense, there is another aspect which is sometimes overlooked, in the comparison of television and sound broadcasting. In the latter, sound is all-important, and nothing else has to be considered. In television, not only is sound required, but the added visual problem corresponds to that of making a sound motion picture. Scenery, special lighting, and costumes are required, actors must be letter perfect in their parts—and retakes are not possible. This means that the more economical types of program will be those where artificial aids are minimized—for example, the football game, or news events generally.

So far, we have not considered the receiver specifically. That, to most people, is the most interesting part of the system. It seems to be the focal point of the thrill and mystery in "pictures from the air". So let us now consider the receiver, but let us do so with clear understanding that it is only part of a *system*, and that it must have and maintain an intimate, accurate relationship to the rest of the system.

The television receiver antenna is energized by the travelling waves, which cause corresponding currents to flow from the antenna to the receiver. The receiver is tuned to the particular frequencies to be received in order to maximize the ones desired, and to minimize undesired ones, just as in a sound receiver. These currents, even when tuned in to maximum, are very small, and are fed into vacuum tubes to be amplified. After this operation they are large enough to operate a device designed to convert them into light images. This device is called the "Kinescope",* and is the inverse of the "Iconoscope". The "Kinescope" has a plate and a beam of electrons playing upon it, just as does the "Iconoscope". In the "Kinescope", however, the plate, or screen, is made differently, in fact it is one end of the tube itself, made nearly flat, and coated on the inside with a very thin layer of material which has the property of fluorescing, or giving off light, whenever electrons strike it. Some fluorescent materials will glow for a considerable time after being struck by electrons. The particular compound used for "Kinescopes" is chosen so that the glow dies out shortly after the electrons beam moves away, and before it returns again.

The tiny electron beam in the "Kinescope", whenever it is not moving and therefore strikes the screen in one spot, causes a bright glowing spot on the screen at the point of contact. This spot is about the size of a pinhead. Although the glow is really on the inside of the tube, it is visible on the outside because the end of the tube is clear glass, and the screen of fluorescent material is very thin. The brightness of the spot depends upon the strength of the electron beam, and varies as the strength of the beam is varied. That spot of light is used to reproduce each spot of the picture, one at a time, by moving it around all over the picture area. It must be moved in exactly the same way that the "Iconoscope" beam at the transmitter is moved, which in modern systems is in horizontal parallel lines from top to bottom. So this beam will be very, very busy too. It is going to move all over the picture in regular fashion, and repeat the travel thirty times per second. Furthermore, while moving, it is going to vary in brightness continually as it "paints" the lights and shadows of each tiny element of the picture. To our slowly reacting human eyes, the *spot* will not be visible because it is moving so rapidly, and the screen will appear to be illuminated evenly all over the picture area, but we must remember that actually the light and the scenes are caused by one tiny spot of light, flying over the screen, and varying in brightness as it goes.

Much of the receiver apparatus is for controlling the movements of the beam, and feeding to it the currents which have been received from the transmitter, in order to vary the strength

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of the beam and therefore the brightness of the flying spot. Of course there are many engineering problems associated with this apparatus. The most interesting ones are those associated with what is called "synchronization", or the necessity of keeping the flying beam of the "Kinescope" in perfect step with the flying beam of the "Iconoscope", even though they may be miles apart with only a tenuous radio connection between. Obviously these two must be kept together very accurately, even though they are moving very rapidly over the picture. It would not do at all to have the beam at the transmitter picking up the sparkle of highlight in the eye of the beautiful television lady artist, while the receiver beam was working where her nose was supposed to be.

The object to be attained may be stated simply. It is merely that the electron beams of the "Iconoscope" and the "Kinescope" are to be kept in perfect step with each other. Each is to travel across its plate or screen in horizontal lines. Each is to start at the upper left corner let us say, move across the first or top line at the proper speed, quickly jump back to the left and start on the second line just below the first line, complete that, jump back for the third, and so on until it has covered all 441 lines, finishing at the lower right corner. Then it must jump up to the upper left corner and begin again on the top line. Perhaps we should note here that the method of scanning actually used in modern systems does not move the spot in quite such a simple regular fashion, but has a more complex movement such as doing lines alternately, all the odd-numbered ones first, and then the even-numbered ones. This is known as "interlaced scanning" and provides several important technical refinements and benefits. It is not necessary to study this more complex method, however, to understand the basic fundamentals of the system, and we may assume that the beam travels over the picture from top to bottom, line after line progressively.

The beams in each case are made to move by magnetic fields produced by currents in coils mounted on the sides of the "Iconoscope" and "Kinescope". If the right currents are fed into these coils at the right times, the beams will move as desired. The currents can be obtained from vacuum tubes arranged as oscillators, but one beam is at the transmitter and one is at the receiver miles away. We must have these oscillators working absolutely together—because if they deliver their currents out of step by even as little as one one-millionth part of a second, the reproduced image will have no likeness to the original. So they must be tied together somehow. At present this is accomplished by making the generators of currents at the transmitter into masters of the situation. They are arranged to send out short timing signals, called synchronizing signals, and there are two of them, one for keeping the beams together horizontally, and one for keeping them together vertically. These signals are additional to the picture signals, so that a television transmitter sends out three different signals, one describing the picture, and two to keep the beams in step horizontally and vertically. Of course if they were all sent out simultaneously they would interfere with each other. Therefore the synchronizing signals are sent out very quickly during the short time intervals when the beams are not being used for the picture, but are occupied in jumping back from right to left preparatory to starting a new line of the picture. This means, in effect, that each receiver of all those which may be "looking-in", is continuously receiving instructions and assistance, from the transmitter, by means of which it is enabled to keep its "Kinescope" picture beam exactly in step with the scanning beam at the transmitter.

Synchronization is one of the television problems which has been solved, and it is a considerable triumph that we are able to control apparatus at a distance with a precision measured in fractional millionths of a second.

A problem of receivers in process of solution is that introduced by the necessity of making them so that they can be operated and adjusted satisfactorily by the general public without their having to take an educational course in television engineering. The television receiver is a complex instrument, far more so than present sound receivers. It includes a complete sound receiver to start with, to receive the sound which accompanies the picture. Beyond that are the circuits and tubes which tune and amplify the picture signals, the circuits and tubes which tune, amplify and utilize the two synchronizing signals, and the "Kinescope" tube with its associated circuits. Many correct adjustments must be made before the picture can be viewed, and if too many of these are required of the operator, or those required are too critical, it will be impossible for the layman to operate the receiver satisfactorily. Therefore most of the adjustments must be accomplished automatically, and only a few left to the operator. This makes the receiver design more difficult of course, but the status of progress toward solution is such today that it is possible to promise that when television receivers are put into public use, they will be sufficiently simple in operational requirements.

A problem always noticed by the layman, is that of size of the reproduced picture at the receiver. At present there are two standard sizes, one about five by seven inches, and the other about seven by ten inches. Scenes of any size can be televised by the transmitter merely by using the appropriate optical lens to focus them on the "Iconoscope". At the receiver, the size of the picture is determined definitely by the size of the screen on the end of the "Kinescope". There is a limit of physical size beyond which it is impracticable either to build these tubes, or to house them in cabinets of reasonable size for the home. It seems to be general experience that the most desirable size of picture for television or motion pictures, is that where the height is about one-fourth the distance between the screen and the observer. Such a size seems to give the maximum of realism or emotional appeal. In the home, the desirable viewing distance is at least eight or ten feet, so that the picture height should preferably be at least two feet. There is good promise of eventual accomplishment of this goal, but at present it seems probable that the television receiver which is "just around the corner", will have a picture about seven by ten inches. Often it is asked why this picture cannot be increased simply by optical means, with a lens to magnify it several times. This could be done insofar as size is concerned, but the brightness of the picture would suffer in proportion, or actually even more than in proportion, and the original amount of light available from the fluorescent screen is not enough to permit so much spreading out.

This matter is perhaps the most serious problem of television, at least from the user's viewpoint, but since it is true that the resources of Nature are infinite, and that we have only to find the way which exists somewhere, it seems definite that sooner or later even this difficult problem will be solved.

And now we have traversed the system, from the beginning where we had only imponderable light waves picked up and focussed by a camera lens, to the "Kinescope" screen, where the well-regimented electrons of a beam have produced an image on a fluorescent screen. A summary of the major problems encountered appears to be in order and may furnish an appropriate conclusion to this discussion.

Foremost among the problems is that of standardization. We have seen how intimately related the transmitter and receiver must be. Consequently many receiver design features and many transmitter design features must be definitely related, and this must obtain whether the apparatus is manufactured by one or any number of manufacturers. In sound receivers, this difficulty does not exist, and any receiver built by any manufacturer, readily receives any station built by any manufacturer, with very little coordination. In television, many factors must be chosen, standardized, adopted, and maintained by all concerned, or the result will be—no picture. If wrong choices were made, the art would be permanently handicapped. Therefore it has been necessary to proceed cautiously, and to make certain that decisions would stand the test of time.

The next most serious problems have been in the development of devices which would convert light to electricity and electricity back to light, in easily and accurately controllable fashion. The "Iconoscope" and the "Kinescope" have answered this need, but studies and experiments to improve them will continue.

The necessity of transmitting so much information in so short time, in order to describe moving pictures electrically, has compelled the use of very high frequency currents and radio waves, much higher than used in previous radio services. This has required development of new tubes and circuits to generate, amplify, and control them. It has required the study of their behavior in space, so that we could know how far and with what results, these new waves would travel.

The problem of synchronizing the receiver with the transmitter has been difficult. It has been solved, but to obtain the solution has required extraordinary amounts of research, patience, ingenuity, time and money.

The problem of network connection of stations, to permit syndication of a program, remains to be solved. Various problems of economic sort having to do with location and cost of stations, and programs, are dependent upon this technical problem.

The problem of increasing the size of the reproduced picture in the receiver is still with us. We expect to solve it, and we probably will. But if we do not, we may well be grateful and content that clear vision of distant events has been given to us, even if not quite as conveniently sized as we might like.

There is one problem which is not an engineering one, strictly speaking, although there is close mutual dependence between it and technical developments. This is the program or studio requirement. No matter how excellent the technical facilities may be, the whole system is a loss if those things put before the "Iconoscope" are not interesting to the watchers at the "Kinescope". Whenever a new technical service is provided, time is required to find out how to use it. Its strong points and its weak points have to be discovered by experience—the former capitalized and the latter avoided. If television had come to a world which knew nothing of sound broadcasting or of motion pictures, any kind of program material, no matter how poor, would have been acceptable initially, and improvement in program to good standards might have been allowed to take considerable time. But television will come to a world already accustomed to reproduction of sound and pictures having very high program excellence and effectiveness. If the television receiver is to have interest longer than a few days after its purchase, the program it delivers must supply the interest. Therefore it is necessary to solve the studio problems of television—the lighting, make-up, costuming, scenery, scenarios, actors, and all the rest—before television can be made a public service.

Questions are often asked concerning the possible effect of television upon sound broadcasting and sound motion pictures. The answer is simple and the gift of prophecy is not needed in order to be able to make it. The answer is apparent from the outcome of many similar situations in the past. The telephone did not supplant the telegraph, it supplemented it. We still have messages to transmit which do not require person to person conversation. The telegraph cannot serve as telephone, but neither can the telephone do things which the telegraph can.

Similarly, sound broadcasting did not ruin the theater and the motion picture. Instead it added to their appeal and their profits. At first there were many fears. Opera managers would not permit performances to be broadcast. Boxing promoters would not permit their fights to be heard over the air. But after things settled down, the actual results were—the million dollar boxing gate, the S.R.O. sign in opera houses, the addition of sound to the motion picture, increased public interest in the theater generally.

And so it will be with television, no matter how excellently that develops in years to come. There will be some things which television can do which previous arts could not do, a few things which it can do better than can they, but there will be many things which they can continue to do which television cannot do at all. So they will continue, and we shall have added another art and public service to the continually growing list. As a matter of fact, rather than being harmed by television, many of the older services are going to be helped, just as the silent motion picture was enabled by radio sound apparatus to find its voice and expand its possibilities. The older arts will find much help from the gadgets of television, should therefore welcome it, and need not fear it.

Only one problem remains to mention. It is one which is encountered by television workers more frequently than any other. It is the question "When will we have television?" That is one problem which has *not* been solved! A simple answer is not possible, because the question is not simple without several definitions. We have television right *now*, under the definition of technical possibility. We will probably have it in a year or two if we limit the definition to include only those people who live within a few miles of a station, with only two or three stations in the country. However, if we mean when will television service be available to most of the people of the country, it seems safe to say that the years between then and now will be goodly in number.

COMMERCIAL TELEVISION — AND ITS NEEDS

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IT HAS been well said that anyone may be excused for making some mistakes, at least once — but that only a fool continues to make the same mistakes in the face of past experience. We in the radio industry cannot assert that we have made no mistakes in the past; despite the fine growth of the industry and its genuine contribution to our national life, there has been much friction and lost motion. And we now face a complicated situation in the case of television broadcasting which seems to impend. Shall we plunge wildly forward, substituting enthusiasm for analysis? Or shall we remain calm in our planning and activities, leaving the excitement to the properly persuasive advertisements of television receivers and programs, to the active salesmen, and to the delighted lookers and listeners in the home? With the confused past of radio in mind, shall we "try everything"—not once, but twice? Of shall we do as little "muddling through" as is humanly possible?

Commercial television broadcasting, to win general public acceptance and to enjoy a healthy growth, must be built on the basis of a group of necessary elements. These are a constructive Governmental attitude implemented by corresponding regulation, an active group of television broadcasting stations at least partly interconnected into national networks for program syndication, forward-looking program-building organizations, careful engineering and manufacturing methods rendered effective by suitable merchandising practices and satisfactory servicing, an enthusiastic and numerous group of home lookers, and finally a number of broadcast advertisers willing and able to secure the part-time attention of the home audience. To just the extent that any of these elements are missing from the television picture, the day of widespread public acceptance of television-telephone broadcasting will be delayed and the success of the radio industry reduced.

We believe that optimism for the future of television is well-founded, but we do not believe that the full measure of its success is attainable automatically and without at least some careful planning. Looking back on some of the shortcomings and mistakes of the past, we venture to hope that the future will bring the avoidance of at least some familiar and unnecessary errors. Accordingly it seems in order to study in more detail each of the elements of television success just mentioned, and to sketch the general outlines of the "paths to glory".

At the present time, the policy of the Government of the United States toward the development of television broadcasting is expressed through the radio laws passed by Congress and the regulations promulgated and decisions made under the authority of these laws by the Federal Communications Commission (and, in some cases, by affirming or reversing courts of appeal). It is stimulating to note that the Commission is evidently considering the needs of television broadcasting in an orderly and serious manner, and it is to be hoped that the decisions of the Commission in this field will be both generous and firm. To encourage the development of a new national industry is surely in accord with the spirit and needs of the times. One of the problems under consideration is that of television standards. It is neither easy nor economic, under known methods, to change television receivers from adaptability to a certain transmission to adaptability to a different transmission standard. In this respect television differs markedly—and unfortunately—from telephony; and this factor cannot be neglected in planning for television acceptance. It becomes necessary, from the very commercial beginning, to establish standards which have every likelihood of being satisfactory to the public for a long period of years in order to avoid speedy obsolescence of these early television receivers in the higher price ranges with consequent general dissatisfaction and loss of confidence. This is one case where we must "aim high" regardless of temptation to "cut corners". As we have repeatedly pointed out, the criterion of any television service is its continuing entertainment value; and it is now the consensus of more informed opinion that this specification requires pictures having of the order of 400 lines or more. Particularly is this the case if the pictures are to be increased in size from their present modest dimensions; and we do not doubt that such an increase will in due course be found commercially feasible. Another group of standards, in addition to the basic requirements of band width and ultra-high-frequency allocations, deals with picture repetition rate, scanning method, aspect of ratio, and synchronizing methods. Here again, the regulatory authorities will be well advised to require any essential uniformity even at the cost of some inconvenience to individual groups and in the interests of the general public.

In carrying out its tasks, the Commission will face the problem of allocating individual frequency bands for television to particular organizations in certain localities. For example, the question may arise: to whom shall be assigned, upon application, the available ultra-high-frequency bands in a given city for use in television broadcasting? There may well be numerous claimants actuated by a wide variety of motives. Some will desire to carry out a scientific experiment; others a commercial venture. Some will be highly experienced in broadcasting; others may be ambitious newcomers seeking a meteoric career in the television field. Some will have extensive technical and program background, while others will lack interest in the engineering and entertainment aspects of station operation. Much wisdom and restraint will be required of any regulatory body which faces the necessity for such decisions as are implied in the foregoing. We may venture the general suggestions that television broadcasting allocations should be granted to those who are best qualified by parallel experience, by technical and other resources, and who are most likely in the long run to keep abreast of engineering and program progress and the most modern operating methods. It is not our belief that, on the average, television broadcasting could be better handled by those who have had no previous experience with telephone broadcasting than by those who have carried the burdens and enjoyed the privileges of our present broadcasting system for many years. Nor do we see any compelling considerations in favor of granting television broadcasting priorities to expanding groups in the entertainment, news-disseminating, or advertising fields. It is more reasonable to expect that the healthy development of television and the solution of its highly specialised problems will result from an independent broadcasting industry rather than from a group of by-product activities of other (and seemingly competitive) industries. Accordingly it is urged that, in a reasonable time, there be granted the necessary allocations to qualified applicants for local transmitting rights in the commercial television broadcasting field.

In developing television broadcasting, it is necessary dispassionately to consider the best way of reaching a multitude of homes with program material of continuing interest. On one side of the ledger—the expense side—we find the cost of the transmitting facilities and of their operation together with the cost of creating the programs and syndicating them. It is a truism that the more persons reached effectively by a given program of quality, the clearer the justification for that program and its cost and the greater the likelihood that there will be a continuance of programs of like quality. We face then the dominant factor of the *program cost per listener.* This is the Sphinx at which every broadcaster thoughtfully stares, awaiting an answer to his questions. When it is considered that qualified artists, authors, arrangers, and directors are relatively shy and rare birds found in few localities (and therefore purchaseable only at a price) but that the audience is widely scattered, it again becomes evident that the only known way of reducing program-delivery cost per listener (which is another way of saying: increasing program quality per listener) is by program syndication. We are not here discussing the relative merits of various methods of total or partial syndication of programs such as transcriptions on wax or film, circulation of performers by road-shows, wireline or coaxial-cable interconnection of stations, and connection by radio relay systems. Nor yet are we considering the commercial and administrative aspects and problems of net work operation. We wish only to emphasize that syndication is of the essence of high-quality and stable television broadcasting and that it merits aid and support from all who are genuinely interested in the commercial success of that art.

Another nation-wide problem is that of avoidable man-made interference with radio reception. Like the poor, we have always had this electrical enigma facing us. An excellent beginning has been made in tackling this problem by the recently organized Sectional Committee on Radio-Electrical Coordination of the American Standards Association. But television broadcasting will be radiated in an unusually vulnerable region, namely the ultra-high frequencies. Automobile ignition systems and similar sources can superimpose on the television picture the perpetual twinkling of a myriad of stars—an effect as startling as it is unwelcome. There is a trend in some quarters to suggest legislation and resulting Commission action in the abatement of this trouble. One need not accept nor reject this suggestion in making the statement that, in one way or another, interference with satisfactory television reception at reasonable signal levels and for proper home installations *must* be accomplished. The prophecy can also safely be made that it *will* be accomplished since millions of otherwise embattled lookers (who happen also to be voters) will receive friendly consideration by prudent powers that be.

It is fortunate for television development that one of the ancient and popular fallacies of broadcasting—namely, the opposition to high-power, so called, in transmission—has largely had its day and been relegated in the main to the dust pile of forgotten errors. We can well remember the learned gentleman who, little more than a decade ago, hotly informed a gaping radio conference that no one needed a higher transmitting power that the half-kilowatt of his own station; and who justified this by stating that he had "national coverage" as evidenced in the form of letters from most states of the Union where listeners had heard his station! Were this gentleman dead—which we are happy to say he is not—he would undoubtedly turn in his grave at the solemn proposal to limit the power of a certain class of broadcasting stations to *not less than 50 kilowatts* with the hope that 500 kilowatts will be widely used. Thus we may expect that powers of tens of kilowatts or more for television stations in the larger cities will be taken as a matter of course and wisely regarded as the boon to good service which such stations actually are. In this regard, at least, the Commission inherits a well-ploughed and fertile field.

Any reviewer of television needs would be but too happy to find no occasion to mention such matters as the briefness of assured tenure of television licenses, on the one hand, and the apparent occasional interaction of governmental action and political considerations on the other hand. Yet the picture would not be complete were these factors to be omitted nor would justice to the future television audience be done. We believe that few men would be willing to build a home or erect a factory if their leasehold were limited to uncertain successive six-month periods. Particularly would this be the case if there were much of pioneering and risk in their building activities. Those who bravely enter into television development in these parlous times are entitled to friendly consideration and no little encouragement. We submit the thought that it will be a stimulant to television development to relieve those who enter it from the parallel and non-profitable activity of prosecuting applications for license renewals in a steady stream and to permit them to bring a peaceful and unapprehensive mind to bear on their major (and sufficiently difficult) problems of providing good television service. A considerable extension of the license period for broadcasting would be a genuine contribution to the development of that field.

Insofar as broad questions of the public welfare are involved in legislation, regulation, and external administration of radio broadcasting, the influence of the statesman and legislator is to be sought. But whenever questions of complicated technical nature, of internal administration, and of detailed planning are before the Commission or the broadcasters, we have little expectation of real assistance from politicians. Broadcasting has been an effective means for bringing the views of the political leaders of this country to their constituencies. Enlightened self-interest will prompt a corresponding policy of non-interference with television development on their part or disregard of attempted interference.

The second necessary element for television success is a group of well-constructed and capably managed transmitting stations with a suitable measure of interconnection for program syndication. It is thus incumbent on the present-day broadcasters and networks to take up the burden of establishing the necessary facilities. Only by so doing can they hope to assume that position in the future television set-up to which they appear normally entitled. That television will come can hardly be doubted. If it does not come through an expansion of the facilities of those now engaged in telephone broadcasting, it will come through the enterprise of others—and, as we have previously indicated. this is not in our opinion a desirable process of evolution so far as a healthy and normal growth of television is concerned.

It is necessary that there shall be available transmitters and studio equipment of suitable powers for various localities —and it is fair to assume that the manufacturers of such equipment will make it available as soon as their own tests of sample models shall have inspired confidence in the performance of the available equipment. The engineers are now a part of a great movement in the direction of commercializing television, and any engineer who is giving his best efforts to the improvement of transmitting or receiving equipment of that type is taking his earned place abreast of the radio pioneers of the past. The manufacturing of transmitting equipment will also do well to remember that the initial impressions of the public will largely depend on the quality of the transmissions, and that the best that can be produced will probably be none too good. Let there be no casual or careless transmitter production for television, in the interest of the entire industry as well as the public.

We have noticed with some concern what is, in the last analysis, an occasional and largely meaningless friction between the so-called local stations and the networks. As well might the hand object to the arm. Networks and outlet stations are an organic unit, and each equally needs the other. Stations not connected to any network render a related and parallel service. Dissension in these quarters represents merely an army divided within itself and thus facing combat with less chance of winning. To some extent, every entertainment industry tries to secure its share of the attention and leisure time of the public. Those industries which overlook small jealousies or fancied advantages in the interests of general advance will make the best public showing; and this is always reflected in that grim index of public acceptance: the balance sheet. For this reason the growth of cordial relations within the broadcasting groups is greatly to be desired; and we feel fairly confident that common sense will triumph to that effect. Then, too, if television broadcasters desire due consideration to be paid by legislators to their views, they must not present the unsavoury spectacle of a house quarreling within itself and speaking only through an angry babel of conflicting voices. The broadcasting organizations should rise to this opportunity to speak for all and with approval from all, on a basis so broad and farseeing that they will compel the attention and win the acquiescence of reasonable men.

No one can long study television broadcasting without becoming somewhat concerned as to the mode of program-department organization and the subsequent production of the necessary program material. The need for progressive program-creating groups in television broadcasting will be great indeed. On any reasonable standard of appearance and performance, it is clear that there are not available in clamoring throngs the necessary regiments of satisfactory performing artists for the new field. The stage and screen have preëmpted (at substantial cost) those who are judged most worthy of winning public favor through their appearance and performance. In the radio field, performance only (and that in the restricted range of sound) has hitherto been the sole criterion of artist success. Now the requirements broaden—but the supply of available talent does not. There should be a host of opportunities for a new generation of artists having "television personalities"—and what is the basis of such personalities, only time and experience will disclose. The grist to the artists' mill may well be numbered in tens of thousands of candidates; the chaff in thousands; and the finely winnowed grain in hundreds. Yet only along this hard road can be found those who will successfully face the public on the television screen.

Radio telephone broadcasting evolved, as an entertainment enterprise, in a curiously segregated fashion. Its relationships with other branches of the entertainment field have mostly been conspicuous by their absence. The phonograph, the disc record, the legitimate stage, the motion picture studio and theater, musicians, authors, copyright owners, actors, instrumentalities and soloists have all been involved in radio development in one way or another, but he would be bold who would say that radio had made the most of its contacts with these fields or that the relationships which existed were, in the main, more than haphazard and occasionally unhappy. Television broadcasting faces similar, but even more complicated and trying situations in this regard. and it would be well to remember that disregard or hostility, together with non-cooperation, rarely accomplish much. This thought applies, of course, not only to the radio facet of the situation, but to all the other interests involved. We have particularly in mind that the motion picture field (which, in our opinion, has little to fear from television broadcasting if it maintains a forward-looking outlook and is well guided), will have methods aid output which can be somewhat adapted to the needs of a certain part of television procedure. Television can, in turn place at the disposal of the motion picture industry certain new methods and devices which should be useful. Certainly the relationship between these sister arts could and should be pleasant and mutually helpful, in the best interests of each.

At this point we urge that television broadcasting adopt the desirable practice of totally excluding the public from actual attendance at all rehearsals and broadcast events in the studio. It must be remembered that broadcasting aims to serve the millions of its radio audience in the home. It should not be so necessary to stress that it is not properly a mode of amusing the advertising sponsor (who should have other and more practical aims) nor yet of entertaining the client's advertising agency. There is no question that the program timing and the methods of production suffers when a compromise between the home audience and the studio audience is adopted.

It is also well known in the entertainment field that the illusion is spoiled when the audience "sees the wheels go round". What stage magician would show the audience how he performs his tricks? What great dramatic company on the stage would invite the audience to watch the scenery being shifted and to inspect the prompter at his work? Even the concert soloist keeps himself in desirable seclusion until the moment comes for him to step upon the stage. The motion picture industry has well realized this and has practically closed its studios to the public. This wise measure might well be adopted by television broadcasters who are in a similar position as regards entertainment possibilities.

There are other incidental advantages in the elimination of the studio audience. Annoyance resulting from alleged competition with theaters, and the municipal licensing problems which accompany theater operation would be eliminated. Economy in operation is effected and greater freedom in procedure without interference. The mixture of film sequences and personal performances is more readily developed. The locating of television studios is simplified when only the home audience need be considered, and the studio arrangements and facilities will be more efficient and cost considerably less. Then, too, the rapid switching from one studio to another or the introduction of long or short motion picture subjects into the program can be carried out without worrying about the supposed reaction on the visitors to the studio.

Speaking frankly, we realize that building studios for home audiences only, conducting them in a practical, modest, and businesslike way, and retaining the illusion and consequent enjoyment of the home audience will involve some sacrifice of vanity on the part of client, agency, and broadcaster alike. But, as has been said, the entertainer is a vendor of illusion and a seller of glamor—or else he is nothing. Why then should he deliberately destroy part of his stock in trade? We have often heard persons who have just left a studio broadcast protest that they would not enjoy radio nearly so much now that they had seen the way in which program matters were actually handled or had a clearer picture of their favorite and previously idealized performer. We have listened to the annoyed protest of those who conduct broadcasting and who are compelled to go through useless motions and elaborate procedure for the hundreds in the studio in disregard of the millions in the home. Let television broadcasting, at least, be democratic and devote its efficient, concentrated, and exclusive attention to the home audiences who purchase the receivers, who watch the performances and who give television broadcasting its very life.

So far as the commercial leaders and engineers of the radio manufacturing industry are concerned, their tasks in the new television field will be heavy indeed. Every mistake or omission of the past should be carefully remembered and as sedulously avoided in the future. If the industry elects to make a "breadboard model" of a television receiver one day and to turn out allegedly commercial manufactured product immediately thereafter, without adequate field tests and painstaking engineering study and improvement in the interim, the public will gain an unfavorable impression of the quality, performance, and returns of the resulting product. It is hardly possible to devote too much care to the engineering design and test of the first large group of television receivers which the public purchases. A negative first impression at this point will take years to eradicate. And in such engineering work, let us remember that, although the skilled technician can handle a multiplicity of new, complicated, and delicate adjustments, the average tired man or woman at home neither can nor will go to the trouble of learning how to juggle a small-scale switchboard nor expend the time and effort necessary to continue to use the electrical cross-word which is thus presented. In other words, the engineers must be "home-minded" and leave the rarefied air of high but complicated technical achievement to come down to the lower and safer levels of simplicity and comfort in the use of television receivers.

Television comes into the world at a time when its nearest relatives have grown to maturity. For a relatively small sum, the public can see large, clear, and well-planned sound-motion pictures in impressive surroundings and under favorable physical and psychological conditions of presentation. In the home, not all the conditions are so favorable. Noise, stray light, interruptions both natural and man-made, inadequate seating arrangements for the audience and the like must be anticipated. Thus, we need the brightest, sharpest, and largest picture which can be economically and technically produced; and we must continue to improve the picture (and sound) in these regards as time goes on to hold public favor.

Further, it would be a wise investment to enlarge markedly the testing and supervisory force in factories devoted to television receiver manufacture. At best these new devices must be expected to develop unexpected troubles; and it is far better to discover these in the comparative privacy of the factory test than in the glaring spotlight of public indignation. Then, too, it will not be enough for the receiver to work as it leaves the factory. Every part should be carefully studied to make sure that it will stand up. It must be remembered that skilled television service men will not be too plentiful for the first months or years of television commercialization; and a dark television screen is as unattractive to the purchaser as a silent loud speaker.

We may presume that television circuits and models will naturally change fairly rapidly during the years of the introduction of television on a large scale to the public. This being the case, it is inadvisable further to complicate the commercial situation by exaggerating this tendency through the deliberate introduction of inconsequential or even imaginary "improvements", so-called, in reasonably satisfactory receiver models. A firm hand will be required on the commercial helm in this regard in every television-receiver factory. We must not be misinterpreted as regarding the early introduction of an actual and marked improvement as undesirable; we mean rather than we urge that television manufacture be not made the "happy hunting ground" of mere "gadgeteers".

Since, as has been mentioned, the quality of the television image can be affected by man-made static, associations of radio manufacturers should give every possible aid and encouragement to any groups that aim to reduce such interference. Information on installations, interference-reducing devices and methods, and cooperation with the automotive industry and the makers of diathermal equipment are matters of concern to the manufacturers. To the extent that these are handled and funds for their prosecution made available, the advent of wide-spread television sales will be hastened.

The service problem for television should not be left to grow at random as it largely did until recently in the case of present-day broadcasting. Training of service men by the manufacturers, radio schools, and associations of service men are notably in order. Since it wil probably take a fair time to train a man to locate trouble in so elaborate a device as a television-telephone receiver and then to repair the fault, early consideration should be given to this need for training.

We have noticed without pleasure or approval some of the published material of a rather wild sort dealing with television. The implication of such sensational statements is that the fortunate owner of a cheap television receiver, seated in a comfortable armchair in his home, will touch a button and on the opposite wall will appear what looks like a huge motion picture in color, with sound, which reaches him by television. A twist of the tuning dial and he will see at will a battlefield abroad, a performance equal to the finest feature films, a football game, or whatever other delightful performance his fancy can conjure up. Without wishing in any way to present a gloomy picture of what will actually occur, it is fair to say that those who expect what has just been described will be disappointed by the actual performance. A reasonable restraint in all statements made by individuals or by associations of manufacturers, of broadcasters, and of engineers will be useful in enabling performance to realize or, still better, to exceed expectations.

This leads to the final thought that the leading associations in the radio field should continue to cooperate fully in the interest of the successful commercial development of television broadcasting. Whether the existing contacts are close enough and extensive enough might well be submitted to keen scrutiny in the light of the need for most effective industry action, to the end that the fine possibilities of television broadcasting may be fully realized to the satisfaction of the public and the industry alike.

FIELD STRENGTH OBSERVATIONS OF TRANS-ATLANTIC SIGNALS, 40 TO 45 MEGACYCLES

BY

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Summary.—The results of daily observations at Riverhead, N. Y., since the middle of January, 1937 are reported. Some of the schedules of London and Berlin television transmitters are reported as being heard, and measurements of field strengths are summarized. The vertical angle of arrival was measured, and by means of a reversible directive antenna it was determined that the signal at times arrives from the reverse direction over the longest way around the world.

THIS paper will report briefly on the results of a series of observations started at Riverhead, N. Y., January 11th, 1937 on the frequencies of the television transmitters at Alexandra Palace, London, and which later included also the frequencies of the television transmitters at Berlin.

London was understood to have a sound channel on 41.5 megacycles per second, with a power rating of 3 kw and a vision channel on 45 megacycles with a rating of 5 kw. The Berlin transmissions consisted of a sound channel on 42.5 megacycles and a vision channel on 44.3 megacycles. The transmitting antennas were vertically polarized. The distances involved were 3400 miles for London and 3900 miles for Berlin.

Most of the observations took place between 1000 and 1100 E.S.T. Observations were, however, also made at other hours between 600 and 1700 E.S.T. The observations were at first made at the Frequency Measuring Laboratory of the Riverhead Station. They were later extended to another site where special antennas could be erected.

To facilitate the design of an antenna some measurements of the vertical angle of arrival were made. For these measurements, three horizontal dipoles were erected at 16.7 feet, 27.3 feet and 50 feet above ground. Figure 1 shows how these antennas were arranged. By comparing the strengths of the signals picked up on each of these dipoles the vertical arrival anle

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was determined, according to the method described by Friis, Feldman and Sharpless.[1] In order not to introduce errors due to transmission-line losses and standing-wave patterns, the transmission lines from the dipoles were made of equal lengths. A receiver was mounted in the survey car shown, which could be parked near the antennas. The three transmission lines passed to the receiver through a plug and jack arrangement providing rapid change from one antenna to another.

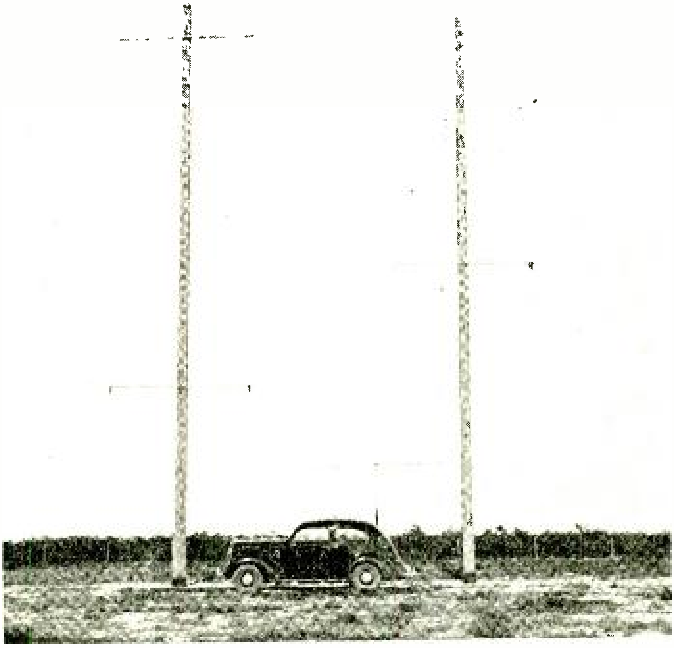

Fig. 1—Three Horizontal dipoles and survey car containing receiver used for vertical arrival angle measurements.

A number of measurements made showed that the vertical arrival angle of the signals heard was close to 7.5 degrees. A horizontal rhombic antenna was then constructed so as to have its maximum lobe towards England at this angle. Its effective height was about 8 meters.

As the observations made at the Frequency Measuring Laboratory indicated that possibly the signal was arriving along paths other than the shorter arc of the great circle from Eng-

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[1] "The Determination of the Direction of Arrival of Short Radio Waves", H. T. Friis, C. B. Feldman, and W. M. Sharpless, *Proc. I.R.E.*, Jan. 1934.

land to Riverhead, it was decided to arrange the rhombic antenna in such a fashion that its direction of reception could be reversed. This was done by installing at each end of the antenna remotely controlled double-pole double-throw switches. From the blades of these switches transmission lines of equal length were run to another remotely controlled double-pole double-throw switch and from the blades of this latter switch a transmission line was run to a receiver. Figure 2 shows a diagram of the antenna and the way in which these switches were connected. The control circuits of the switches were connected so that by operating a toggle switch at the receiver it was possible to connect the receiver to either end of the antenna and simultaneously connect a damping network to the other end. This made it possible to "listen" in either a northeasterly or southwesterly direction. It was found that the damping network reduced the back-end signal sensitivity about 28 db. Figure 3 shows the receiver and measuring equipment used.

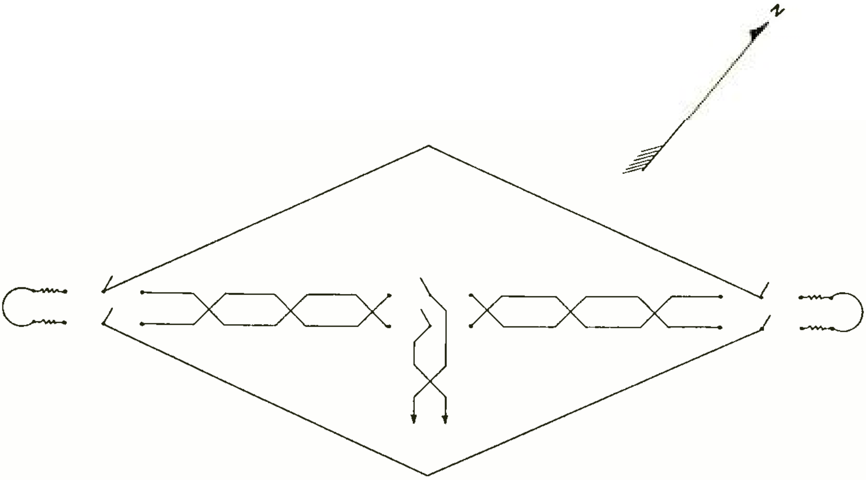

Fig. 2—41.5-Megacycle horizontal rhombic antenna fitted with remotely controlled switches to reverse directivity.

The measurements were made by dividing the observations into five-minute periods and alternately measuring the 41.5 and 45-megacycle emissions. During each period maximum and minimum signal strengths were recorded.

Figure 4 shows the results of one day's measurements. The solid lines indicate the maximum and minimum values obtained on the London 45-megacycle channel. The broken lines indicate the maximum and minimum values obtained from the 41.5-megacycle channel. It shows the maximum signal received at the terminals of the receiver to have reached a peak value of about 700 microvolts on the 45-megacycle channel. It is also evident that there is a fairly constant ratio of fading of about 25 to 30 db on this channel. This phenomenon was observed on several occasions, but was not evident on the 41.5-megacycle signal.

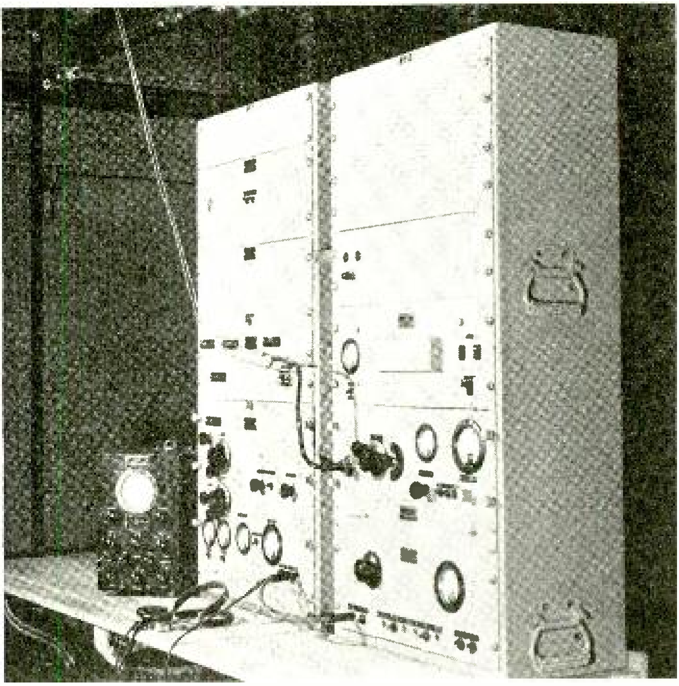

Fig. 3—Ultra-high-frequency receiver and signal operator used for field strength measurements.

Figure 5 gives a summary of all daily observations made on 41.5 and 45 megacycles between 1000 and 1100 E.S.T. The solid lines represent the daily ranges of the 41.5-megacycle field strength and the dotted lines represent the same for the 45-megacycle channel. Dates on which no observations were made are by "X". It will be noted that the signals were first heard January 21st. Conditions for this form of propagation seemed to be at their best during February, falling off badly in March. Whilst the data have not been plotted for the Berlin signals, these were also heard on a number of occasions in February.

Since a possible explanation for long distance propagation at these frequencies is that perhaps they are reflected by the F_2 layer, an examination of the F_2 critical frequencies for vertical incidence is of interest. Figure 6 shows a plot of monthly averages of the F_2 critical frequency for noon, Eastern Standard Time, as measured at Washington, D. C. by the National Bureau of Standards[2] over a period of years. It will be noted that the tendency has been toward higher values of F_2 critical frequency. It seems this tendency is in phase with the increase of sunspot numbers on the present eleven-year cycle of solar disturbances, which is due to reach a maximum about 1939.

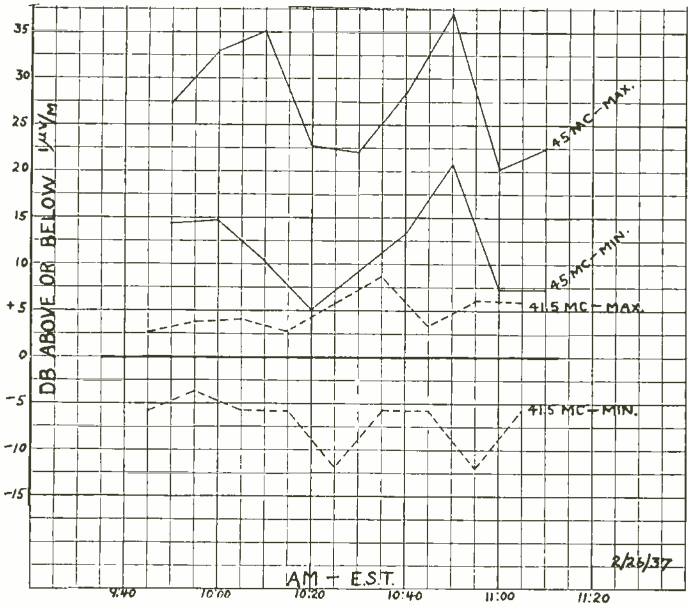

Fig. 4—Plot of single day's observation of the two transmitters at Alexandra Palace showing maximum and minimum values for each.

Figure 7 shows F_2 critical frequencies as measured at Washington, D. C., by the Bureau of Standards,[3] each Wednesday between the hours of 1000 and 1600 E.S.T. plotted along with data relative to conditions observed on the 41.5-megacycle and

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[2] "Averages of Critical Frequencies and Virtual Heights of the Ionosphere, observed by the National Bureau of Standards, Washington, D. C., 1934-1936," by T. R. Gilliland, S. S. Kirby, N. Smith, and S. E. Reymer, in Terrestrial Magnetism and Atmospheric Electricity, Dec. 1936, Johns Hopkins Press, Baltimore, Maryland.

[3] The critical frequency data for Jan., Feb. and March of 1937 were kindly furnished by Dr. J. H. Dellinger of the Bureau of Standards.

45-megacycle channels on the same days. It is noted that the correlation is not perfect. Perhaps better correlation could be had if data were used for critical frequency measurements made more nearly on the path of propagation. Such data however, were not available at the time.

The types of fading observed on the 41.5 and 45-megacycle channels differed greatly. Usually the 41.5-megacycle channel faded rapidly and deeply while the 45-megacycle channel was quite steady for several minutes at a time and would then slowly fade to a new signal level or pass through a shallow dip. The maximum field strength observed on the 45-megacycle channel was about 37 db above 1 microvolt per meter.

Normally the schedule of operation of the English transmitters was from 9:45 a.m. and again from 4 to 5 p.m. Eastern Standard Time. The 4 to 5 p.m. schedule so far has not definitely been heard at Riverhead.

For the week of February 8 the 41.5-megacycle transmitter was kept in operation until noon, Eastern Standard Time, but no definite improvement in field strength was observed during the additional hour. On March 31 the 41.5-megacycle transmitter was operated continuously from 6:30 a.m. until 1:00 p.m. Eastern Standard Time, but during this run the signal was unheard at Riverhead.

Observations were made simultaneously at LeRoy, Indiana from March 3 to March 31 inclusive. The 41.5-megacycle channel was heard on four occasions at LeRoy. On these four occasions, the signal was also heard at Riverhead, the field strength being somewhat higher at Riverhead. Apparently conditions favorable to transmission affect large areas at the same time.

The measurements made at the Frequency Measuring Laboratory consisted in observing both the 41.5 and 45-megacycle signals on various antennas. There were available several short wave fishbone antennas directed toward Europe, South America, the West Coast, etc. All of these were tried and it was frequently noted that when the signal was weak, best reception could be obtained by using an antenna directed toward the West Coast. On several occasions the signal was inaudible on antennas directed toward Europe, but of reasonable strength on the West Coast antenna. However, during periods of strong signal the European antennas gave the best results. In general the reversible rhombic antenna gave similar results except that at no time did this antenna show an improved signal from the southwest-

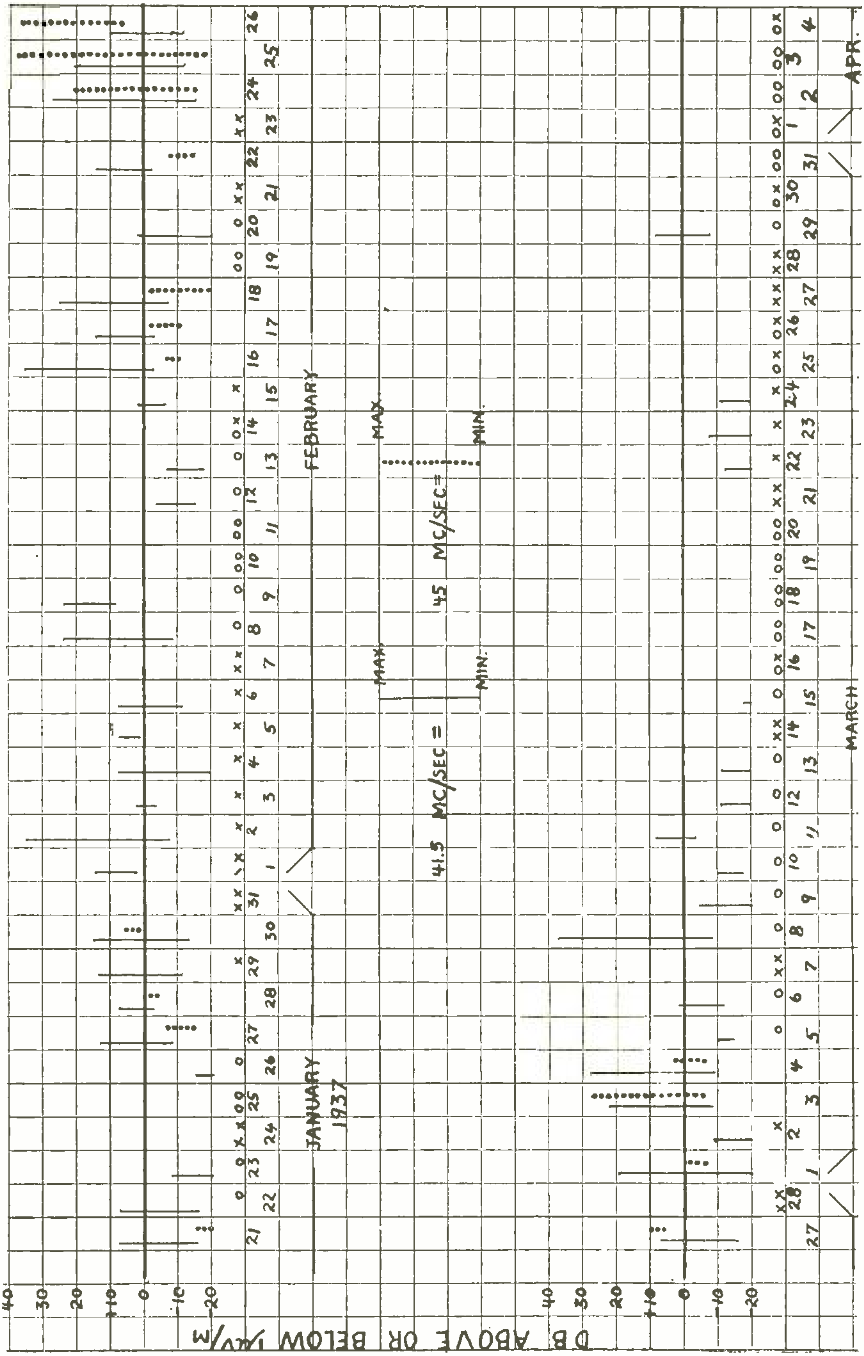

Fig. 5—Daily maximum and minimum field strengths. "X's" indicate no observation made. "O's" indicate signal unheard.

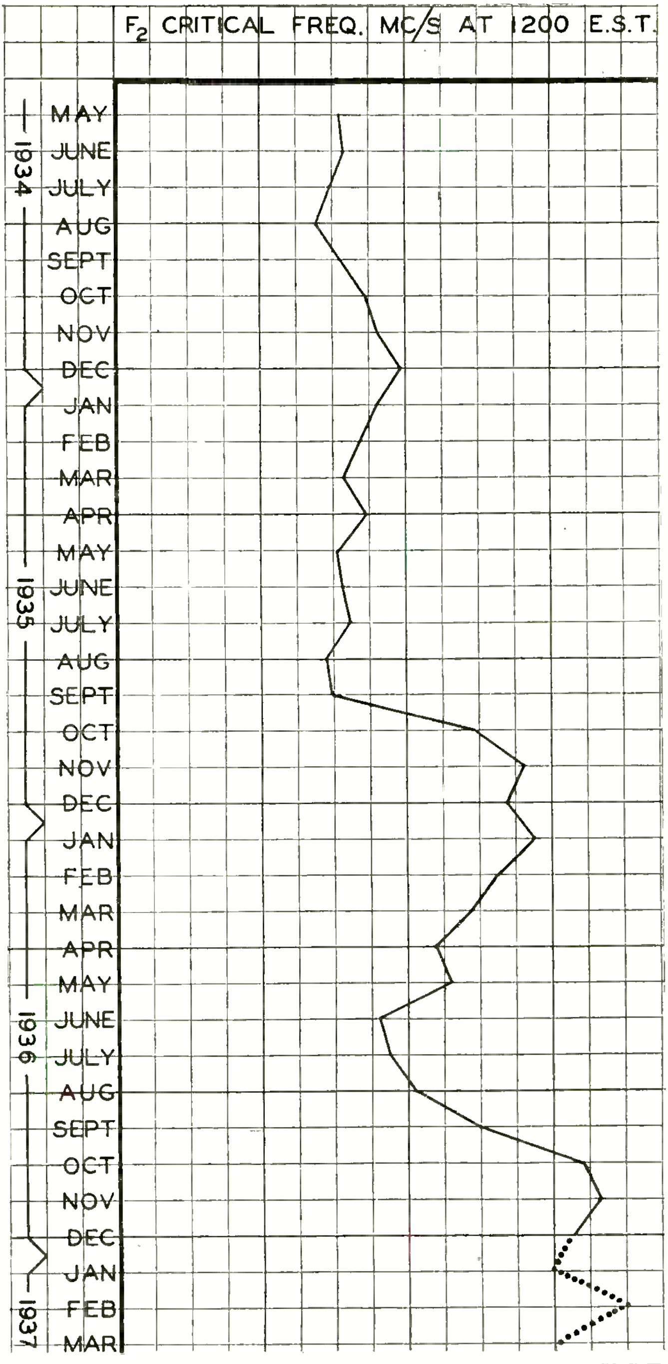

Fig. 6—Monthly averages of F_2 critical frequency, noon E.S.T. at Washington, D. C.

erly direction. Usually during periods of weak signal the normal direction gave from 6 to 12 db better signal than the reverse direction. However, on two occasions for a period of several minutes each, the signals from both directions were of equal strength.

A possible explanation for the failure of the reversible rhombic antenna to show a good signal from the reverse direction is that the signal may have been coming to Riverhead over some path other than the great circle one. If this had been the case the rhombic antenna, being rather sharply directive, would show a good back-end response from the southwest only, whereas the Frequency Measuring Laboratory reported best reception either from the northeast or west.

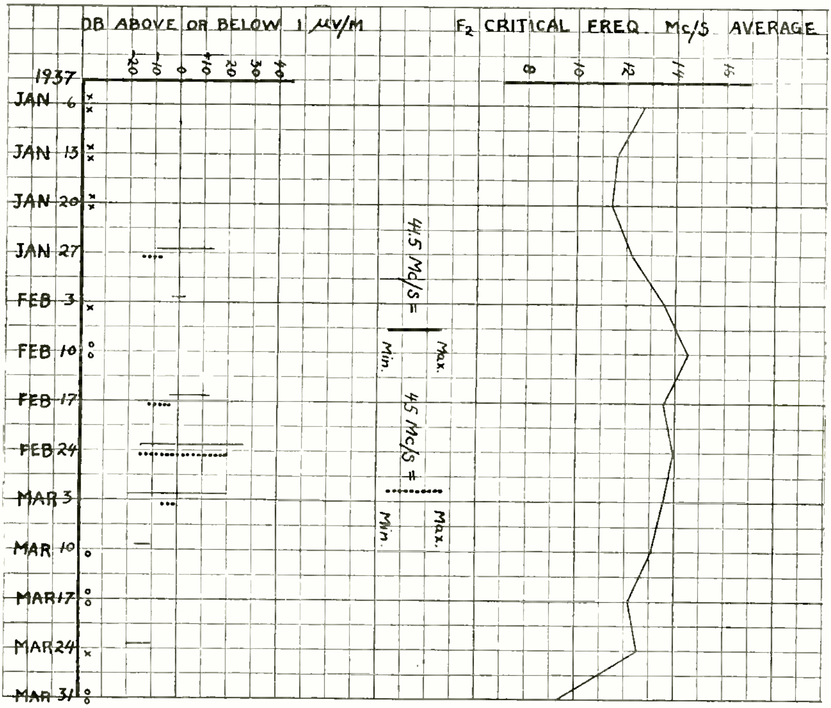

Fig. 7—Average F_2 critical frequency 10 A.M. to 4 P.M. E.S.T. each Wednesday at Washington, D. C., plotted with field strength ranges on same days. "X" indicates no observation made. "O" indicates signal unheard.

Towards the end of the observations the front-to-back ratio arrangement was dismantled, and the remotely controlled antenna switches were arranged to transfer the receiver to either the rhombic antenna directed toward England, or a sloping wire antenna designed to receive vertically polarized waves arriving at a vertical angle of $7\frac{1}{2}$ degrees also directed toward England. The few times that it was possible to compare this new antenna with the rhombic indicated no instances of better results with the vertically polarized receiving antenna. The fact of the polarization of the received signal being independent of the polarization of the transmitting antenna supports the conclusion that propagation was by refraction phenomena in the ionosphere much the same as in the case of frequencies on the order of 10 to 20 megacycles.

Some additional vertical arrival angle measurements were made in the 29-megacycle amateur band. Figure 8 shows a table of the amateurs observed on March 4, 1937. The vertical arrival angle together with the distance between Riverhead and the transmitter location allows a figure for the reflecting layer height to be computed if an assumption is made as to the number of reflections. In the calculations made to determine the column on the right a single reflection was assumed in all but two cases, in which two reflections were assumed. The average apparent layer height derived by this method on these assumptions was 346 kilometers. The average minimum F_2 layer height as measured by the Bureau of Standards at Washington, D. C. on March 3 during approximately the same time of day was 240 km. The difference may be due either to the method of measurement or to an error in the assumption made as to the number of reflections.

LAYER HEIGHT DETERMINATIONS AT RIVERHEAD, N. Y.
29 MC—AMATEURS

Call	*Location*	*Distance KM*	*Arrival Angle Degrees*	*Layer Height KM*
W5FHJ	Ruleville, Miss.	1800	17.2	360
....	Dallas, Tex.	2340	8.9	282
W9YUD	Fremont, Neb.	2040	14.1	378
W9DHO	Wisner, Neb.	2090	13.7	358
W5CZZ	Terrill, Tex.	2280	11.7	357
W5EYV	Refugio, Tex.	2600	9.0	357
W9JWI	Independence, Mo.	1960	17.2	402
W6LUL	Los Angeles, Cal.	4050	11.6	302
W9GND	Grand Falls, N. D.	2070	12.6	331
W9DHQ	Wishek, N. D.	2200	9.5	290
W5FNH	Kerrville, Tex.	2720	8.1	353
W5CZZ	Terrill, Tex.	2280	10.6	332
....	Kansas City, Mo.	1950	16.2	378
W7CKZ	Aberdeen, Wash.	4050	12.4	318
W9LKD	Wichita, Kans.	2180	10.9	332

MEAN LAYER HEIGHT—346 KM

Fig. 8—Layer height and vertical arrival angle determinations made with setup shown in Fig. 3.

SOME NOTES ON ULTRA HIGH FREQUENCY PROPAGATION

By

H. H. BEVERAGE

Chief Research Engineer, R.C.A. Communications, Inc.

INTRODUCTION

THE propagation characteristics of ultra high frequencies above 30 megacycles have been studied for many years. While many observations have been made, it is unfortunate that a substantial proportion of these observations have been qualitative only, due to the difficulty in constructing suitable equipment for quantitative measurements. It has also been difficult to build transmitters of sufficient power and stability to make possible the quantitative measurement of signals at considerable distances beyond the horizon. It is the purpose of this paper to review some of the available information concerning ultra high frequency propagation, including some studies which have recently been made by engineers of R.C.A. Communications, Inc. of propagation at various frequencies both within and beyond the optical distance.

The study of ultra high frequency propagation falls logically into three divisions, namely, (1) Propagation within the optical distance; (2) Ground Wave propagation beyond the horizon; (3) Sky Wave propagation.

PROPAGATION WITHIN THE OPTICAL DISTANCE

The theoretical laws of ground wave propagation over optical paths are fairly well known. Several excellent papers have been published on this subject.[1-2-3-4-13-14] It has been shown that the received signal is the resultant of the direct ray and a ray reflected from the ground. For most practical cases the reflected ray impinges upon the ground at nearly grazing incidence and is usually reflected at high efficiency with a 180-degree phase reversal. Consequently, the direct ray and the reflected ray arrive at the receiving antenna at equal intensity and nearly out of phase. The phase difference between the two paths depends upon the location of the transmitting and receiving antenna and the nature of the intervening ground. For flat ground, Trevor

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and Carter[1] have shown that the phase difference for grazing angles is

$$\Psi = \frac{4\pi a h}{\lambda \tau} \qquad (1)$$

where h is the height of the transmitting antenna, in meters
a is the height of the receiving antenna, in meters
τ is the distance, in meters
λ is the wavelength, in meters

The direct field E_0 from a half-wave dipole is $7(\sqrt{W}/\tau)$, where W is the watts radiated. The received field for grazing angles then becomes,

$$E = \frac{7\sqrt{W}}{\tau} \times \frac{4\pi a h}{\lambda \tau}$$

$$= \frac{88\sqrt{W}\,ah}{\lambda \tau^2} \qquad \text{Volts per meter} \qquad (2)$$

From equation (2), it will be noted that for the conditions assumed, the signal intensity is inversely proportional to the square of the distance; is directly proportional to the heights of the transmitting and receiving antennas above ground; and is inversely proportional to the wavelength. For a given height for the receiving antenna, the transmitting antenna height must be proportional to the wavelength to obtain a given signal intensity. For a given wavelength, the signal intensity will increase directly in proportion to the increase in height of either the receiving antenna or the transmitting antenna. For given antenna heights, the signal intensity will be proportional to frequency. All of these factors are favorable to the use of higher frequencies.

The above simple equation applies only for grazing incidence over flat land, free from obstructions. If both the transmitting and receiving antennas are high and fairly close together, as, for example, transmission from the Empire State Building to an airplane, or between the tops of the Empire State Building and the RCA Building[14], the geometry is such that the difference in path length is no longer a small fraction of a wavelength, and the simple equation no longer holds. In general, standing waves occur which may be greatly complicated by reflections from more than one point. The observations on the signals from the Empire State Building with the receiver in an airplane over North Beach, Farmingdale and Patchogue, as reported by Trevor and Carter[1], clearly show and explain these phenomena.

If the transmission takes place over sea water, there should be a marked difference between vertical and horizontal polarization. For sea water, horizontally polarized waves are reflected nearly 100 per cent for all angles, and the phase shift changes gradually from 180 degrees at grazing incidence to about 178 degrees at perpendicular incidence. On the other hand, for vertically polarized waves, the phase angle and per cent reflection change very rapidly with angle of incidence so that transmission over sea water should be excellent.

Trevor and Carter reported on some propagation measurements over sea water transmitting from an antenna a few feet above the water to a motor boat.[1] They found that the propagation of horizontally polarized waves was extremely poor as compared with vertically polarized waves, as predicted by the theory given in their paper. On the other hand, when the antennas are located at considerable elevations on mountains, as was the case during some observations between the islands of the Hawaiian group several years ago,[5] it was found that there was no marked difference between horizontal and vertical polarization, even though the transmission path was mostly over sea water and distances greater than the optical path were involved.

In applying equation (2), it is obvious that if the transmitting antenna is directive, either in the horizontal or vertical plane, or both, the directivity factor should be taken into account, since the equation was developed on the basis of transmission from a simple half-wave dipole.

GROUND WAVE PROPAGATION BEYOND THE HORIZON

Comparatively few data are available for determining the laws of ultra high frequency propagation beyond the horizon. Handel and Pfister[6] in a recent paper (published in German) have shown that the penetration of ultra short wave radiation beyond the range of optical sight takes place due to both diffraction and refraction. They state that the field due to diffraction at the earth's surface is independent of diurnal and seasonal times. Methods for calculating the diffraction field together with calculated curves and some measured values are included in their paper. The calculated diffraction fields agree very well with the observed fields in most instances, but at times the observed fields beyond the horizon are shown to be considerably higher than the values calculated from the laws of diffraction. The authors attribute this to refraction phenomenon, apparently within the troposphere. The refraction field shows strong variations and produces an effect similar to fading in short wave reception, whereas, the field intensities in the diffraction zone are very stable. The authors point out that the refraction fields appear more frequently and strongly

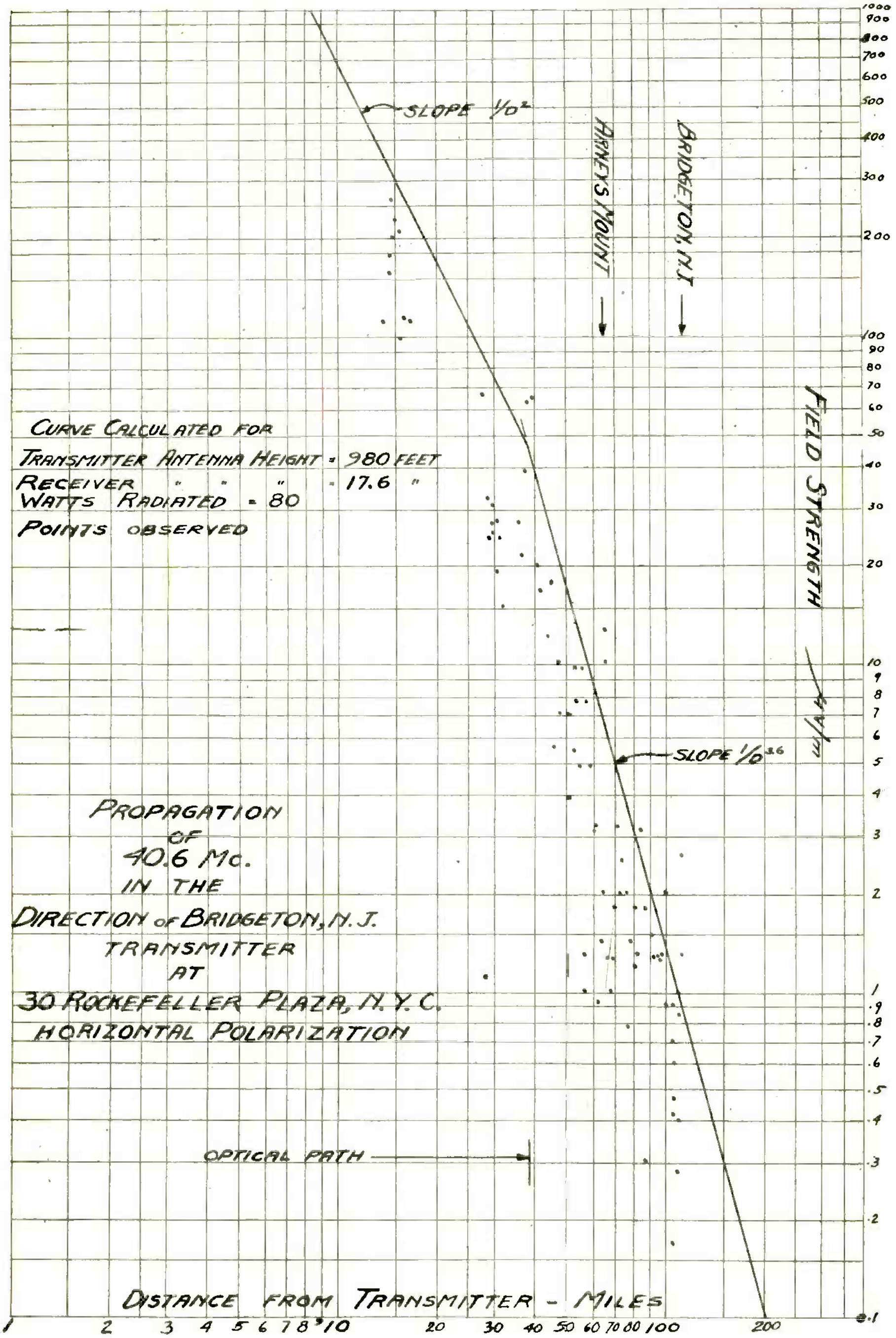
SLOPE $1/D^2$
ARNEYS MOUNT
BRIDGETON, N.J.
CURVE CALCULATED FOR
TRANSMITTER ANTENNA HEIGHT = 980 FEET
RECEIVER " " " = 17.6 "
WATTS RADIATED = 80
POINTS OBSERVED
FIELD STRENGTH
μV/m
SLOPE $1/D^{3.6}$
PROPAGATION
OF
40.6 Mc.
IN THE
DIRECTION of BRIDGETON, N.J.
TRANSMITTER
AT
30 ROCKEFELLER PLAZA, N.Y.C.
HORIZONTAL POLARIZATION
OPTICAL PATH
DISTANCE FROM TRANSMITTER - MILES
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
100
200
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
.9
.8
.7
.6
.5
.4
.3
.2
.1

Fig. 1

in summer than in winter and that the refraction over sea is stronger than over land.

Ross Hull[7] has made some very interesting studies of the refraction field and has shown that there is excellent correlation between signal intensity and temperature inversion. That is, when warm air masses exist above colder air masses near the ground, the signals are refracted down to earth beyond the horizon by the warm air. The existence of the warm air masses are determined by temperature measurements with balloons or airplanes. Considerably more data are required before it will be possible to evaluate these refraction fields or to predict their frequency of occurrence.

It may be of interest to examine some of the available propagation data which includes the refraction fields beyond the horizon as evidenced by fading.

Figure 1 is a typical set of observations made by Mr. G. S. Wickizer on the signals from the Empire State Building operating on a frequency of 41 megacycles with about 1200 watts in the antenna. The transmitting antenna was about 1300 feet above sea level. The receiving antenna was a dipole mounted on a bamboo pole, the center of the dipole being 17.6 feet above the ground. By substituting the above constants in equation (2) with distance as a variable, the curve marked "Slope $1/D^2$" was obtained. Beyond the horizon the field intensity falls off faster than the inverse square of the distance. A curve with a slope proportion to $1/D^{3.6}$ seems to fit the observations fairly well.

It will be noted that the observed intensities come up to the calculated curve frequently, but seldom exceed it, excepting in a few cases such as the points taken at Arney's Mount, where the receiver was on a high hill unobstructed in the direction of the transmitter. Most of the observations lie between the calculated curve and a similar parallel curve drawn at 10 per cent of the intensity of the calculated curve. The average intensity appears to be about one-third of the calculated intensity. Beyond the horizon, the scattering is probably largely due to fading of the refraction field, as it was found to be difficult to check the readings by returning to the same observation points at different times.

Within the optical distance, the attenuation is probably relatively high due to large buildings and other obstructions. Burrows, Hunt and Decino[3] have shown that the average fields in the City of Boston on a frequency of 34.6 megacycles follow the inverse square law but average 10 or 12 db below the calculated level terrain values.

Holmes and Turner[8], on the other hand, have shown that under some conditions, the observed attenuation in urban areas does not

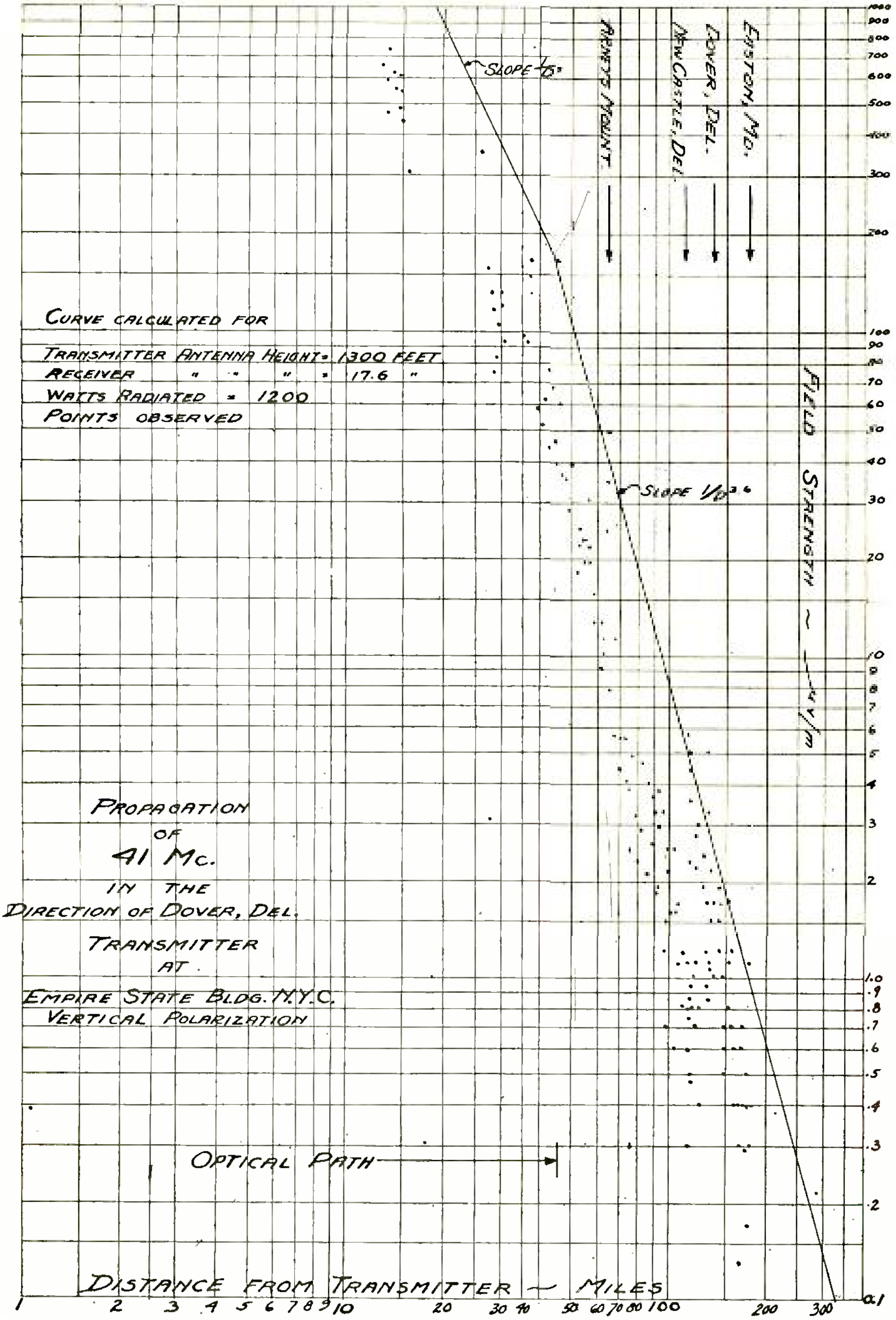
SLOPE $1/D^5$
ARNEYS MOUNT
NEW CASTLE, DEL.
DOVER, DEL.
EASTON, MD.
CURVE CALCULATED FOR
TRANSMITTER ANTENNA HEIGHT = 1300 FEET
RECEIVER " " " = 17.6 "
WATTS RADIATED = 1200
POINTS OBSERVED
SLOPE $1/D^{3.6}$
FIELD STRENGTH ~ μV/m
PROPAGATION OF 41 MC. IN THE DIRECTION OF DOVER, DEL.
TRANSMITTER AT EMPIRE STATE BLDG. N.Y.C.
VERTICAL POLARIZATION
OPTICAL PATH
DISTANCE FROM TRANSMITTER ~ MILES
1000 900 800 700 600 500 400 300 200 100 90 80 70 60 50 40 30 20 10 9 8 7 6 5 4 3 2 1.0 .9 .8 .7 .6 .5 .4 .3 .2 0.1
1 2 3 4 5 6 7 8 9 10 20 30 40 50 60 70 80 100 200 300

Fig. 2

seem to fit the inverse square law very exactly. They also show that the attenuation increases markedly with frequency, so that 100 megacycles is considerably inferior to 30 megacycles in an urban area, whereas, equation (2) indicates that the optical path transmission should be better on the higher frequency in the absence of obstructions. It should be noted, however, that the transmitting antenna used by Holmes and Turner was only 190 feet above the ground. Somewhat different results might have been obtained if the transmitting antenna had been at a greater elevation so as to clear the obstructing buildings more effectively. Nevertheless, the survey reported by Holmes and Turner indicates very definitely that in the presence of obstructions, the attenuation increases greatly as the frequency is increased.

Figure 2 is a set of observations for an entirely different transmitting condition, but with nearly the same frequency as Figure 1. The transmitter was located on top of the RCA Building at 30 Rockefeller Plaza in New York City. The antenna was about 980 feet above sea level and was horizontally polarized. The power in the antenna was about 80 watts. The calculated curve for inverse square law up to the horizon and inverse 3.6 power law beyond the horizon, again seems to fit the maximum signal intensities fairly well.

Figure 3 shows the results of observations made by B. Trevor and R. W. George on the much higher frequency of 91.8 megacycles. The antenna was a simple half-wave dipole on the roof of the Continental Bank Building at 30 Broad Street, New York City. The antenna was about 600 feet above the street level. The power in the antenna was about 50 watts. The antenna was readily adjusted to radiate either horizontally or vertically polarized waves. The receiving antenna was a dipole rigged on the roof of a car, the center of the dipole being about ten feet from the ground.

Substituting the above data in equation (2) gives the curve marked "Slope $1/D^2$." Beyond the horizon a curve with a slope of $1/D^5$ seemed to fit the maximum points with the exception of the points measured on top of hills, as indicated. There was apparently no consistent difference between the transmission characteristics of horizontal and vertical polarization over land.

Observations on transmission from the top of the RCA Building with a frequency of 25.7 megacycles indicate that the signal beyond the horizon falls off about as the 3.2 power of the distance.

Airplane observations on a frequency of 411 megacycles reported by Trevor and George[9] indicate that the signals fall off approximately as the 9th power of the distance beyond the horizon.

Figure 4 shows the observed rates of attenuation beyond the horizon plotted against frequency. The factors determined for the four frequencies fall on a smooth curve, but the data are too few to warrant much confidence being put in this curve. The curve does indicate, however, that the attenuation beyond the horizon increases rapidly for the higher frequencies. Perhaps the attenuation law changes for increasing distance beyond the horizon, but there are insufficient data to indicate whether this is so or not. When higher powered transmitters become available, the attenuation laws beyond the horizon can be determined more accurately.

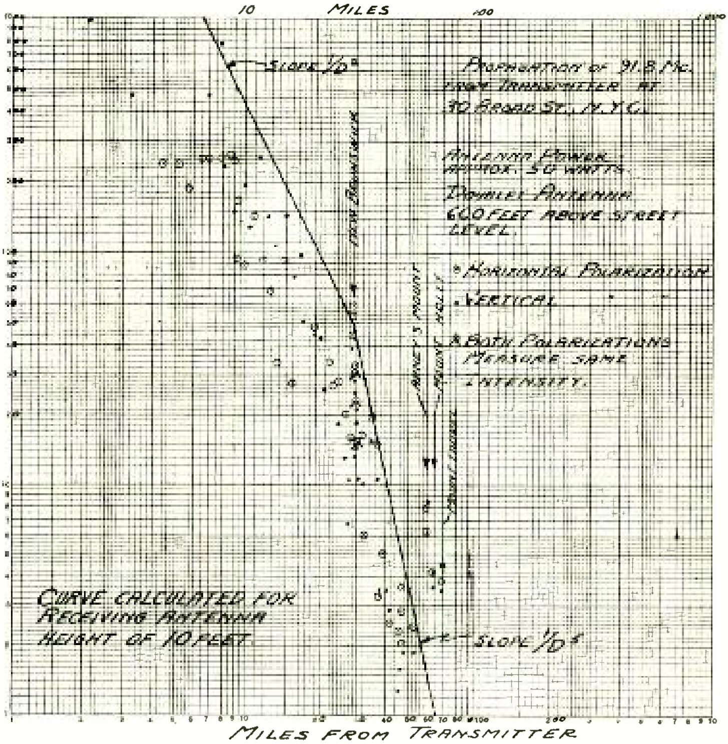

Fig. 3

SKY WAVE PROPAGATION

As the frequency is increased, a point is eventually reached where the sky wave is not bent sufficiently to come back to earth. This is an advantage for certain services, such as television, as there is essentially only one path and multiple images are absent. It is also possible to duplicate the frequencies at moderate distances without fear of interference. The lowest frequency that will just fail to have the sky wave returned to earth depends upon several factors. In general, the higher frequencies are returned to earth in the early afternoon. Contrary to what one might expect, there is some evidence that the high frequency sky waves are transmitted better in winter than in summer, particularly over the north Atlantic path[10]. The transmission also is apparently associated with the 11-year sunspot cycle. For example, the high frequency sky waves were getting through quite frequently during 1927 and 1928 when extensive observations on frequencies above 30 megacycles were first made. Subsequent to 1928, high frequency sky wave transmission was relatively poor until the spring of 1935. Accordingly, there is relatively little information available concerning the transmission of very high frequency sky waves. The long distance transmission on these frequencies is very irregular, which adds to the difficulty of obtaining consistent data. As the frequency is raised, the sky wave transmission becomes more and more

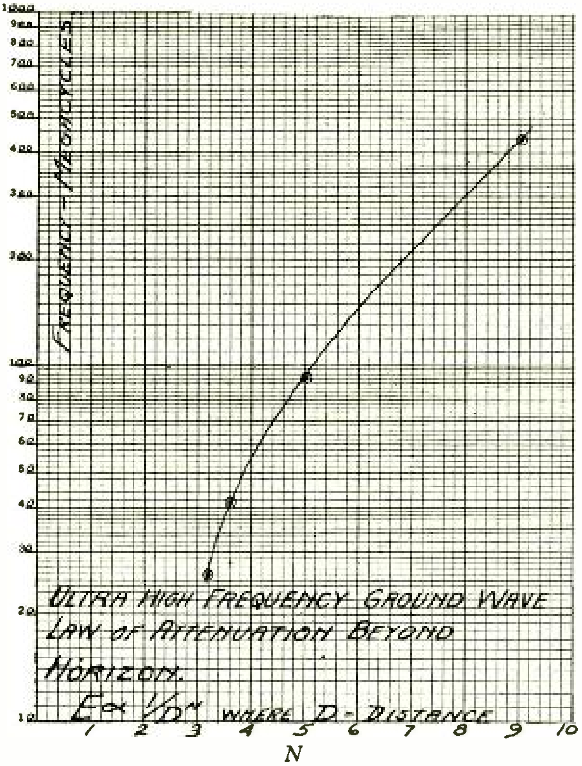

Fig. 4

erratic. Above about 45 megacycles, the sky wave transmission appears to rarely occur, and when it does occur, it tends to appear as a "burst." That is, the signal comes up very suddenly, remains fairly strong for a few seconds or even minutes, and suddenly disappears, perhaps not to be heard again over that particular path for months. This "burst" phenomenon was apparently first observed by W. I. Matthews on 50 megacycles over a distance of about 240 miles.[5]

In May and June, 1935, amateurs reported hearing 5-meter signals over distances of 900 miles. Amateurs in the vicinity of Chicago heard several New England amateurs working in the 50-60 megacycle band, and at least one two-way contact was established.[11] A similar effect was reported for May 9, 1936.[12] On this occasion, several two-way contacts were made between East Coast and Middle West amateurs. Many signals were heard over a period of some three hours, beginning at approximately 8:30 P.M. Several of the amateurs reported severe selective fading, with part of the signal dropping out and the rest remaining.

It seems probable that the transmissions on these occasions were due to sky waves and not refraction. Probably the suggestion that the signals were bent down by "unusually heavy sporadic *E*-region ionization" is the correct explanation.

From the available information, it would seem that little sky wave transmission takes place above about 45 megacycles, and that such transmissions that do occur above 45 megacycles are produced by unusual ionization conditions which probably will rarely occur. Amateur operators spread over a wide area are in an excellent position to observe these sporadic transmissions and their observations should be extremely valuable for indicating the location, duration and frequency of occurrence of these sky wave transmissions, as well as diurnal and seasonal effects.

CONCLUSION

There are apparently four mechanisms which may be involved in ultra short wave propagation. These are (1) combination of the direct ray and the ray reflected from the ground; (2) diffraction at the earth's surface; (3) refraction in the troposphere; (4) sky wave transmission.

The first mechanism is the principal effect within the optical path. It shows that the signals are attenuated according to the inverse square law of the distance for grazing incidence within the optical range. The signal intensity can be calculated by simple equations, although scattering and absorption, even in open country, tend to reduce the average intensity to something in the order of 30 to 60 per cent of the calculated value. In urban areas, the scattering and absorption due to buildings, increases the attenuation considerably, particularly at the higher frequencies. The amount of this increase in attenuation on the higher frequencies probably depends to a great extent on the height of the transmitting antenna in relation to the obstructing objects in its vicinity. More data are required before the relative performance of various frequencies in urban areas can properly be evaluated and compared.

The diffraction factor becomes important beyond the horizon. The diffraction field can be calculated by the methods indicated by Handel and Pfister[6]. In addition to the diffraction field, which is believed to be constant and stable, the refraction field is important beyond the horizon. The refraction field is variable and produces fading. There is insufficient information available to calculate the refraction field.

In general, it is definitely known that the attenuation beyond the horizon increases rapidly as the frequency is increased. The slope of the attenuation curve that fits the available observations best is indicated in Figure 4. An approximation of the attenuation for a given circuit may be calculated by using equation (2) up to the horizon and plotting the calculated points on log-log paper. These points will lie on a straight line having a slope of $1/D^2$. At the horizon, another straight line having a slope determined from Figure 4 should be drawn. This line will indicate the order for the attenuation beyond the horizon for a particular frequency. In general, the signal intensity determined in the above manner should represent the maximum, excepting for unusual conditions such as locating the receiver on a mountain top, abnormal refraction fields, sky wave transmission, etc. The available data are based on overland transmission, for which case there seems to be little difference between vertical and horizontal polarization. Over sea water, vertical polarization is superior to horizontal polarization, at least for moderate distances with relatively low antennas.[1]

The optical distance for flat ground is easily calculated from the equation:

$$\text{Distance in miles} = 1.22 \sqrt{\text{Height in feet}}$$

If the receiving antenna is also at a high elevation, the same equation may be applied to determine the horizon for the receiving antenna, and this added to the horizon for the transmitting antenna gives the total optical path for that particular set of conditions.

Too little is known about sky wave transmission on the ultra high frequencies. From available information to date, it would seem that sky wave transmission above about 45 megacycles is too spasmodic to give much concern. However, it is possible that more frequent sky wave transmission may be observed at some more favorable phase of the sun spot cycle.

BIBLIOGRAPHY

[1] "Notes on Propagation of Waves Below Ten Meters in Length"—Trevor and Carter, *Proc. I.R.E.*, March 1933.

[2] "Ultra-Short-Wave Propagation"—Shellung, Burrows and Ferrell, *Proc. I.R.E.*, March 1933.

[3] "Ultra-Short-Wave Propagation: Mobile Urban Transmission Characteristics" Burrows, Hunt, and Decino—*Bell System Tech. Journal,* 1935.

[4] "Some Results of a Study of Ultra-Short-Wave Transmission Phenomena"—Englund, Crawford and Mumford, *Proc. I.R.E.*, March 1933.

[5] "Application of Frequencies Above 30,000 Kilocycles to Communication Problems"—Beverage, Peterson and Hansell, *Proc. I.R.E.*, August 1931.

[6] "Ultra Short Wave Propagation Along the Curved Earth's Surface"—Paul V. Handel and Wolfgang Pfister, *Hochfrequenztechnik Und Electroakustik*, Vol. 47, No. 6, June 1936.

[7] "Air-Mass Conditions and the Bending of Ultra-High Frequency Waves"—Ross Hull, *QST*, June 1935, Page 13.

[8] "An Urban Field Strength Survey at Thirty and One Hundred Megacycles"—R. S. Holmes and A. H. Turner, *Proc. I.R.E.*, May 1936.

[9] "Notes on Propagation at a Wavelength of Seventy-Three Centimeters"—Trevor and George, *Proc. I.R.E.*, May 1935.

[10] "The Propagation of Short Radio Waves Over the North Atlantic"—C. R. Burrows, *Proc. I.R.E.*, September 1931.

[11] "Five-Meter Signals Do the Impossible. Signals Swapped Over 900-Mile Path; WICBJ Contacts W8CYE", *QST*, August 1935, Page 17.

[12] "Five Meters Again Shoots the Works", *QST*, July 1936, Page 9.

[13] "A Study of the Propagation of Wavelengths Between 3 and 8 Meters," L. F. Jones, *Proc. I.R.E.*, March 1933.

[14] "Ultra High Frequency Transmission Between the RCA Building and the Empire State Building in New York City"—P. S. Carter and G. S. Wickizer, *Proc. I.R.E.*, August 1936.

TELEVISION TRANSMITTERS OPERATING AT HIGH POWERS AND ULTRA-HIGH FREQUENCIES

By

J. W. Conklin and H. E. Gihring
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THE advent of high-definition television, involving modulation frequencies up to several million cycles, has necessitated the development of high-power, ultra-high-frequency transmitters. The unique tube and circuit problems encountered and the practicability of line sections as circuit elements has resulted in radical departures from conventions in transmitter design as may be seen from the accompanying illustrations, showing features of high-power, ultra-high-frequency television transmitters.

Vacuum Tube Problems

In ultra-high frequency development the vacuum tubes have always been one of the major sources of difficulty. Vacuum tubes developed for lower frequencies have a number of limitations rendering them unsuitable for u-h-f applications. For low-power u-h-f transmitters and receivers, special tubes having low internal capacities, short leads, and other features are available, permitting conventional designs insofar as tubes are concerned. Television transmitters with carrier powers between five and ten kilowatts require tubes with dissipation capabilities of the order of thirty kilowatts. The Type 899 shown in Figure 2, is one of the tubes now used in these applications. Some of the problems of high-power u-h-f transmitters are due to the large physical size of tubes now available.

Water cooled tubes have glass envelopes to provide insulating supports for grid and filament structures in high-power tubes. For manufacturing reasons, these envelopes are made of considerable length since the resulting lengths of filament and grid leads do not present serious difficulties at low frequencies. At ultra-high frequencies the inductance of the leads, plus the loading effects of the inter-element capacities, result in potential and phase differences between the actual internal elements and their external terminals, which increase roughly with the square of the frequency. There exist, in effect, standing waves on the leads and as the frequency increases, a condition is reached

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where the voltage nodes move inside the envelope, i.e., the effective lengths of the internal leads are greater than a quarter wavelength. In common high-power, water-cooled tubes, this condition occurs at frequencies from 30 to 50 megacycles. As a result, at ultra-high frequency it is impossible directly to ground the filaments for radio frequencies or achieve satisfactory neutralization, because of the length of the grid and filament leads.

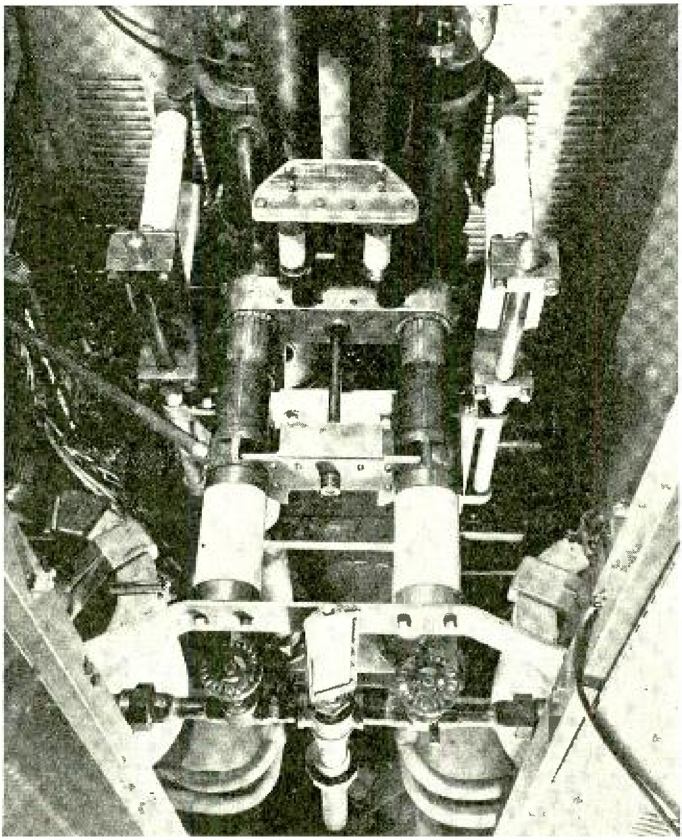

Fig. 1—Tank circuit of a fifty-megacycle television power amplifier. The inductive section is very short and tuned by an adjustable shorting bar. The two tubes dropping from the top carry the antenna coupling leads.

In Figure 3-A are shown graphically the voltage gradients existing on the elements of Type 899 as observed in actual operation at 50 megacycles. Figure 3-B shows an approximate equivalent network representing the tube under these conditions. It will be noted that the external grid terminal is actually at a voltage nodal point.

In Figure 2 there are also shown two smaller water-cooled tubes which are used in ultra-high-frequency transmitters, Types 846 and 858. It will be noted that these tubes are of the single-ended type, that is, the filament and grid leads enter a common envelope, the opposite end of the anode being closed as contrasted with Type 899 which is double ended, that is, the grid and filament structures are supported by separate envelopes at opposite ends of the tube. The single-ended construction has generally been found easier to handle at ultra-high frequency as the excitation is normally introduced as a grid-filament potential. For this reason it is convenient to have the external terminals for these elements close together. Also in ultra-high frequency circuits it has been found convenient to form the tank-circuit inductance from straight tubings which are a continuance of the water-jacket assemblies. Examples of this type of tube mounting are shown in Figures 6 and 7. Type 846 tube, because of its small

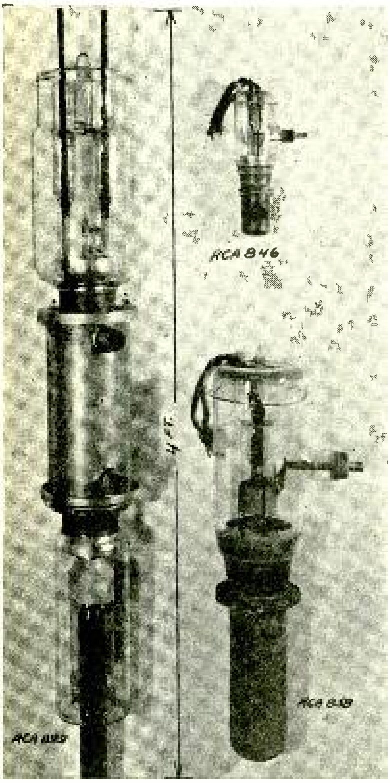

Fig. 2—Water-cooled vacuum tubes used in ultra-high-frequency television transmitters.

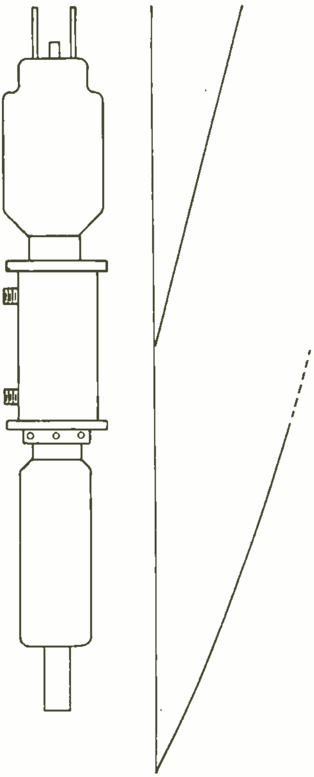

Fig. 3A—Voltage gradients in 899 Tube at 50 mc.

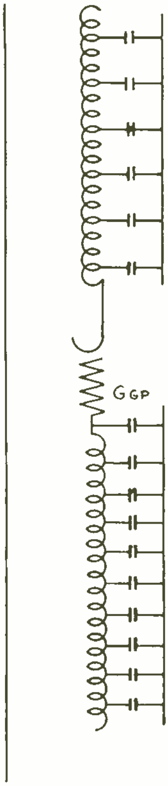

Fig. 3B—Approximate equivalent network.

physical size, functions satisfactorily in conventional circuits at frequencies as high as 100 megacycles. Type 858, which is considerably larger, has been found most useful for frequencies below 40 to 45 megacycles.

REACTANCE OF FILAMENT LEADS

In operation the reactance of the filament leads is common to the plate and grid circuit, as shown in Figure 4-A, and in tubes of large physical size, the internal reactance is great enough to make satisfactory neutralization difficult when the filaments are grounded directly. Even when satisfactory neutralization can be achieved, this filament-lead reactance prevents attainment of 100 per cent modulation of a modulated stage, as it permits radiation of the excitation power on negative-modulation peaks.

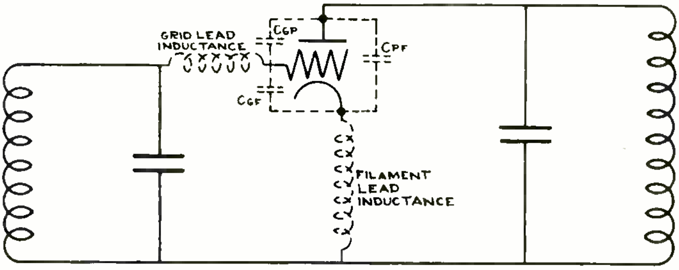

Fig. 4A—Circuit illustrating grid circuit-plate circuit coupling from filament-lead reactance.

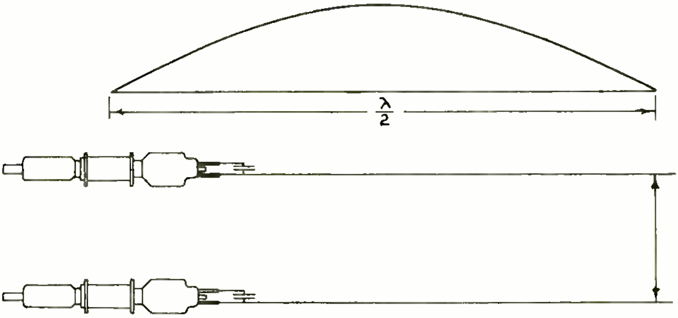

Fig. 4B—Showing how half-wavelength leads overcome internal filament-lead reactance.

For several reasons to be discussed later, push-pull circuits are used almost entirely for large high-power u-h-f transmitter stages. This permits a simple method of overcoming the reactance of the filament leads by interconnecting the filaments of the opposing tubes through a pair of parallel conductors, as shown in Figure 4-B. These are inter-connected at a point effectively one-half wavelength from the actual cathodes, giving an effect substantially the same as a direct inter-connection between filaments. In practice, the inter-connecting bar is made adjustable and the correct setting determined as a part of the neutralizing procedure. Figure 5 shows the installation of such filament lines. At 50 megacycles these filament lines are of the order of 10 feet in length and for convenience they are doubled back on themselves to reduce the size of the inclosure required.

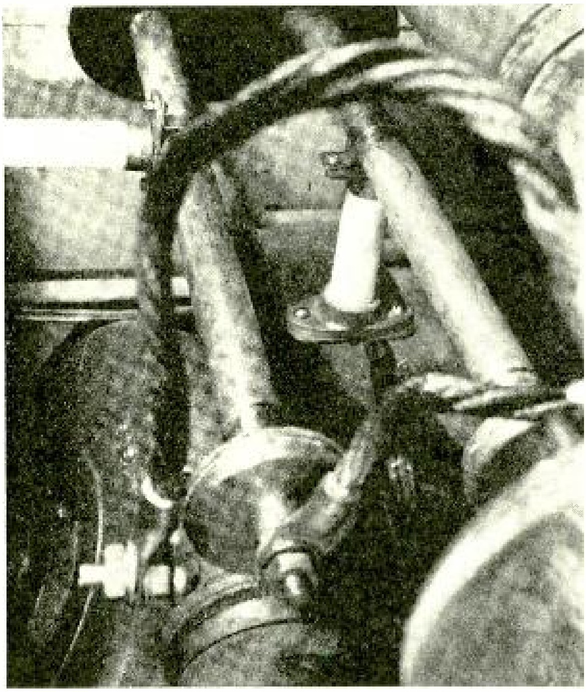

Fig. 5—Filament tuning lines used with Type 899 tubes on a 50-mc. transmitter. Note by-pass condensers which by-pass opposite side of filament to line. The heating current circuit is completed through an internal conductor.

NEUTRALIZATION PROBLEMS

Long internal grid leads result in difficulties in cross-grid, cross-plate neutralizing, which may be further increased by necessarily long external neutralizing leads. In the case of Type 899 the internal grid lead is effectively a quarter wavelength at 50 megacycles and this makes neutralization difficult through connections to the external grid terminal. Fortunately, the grid end of this tube is of such construction that it was found feasible to form the cross-grid or cross-plate neutralizing capacity directly between the internal grid-lead and external concentric-sleeve fitting over the glass envelope. These neutralizing sleeves may be seen in Figure 8. Even with this arrangement it is not possible to form a true reactance bridge, because there is still left a considerable length of free grid reactance and the circuit is neutralized only over a small band near the operating frequency and has to be heavily loaded to prevent oscillation.

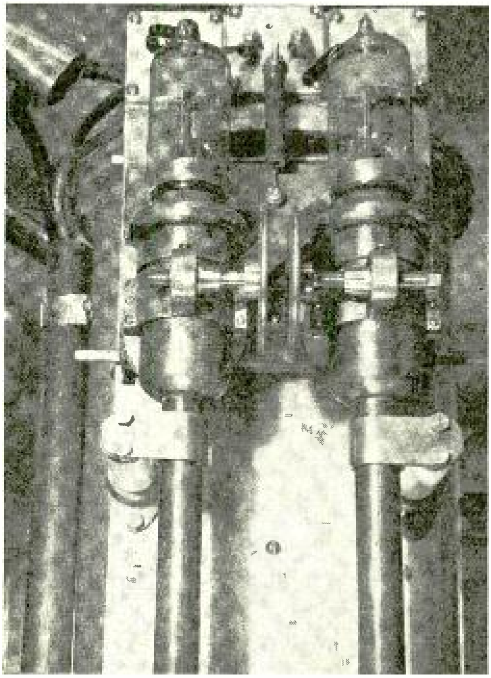

Fig. 6—A 50-megacycle amplifier. Tank circuit is of the parallel line type using a small disc condenser for fine adjustment. Compare the size of the tank conductors with the 90-mc. unit shown in Fig. 7.

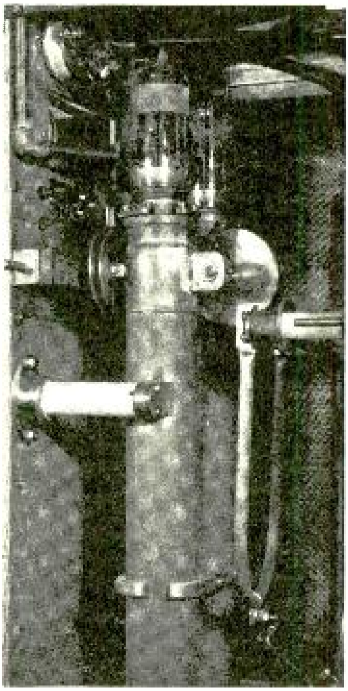

Fig. 7 — A five-kilowatt power-amplifier adjusted for operation at 90 megacycles. Note length of tank circuit as a result of using large diameter conductors.

INTER-ELECTRODE CAPACITIES

Inter-electrode tube capacities impose a number of u-h-f limitations on tube performance. In the case of high-power transmitting tubes, these limitations are of a different nature than those generally associated with low power and receiver applications. Large water-cooled tubes have high inter-electrode capacities, output capacities ranging from 25 to 50 $\mu\mu f$. These capacities do not impose serious tuning difficulties as the physical size of the tube makes it convenient to use large tank circuits having very low inductance. Figure 7 is a view of a tank circuit of the parallel-line type, using an adjustable shorting bar with a small vernier condenser to cover a tuning range from 40 to 90 megacycles. However, from the standpoint of neutralizing, high grid-plate capacities are awkward as the physical size of the neutralizing condensers necessitates long leads and increases stray capacity effects.

At ultra-high frequencies, the inter-electrode capacities have very low reactance values and, as a result, the circulating currents in the tubes become unusually high. These high currents cause excessive heating of the elements, leads, and seals and in general necessitate extra precautions in air cooling of all glass parts, particularly the seals. This heating is also increased at ultra-high frequencies by the increase of the radio-frequency resistance because of skin effect.

In television applications, inter-electrode capacities have a more serious effect particularly in r-f power amplifiers required to pass modulation side bands, which under present standards may be 2.5 megacycles from the carrier. It is not generally realized that for a desired tank-circuit frequency response, the tube, neutralizing and associated stray capacities, automatically determine the load resistance regardless of carrier frequency. In practical cases, this has generally necessitated operating tubes into load resistances considerably lower than normal with resulting poor plate efficiency.

In television power-amplifier applications, tube efficiency in one respect depends upon the ratio of tube capacity to plate conductance. Unfortunately, this ratio is a fundamental inherent relation in practical vacuum tubes of the triode type, and while tubes may be improved, it is doubtful if the present conception of a triode r-f power amplifier is the final answer for high-definition television applications.

The high side-band frequencies do not require 100 per cent modulation of the transmitter. It is thus possible to compensate partially for discrimination against high frequencies occurring in the radio-frequency circuits by equalizing at low levels in the video amplifier. However, excessive compensation in this type usually introduces objectionable phase shifts and transients. The problems of relaying a picture from the studio to the radiating transmitter and amplifying it to modulation power, is of itself a sufficient problem. It is therefore desirable that the radio-frequency circuits of the transmitter have a flat characteristic over the frequency band to be transmitted.

In one case of a 7.5-kilowatt, 50-megacycle television transmitter, in order to obtain a power-amplifier frequency response flat within 3 decibels over a 1.5-megacycle band, it was necessary to overload the power amplifier to a point where the plate efficiency was less than 15 per cent. The power amplifier used two Type 899 tubes in push-pull and the total plate input was approximately 60 kilowatts when delivering 7.5-kilowatts carrier-wave output.

New tube developments increasing the ratio of output conductance to output capacity may partially alleviate the poor power efficiency at

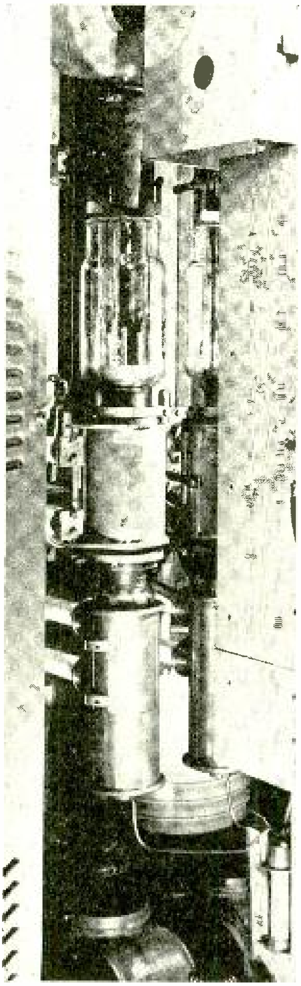

Fig. 8 — Showing neutralizing sleeves enclosing grid end of Type 899 tubes in a fifty-megacycle power amplifier. Note air blowers above and below tube to cool glass parts.

present obtainable in television transmitters. However, the difficulty is more or less fundamental with tubes of the triode type, and the ultimate solution will, more likely, be the development of entirely new types of power-amplifying tubes and modulation methods.

Because of the difficulties in producing high modulation power at the high side-band frequencies involved in television transmission, grid modulation in the power amplifier has been the most practical method of modulating high-power u-h-f television transmitters. Absorption modulation has been used successfully on low-power transmitters of one or two kilowatts carrier power. The principal advantage of absorption modulation as applied to television is that it removes the band-pass requirements from the power-amplifier circuits and consequently makes possible higher plate efficiency.

CIRCUITS

At ultra-high frequencies, wavelengths reduce to a few feet and in high-power transmitters this fact introduces difficulties, but makes practicable circuits not adapted for lower-frequency design. In general, it becomes convenient to regard all circuit elements as sections of transmission lines and analyze them as such.

To begin with, at frequencies above 40 megacycles, it is found economical to use resonant line-controlled master oscillators as the primary frequency source. In such oscillators, the equivalent of a quarter-wavelength low-loss line resonator is used as the primary oscillatory circuit with power-oscillator tubes. Such resonators become of convenient size in the ultra-high frequency band and it has been found that the total transmitter tube complement is much less than would be required with a conventional frequency source such as a crystal oscillator and subsequent frequency multipliers and amplifiers.[1] Figure 10 shows a 50-mc. quarter-wave, line-controlled power oscillator.

Enclosures or mounting frames used for the high-power stages of u-h-f transmitters, because of their size approach major fractions of the operating wavelengths in dimensions. A true common r-f ground for the inclosed circuit is thus difficult to obtain, and considerable difficulty is experienced with single-tube circuits which necessarily are assymmetrical with respect to an enclosure. Troubles from this source largely disappear when push-pull circuits are used and mounted symmetrically in relation to a large plane-conducting surface. For these reasons, push-pull types of circuits are generally used in preference to single-tube circuits where the physical size is a major part of a wavelength.

At ultra-high frequencies quarter and half-wavelength line sections become reasonably short in length and it is practicable to take advan-

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[1] "Frequency Control by Low-Power-Factor Line Circuits" by P. S. Carter and C. W. Hansell. *Proc. I.R.E.*, April 1936.

tage of some of their particular properties. Thus in u-h-f transmitters quarter-wave line sections are used as impedance transformers, "metallic" insulators, and impedance inverters. In Figure 9 is shown an assemblage of quarter and one-half-wave, coaxial-line sections forming a cross-coupling filter to permit the operation of both the picture and sound transmitters into a common antenna without objectionable cross modulation. A U-shaped section of coaxial line serving as a transformer to couple the 72-ohm coaxial line to a 500-ohm, two-conductor, open-wire line is also shown. Short sections of lines having open or short-circuited terminations are conveniently used as efficient reactances at ultra-high frequency. Examples of this type of application of stub-line sections are the use of parallel tubular conductors having lengths less than a quarter wavelength to form the inductive component in high-power tank circuits. Several such assemblies are shown in the accompanying illustrations.

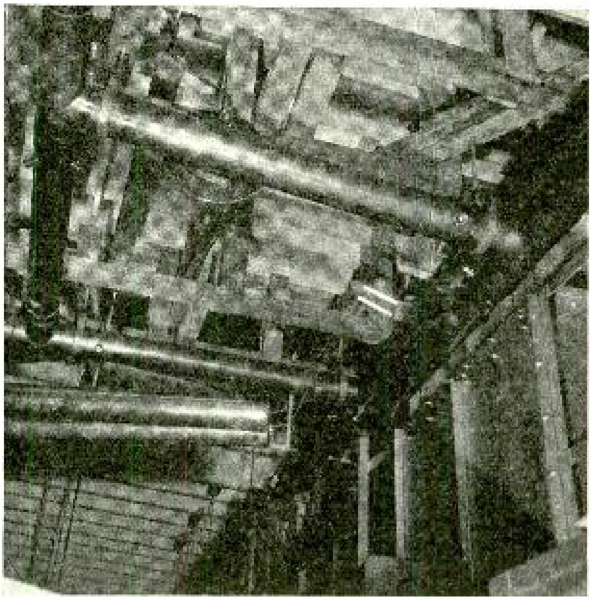

Fig. 9—Quarter and half-wavelength line sections used to form high-"Q" filter elements preventing cross coupling of "sound" and "picture" transmitters separated a few percent in frequency and operated on a common antenna.

At ultra-high frequencies in circuits of large physical size all currents may be assumed to flow in the surfaces of the conductor, that is, constrained to a skin of less than a thousandth of an inch deep. This makes possible the construction of circuit members from inexpensive, easily fabricated materials such as steel which is subsequently plated with a highly conductive metal such as silver. A frequency-controlled resonator may be constructed entirely of cold-rolled steel and invar and silver plated. The actual conducting surface is thus formed of silver which has a very low electrical resistance, and at the same time, the structure is lighter and stronger and has a lower thermal coefficient of expansion than copper, which formerly has been used for these devices. As the practical thickness of plating of this type is limited to a few thousandths of an inch, this type of construction could not be used at lower frequencies where the depth of penetration is greater. It is necessary to consider skin effect and current distribution in the design of u-h-f transmitter components, as these phenomena are of much more importance at these frequencies.

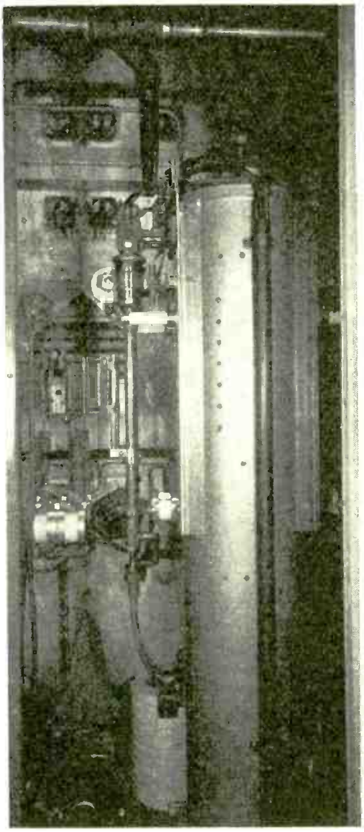

Fig. 10 — 50-megacycle "power" master oscillator. Frequency is stabilized by means of the quarter-wave coaxial line.

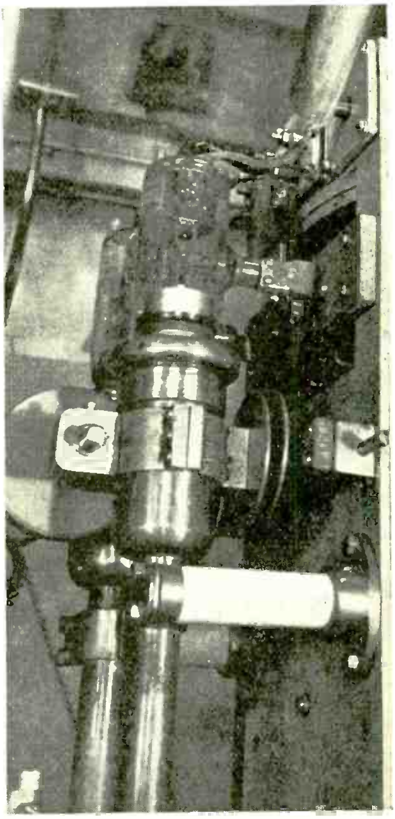

Fig. 11—A close-up of the oscillator shown in Fig. 10. Mechanical arrangement is simple and rugged and provides short electrical connections.

AUXILIARY APPARATUS

The difficulties encountered with tubes for u-h-f work have been previously discussed. Other apparatus such as condensers, resistors, meters, insulators, etc., also have serious limitations.

CONDENSERS

Variable condensers of the conventional type cannot be used at ultra-high frequencies primarily because both minimum and ground capacity values are too high and insulation paths are not very long. For most u-h-f work two circular disks arranged so that the distance between them can be varied continuously have been found to be satisfactory and can be mounted directly on a tank circuit without requiring insulating mountings. In most u-h-f circuits the tube and neutralizing capacities form the major part of the tank capacity. External capacities are added only for tuning purposes. Suitable fixed condensers for by-passing, and coupling present serious difficulties. It is frequently desirable directly to couple the plate circuit of one stage to the grid circuit of the next. A coupling condenser is required to block the d-c plate voltage from the bias voltage of the next stage. In high-power u-h-f transmitters the radio frequency currents in this circuit may reach magnitudes of 30 to 40 amperes or more. At 50 megacycles, 1000 $\mu\mu f$. are required to obtain 3.2 ohms of reactance. A value as high as 15 to 20 ohms may be tolerated in coupling or by-passing, but a higher reactance will cause difficulties. Ultra-high-frequency circuits are usually constructed of low-reactance components, and higher-reactance blocking condensers will greatly disturb the circuit operation.

The condensers usually available for this service consist of a stack of copper sheets with mica insulation impregnated with wax. The dielectric losses in the wax and mica go up rapidly with frequency, resulting in excessive heating of the condenser at values much below its rated current. Another disadvantage with this type of construction is that it often results in having considerable inductance in series with the condenser proper. One alternative is to use high-current-rating condensers and operate them considerably below their rating. This is undesirable because of the bulkiness of the condensers, which is detrimental to good circuit design. Other dielectrics may have possibilities and a suitable condenser may be developed in the future.

Air has proven to be the most reliable dielectric, but has the disadvantage of having a dielectric constant of one, which results in bulky condensers for the conditions mentioned above; namely, 40 amperes r.f. at 50 megacycles, 10,000 volts d.c. and from 200 to 1000 $\mu\mu f$. Compressed air condensers may offer a solution to this problem since the spacing may be decreased approximately as the pressure is increased. However at ultra-high frequencies compressed air condensers present insulation difficulties that offset their advantages.

Vacuum condensers similar in construction to vacuum tubes have been tried in an effort to obtain high voltage rating in small physical space. These failed by going "gassy" as they do not have the "clean-up" feature of vacuum tubes in operation. It is relatively easy to find standard condensers that will stand up for by-passing purposes, since for this condition the r-f current through the condenser is usually small. In many cases, however, the condenser will have considerable impedance to ground, because of its inductance. A case was encountered in which a parasitic oscillation existed with all types of standard condensers used for by-passing. A large parallel-plate condenser of extremely low inductance finally cured this condition.

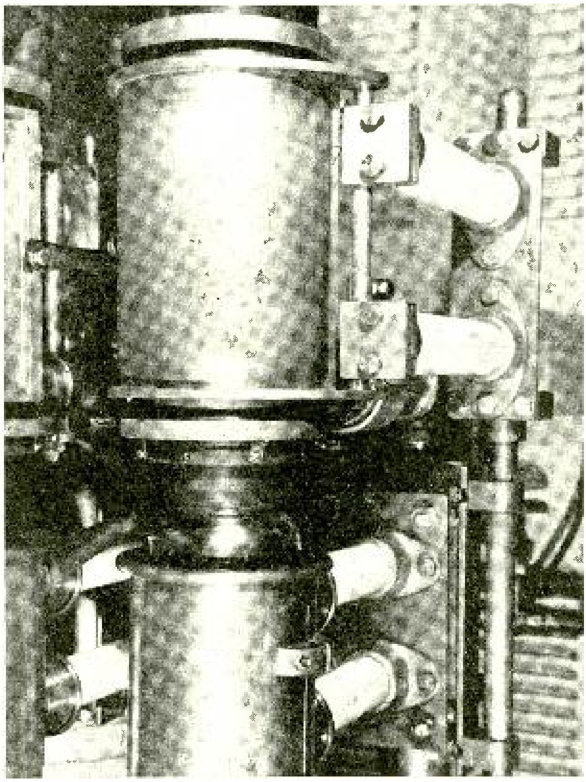

Fig. 12—A tube mounting including neutralizing sleeves and output coupling capacitors.

INSULATORS

Closely associated with condenser problems is the problem of insulation. Any insulator is in a sense a capacity with the insulating material as the dielectric. For lower frequencies, the admittance of an insulator is so slight as to be negligible, but at u.h.f. there are many cases in which the radio-frequency currents flowing through the insulator are of such magnitude as to shatter the insulator, due to the internal heat produced. Points of contact with metal were found to be glowing at white heat. The above conditions as a rule are true only when a metal button or screw extends into the insulating material. This results in internal heating of the insulator, causing it to shatter. A simple remedy lies in the use of a corona shield. The corona shield tends to divert the path of the r-f currents along the outside of the insulator where cooling may take place.

No really suitable insulating material is available for u-h-f high-power transmitter work combining good insulating properties with mechanical strength. For this reason u-h-f transmitters must be constructed to eliminate insulation in high-frequency fields.

METERS

The measurement of u-h-f currents is a difficult problem. The ordinary calibration of thermocouple ammeters does not apply at u.h.f. because the skin effect in the couple causes the meter to read high. This, however, can be taken into account by applying a suitable correction factor.[2] A further difficulty, however, arises when the meter is actually placed in the circuit. In many cases the circuit is disturbed by the presence of the meter, resulting in erroneous readings. Lack of satisfactory voltage and current indicators increase the difficulties of studying problems in connection with u-h-f transmitters.

RESISTORS

Resistors are often desirable in u-h-f television circuits. It is difficult to build good non-inductive resistors at lower frequencies and at u.h.f. the problem is still more difficult. Types that are satisfactory at lower frequencies develop "hot spots" through the presence of standing waves. Carbon resistors become capacities at u.h.f. because of their granular structure. Metal coated resistors are satisfactory for low-power work, but no satisfactory resistors of this type have been

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[2] "Thermocouple Ammeters for Ultra-High Frequencies" by John H. Miller, *Proc. I.R.E.*, December 1936.

developed for high-power work. A pure resistance, free from reactance, is practically impossible to obtain at u.h.f. A possible exception to this statement may be an infinite line having no reflections.

Another method of obtaining a resistance free from reactance is to tune it out. For instance, load circuits have been constructed using a high-resistivity material as the inductance element of a tank circuit. This circuit may be tapped at any two symmetrical points and a pure resistance obtained, the value depending on the tapping points. This method may be used as an artificial load by circulating water through the conductor and measuring the temperature rise and water flow. It has been found desirable to arrange such loading circuits to avoid all coupling with associated circuits since the energy stored is extremely high and its field may interfere with the function of other circuits.

It has been the purpose of this article to give a general description of the problems encountered in the development of high-power television transmitters, and some of the methods used to overcome them. New vacuum tubes and equipment are now being developed with features intended to simplify these problems.

TELEVISUAL USE OF ULTRA-HIGH FREQUENCIES

By

DR. ALFRED N. GOLDSMITH

Consulting Industrial Engineer

SCIENCE moves in cycles its wonders to perform! The first method of producing images was that of the optician. This is the most nearly perfect form of color television of which we know. In every camera, light waves coming from considerable distances are caused to form a colored image on a photographic film or plate. The great industries of motion-picture and still-picture photography have been built up around this type of "television." The wavelengths used are extremely short—in fact, much shorter than we shall probably be able to generate and modulate by any direct electrical means which are now foreseeable. The wavelength is about half a thousandth of a millimeter and the hyper-super-ultra-high frequency of these light waves is about half a billion megacycles!

Long distance radio—and even broadcasting—started out by using fairly long waves, hundreds of thousands of meters in length. The "center of interest" in radio has continually shifted toward the *short* waves. Starting with the 10,000- or 20,000-meter transatlantic communication waves of 10 or 15 years ago, there was a gradual shift toward waves between 100 and 1000 meters in length. These were most popular when broadcasting originated and largely determined our present technique in that field. Then the waves from 10 to 100 meters engaged the attention of all who were concentrating on *long-distance* telegraph or telephone communication, and gave a tremendous impetus to progress by commercial organizations and *amateurs* alike. More recently—in fact, within the last few years—the pioneers have explored the domain from 1 to 10 meters (that is, from 300 to 30 megacycles). These ultra-high frequencies are clearly a sort of intermediate stage between the long waves of radio "antiquity" and the light waves which enable us to see and which are the basis of optics, photography, and picture projection. It is but natural that the *televisual* use of ultra-high frequencies should be promising. The ultra-high-frequency waves are short enough to be transmitted with great steadiness under any conditions, and their frequency is sufficiency high to prevent the Kennelly-Heavyside layer from reflecting them (except, perhaps, very occasionally). Here is a *steady* and *high-quality* medium of communication. Further, their frequency is sufficiently high to permit television modulation to be carried out accurately and without too many electrical circuit problems.

The first question facing the television experimenter is: Shall I use 30-megacycle (10-meter) waves or 300-megacycle (1-meter) waves for television? The lower frequency has some real advantages. These waves pass over the average city with less absorption and are more readily generated by efficient and available tubes. However, they have the disadvantage that they are more prone to jump over long distances, thus causing interference in remote localities and complicating greatly the problem of frequency allocation by governmental authorities. They are also more susceptible to natural static than are the higher frequencies in this band.

These higher frequencies (closer to the 300-megacycle region) have the advantage that they are less open to natural static or even man-made interference and that they can be more accurately radiated in given directions or regions by small reflecting antenna systems. They also have the advantage of a controllable and limited range which makes them suitable for easy regional allocation. But they have the disadvantage that it is difficult to generate much energy efficiently on these extraordinarily high frequencies and that the absorption of these waves, even in smaller towns or open country, is high. In fact, "line-of-sight" transmission is practically essential for these high frequencies.

It is probably best to use the lower end of this ultra-high-frequency band for television, at least for local service in the immediate future. It then becomes possible to cover metropolitan areas twenty or thirty miles in radius with a considerable degree of reliability. Interference from automobile ignition systems and medical diathermal equipment will be encountered, but can be reduced or eliminated by orderly campaigns with public support. The television picture which is transmissible on these frequencies is probably of sufficiently high quality to have continuing entertainment value and to satisfy the public. It may be added that sound programs (that is, telephone broadcasting) of *extremely high fidelity* is also possible on these frequencies. All in all, the recommendation of the radio industry to the Federal

Communications Commission that the ultra-high frequencies from 42 to 90 megacycles (excluding the amateur band from 56 to 60 megacycles) to be used for television appears to be a wise suggestion.

The televisual use of these ultra-high frequencies is certain to bring about a revolution in radio technique. Hardly anything looks the same or acts the same at these frequencies, as at the much lower frequencies which have previously been used.

The television pick-up is of course an extremely novel device which looks like a fantastic camera and contains a sensitive television pick-up tube in place of a photographic plate. The amplification of the video frequencies which are produced by the pick-up camera requires wide-band operation on a hitherto undreamed-of basis. Thus, where 10-kilocycle modulation was regarded as quite a problem in present day broadcasting, 2,000-kilocycle or higher modulation must be commonplace for television pictures of good quality. Oscillators and modulators for these frequencies are also electrical puzzles, and it has taken the utmost resourcefulness of the development engineer to produce adequate equipment of this type. The vacuum tubes which are used at such high frequencies require a design where inter-electrode capacities are made vanishingly small, and where every material is worked to the limit, consistent with its capacities. The construction of the pick-up tubes for the television camera has presented an entirely new array of problems, as has also the construction of the *receiving* cathode-ray tubes. In fact, there has sprung up an entirely new branch of science known as "electron optics," the laws and procedure of which are required to enable satisfactory pick-up and reproduction in television. There is one very encouraging aspect about the *televisional* use of the *ultra-high frequencies.* With its myriad of problems, many of which are as yet only partially solved, it provides rich material for the ambitious and skilled experimenter and development engineer. Here we have a job which will last over decades and which will offer a remarkable successful opportunity to make some careers in a new field which is bound to prove of major interest to humanity.

FREQUENCY ASSIGNMENTS FOR TELEVISION

BY

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Foreword*—This article is not a report of original work, but is a correlation or synthesis of information pertinent to the subject, available to the authors within the RCA Services or through published papers. Since the results of all have been taken into account it has not seemed feasible or desirable to give credit to individual sources except to mention the article by H. H. Beverage entitled "Some Notes on Ultra Short Wave Propagation" appearing in this number of* RCA REVIEW, *and the bibliography forming a part of that article. Much credit is due collectively to the many workers in this field, who have made possible the drawing with reasonable certainty of the conclusions here stated. The basic plan of any new service must always be determined by the work of such pioneers, before commercial experience has made everything plain. Because fundamental plans for broadcast television are now in the making, it is hoped that this brief article will be found both timely and interesting.*

INTRODUCTION

IN TELEVISION we are concerned with a broadcast type of service in which adequate coverage of a service area is the prime consideration. The frequency of the radio carrier must be high enough to permit the relatively wide side bands which are required, and so high that reflections from the ionosphere will not regularly occur. The second requirement is necessary to prevent multiple images caused by reflections from the ionosphere, and to permit duplication of frequency assignments with reasonable geographical separation of stations on the same channel. Further, in television we are concerned with a service requiring high signal strength at the receiver locations. Thus the radio carrier must be sufficiently low in frequency to permit generation of adequate power. The carrier frequency must be low enough so that the attenuation caused by obstacles on or near the transmission path is not too great, and so that the shadows cast by obstacles are not too sharp or too dense. All these considerations point to frequencies above 40 megacycles, and not greatly above 40 megacycles, as necessary if television is to be practicable in the near future.

A more specific discussion follows. It is very difficult to make positive statements because our knowledge of the many relevant factors

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is still so incomplete. Much information has been obtained and correlated, but this is only a small sample of what will be required for a complete and specific analysis. It is believed, however, that this sample is reasonably representative, and therefore that general conclusions convincingly deduced from it are reliable. The following analysis is therefore confidently believed to be correct in its general and major implications, although time may indicate some error in detail.

PROPAGATION WITHIN THE HORIZON WITH RESPECT TO THE TRANSMITTER ANTENNA

The theory of direct transmission over a flat earth, taking into account reflection from the earth, indicates that under certain conditions the field intensity is inversely proportional to the square of the distance, is directly proportional to the heights of the transmitting and receiving antennas, and is proportional to the frequency. For these relationships to be theoretically valid, the reflection from the ground must be at grazing incidence, that is, such that the conductivity and dielectric constant of the ground are not significant factors. The angles of incidence which may be called "grazing" in this sense—depend on the frequency. Thus, in any case, the validity of these simple propagation relationships depends on the geometry of the antennas and earth, on the constants of the reflecting earth, and on the frequency. Measurements, made for the most part under conditions such that these relationships were not strictly applicable, have nevertheless indicated that they are approximately correct for these practical cases, although scattering and absorption, even in open country, tend to reduce the average field intensity to somewhat less than would be calculated from the theory.

In urban areas the scattering and absorption due to buildings results in additional attenuation and this additional attenuation is the predominant factor, as far as propagation effects are concerned, in comparing the suitability of different frequencies for a local broadcast service. It increases rapidly as the frequency is increased, so that, for one set-up investigated, the average field intensity at 30 megacycles measured at a distance of 5 miles was 4.5 times that obtained at 100 megacycles for the same antenna power. The transmitter antenna was relatively low over a flat urban area, but was not overshadowed by higher structures, so that this case was typical for a broadcast service. A higher transmitter antenna might be thought more favorable to the higher frequencies, but the high antenna would only remove the region of high attenuation of the higher frequencies to a greater distance.

A factor likely to be overlooked is that the effective heights of simple and practical receiving antennas tend to be proportional to the wavelength, i. e., inversely proportional to frequency. Thus, to obtain a given voltage at the receiver input, the necessary field strength is proportional to frequency. When this is taken into account, the transmitter power needed is at best the same for higher frequencies, and on the average, for broadcast coverage, higher frequencies will require higher powers because of greater attenuation in transmission over urban areas. In the specific investigation already cited, it was indicated that several hundred times greater power would be required at 100 megacycles compared with 30 megacycles.

This tendency to lower effective height of antennas for the higher frequencies may be partially overcome by using arrays which may occupy no more space than a simple antenna for a lower frequency. However, the gain due to the directional characteristics of an array is never as great as its increased physical expanse, so the offsetting effect is only partial. Furthermore, the selectivity of an array increases with its gain, so that the use of extended arrays is not likely to be practicable for television reception. A further objection to a very selective receiving antenna is that such an antenna could not be used for efficient pickup of signals over a band of television channels.

For broadcast service in urban areas the signal path to the receivers becomes complicated. Shadows are cast by obstacles and signal reflections occur. It has been shown that shadows become sharper and more defined as frequency increases. Thus, complete coverage becomes more difficult with increasing frequency, and a more nearly optical path is required.

Reflections cause the signal for any particular receiver in a service area to arrive over a variety of paths of differing lengths and therefore the corresponding times of arrival will be different. It has been shown that the effect of this on the reproduced image is determined by the multiple path structure and the range of video frequencies (width of side bands) and is independent of the frequency of the radio carrier.

PROPAGATION BEYOND THE HORIZON WITH RESPECT TO THE TRANSMITTER ANTENNA

Comparatively few data are available for determining the laws of propagation beyond the horizon. It is well known that frequencies above 40 mc. fade at points beyond the horizon and that this fading increases as the distance increases. At and beyond the horizon the signal intensity falls off faster than the inverse square of the distance. Such limited data as are available indicate that this increase in rate of attenuation with distance also increases with frequency from approximately a 3.6 power at 40 megacycles to approximately a 5 power at 100 megacycles and to approximately an 8 power at 300 megacycles.

In television it is important that there be no sky wave propagation primarily because this would produce multiple images and secondarily because this would affect duplication of frequency assignments at reasonable distances. American amateurs and others have, on a number of occasions, established communication over long distances by frequencies up to 60 megacycles, apparently as a result of sky wave propagation caused by some sporadic condition in the ionosphere. Because of practical difficulties, quantitative measurements of such propagation have not been made. Since there have been no widespread transmissions at frequencies above 60 megacycles, there has been no opportunity to determine whether such sky wave propagation occurs at these higher frequencies or not. However, it is our opinion, based on such experience as is available, that as the frequency is increased, there is a gradual transition from normal sky wave propagation at about 20 megacycles to a condition of no sky wave propagation at any time at some frequency above 60 megacycles, and that between these limits the time of sky wave propagation becomes less and less and more and more sporadic as the frequency is increased. It is further believed reasonable to assume that sky wave transmission will not occur at frequencies above 40 to 45 megacycles in any but very sporadic instances and that these need not cause concern in the establishment of a television service.

REQUIRED SIGNAL LEVELS

For frequencies above 40 megacycles natural static is not of practical importance. Man-made interference is, however, very serious in urban districts. The major sources of such interference are ignition systems and apparatus for diathermy. In quiet suburban or rural districts, noise generated in the receiver may determine the minimum useful signal. The signal to noise ratio required for satisfactory visual reception has not been very definitely established by experience, but for noise not synchronous in any way with the picture system and not too continuous in character, it is certainly less than is required for sound broadcasting.

It has been found experimently, using frequencies of 40 to 50 megacycles, that a signal of 1 millivolt is required at the receiver input to produce an image satisfactorily free from noise generated in the receiver input circuits. A signal strength of 5 millivolts is required to overcome ignition interference and to produce a satisfactory image in an average residential location. Proportionally higher signal levels are required as the noise interference increases, particularly in areas near disturbing sources, and in congested urban districts. Locating the television broadcasting station in the center of the area to be served is a favorable condition in consideration of noise interference.

Corresponding figures for higher carrier frequencies are not available, because no actual television experience has been had with such frequencies. Effective noise field strengths are somewhat less at higher frequencies, but little quantitative information is available with respect to this. Under assumptions as favorable to the use of higher frequencies as could be made, this could only mean that receiver noise would be the limiting factor, and this would still necessitate an input of over 1 millivolt.

Few experimental data are available as to the magnitude of the interference from another television station on the same frequency channel which can be tolerated in television reception. Assuming that the two carriers are sufficiently spaced to prevent audible beats in the sound channel, say 30 kilocycles, the tolerable signal to interference ratio will be determined by visual conditions, especially image contrast. Such measurements as have been made are not directly useful, since a system having a high inherent noise level was used, but they do indicate, on a conservative basis, that it will be reasonable to assume a carrier signal intensity ratio of about 100 to 1 for allocation purposes.

GENERAL CONSIDERATIONS

Signal is propagated out to the horizon for broadcast service in a manner such that for the areas of most interest, the attenuation will increase with increasing frequency. At and beyond the horizon the attenuation rises sharply for all frequencies and more sharply with increasing frequency. Thus the practical limit of service area is the horizon. Power increases will be useful to the point of providing the desired signal at the horizon (and naturally at locations of high noise interference within the horizon). For a given frequency the power required to produce a given signal input to a receiver at the horizon with respect to the transmitter antenna is approximately constant for all transmitter antenna heights assuming flat unobstructed ground.

A desired condition is a radiation pattern circular in the horizontal plane (or of proper directivity characteristics for the transmitter location and service area). Since sky wave transmission is not desired and is not present it is important to concentrate the energy into low angles in the vertical plane so as to obtain a power gain in transmission. This may be done for either vertical or horizontal polarization, but present known simple structures are most effective for horizontal polarization. For broadcast service, in terms of signal intensity, there appears to be no advantage in one polarization over the other (excluding transmission over sea water). The matter of signal reflections in and around building has not been fully investigated, but again there appears to be no advantage in one over the other. In considering noise interference, complete data are lacking, but some experience has indicated a slightly lower noise level for horizontal polarization.

APPARATUS CONSIDERATIONS

Present vacuum tube and transmitter circuits place limits on the power levels obtainable for television transmission. The conditions of band width and high signal intensity are severe. Greater powers call for larger dissipating surfaces in the output tubes—affecting dimensions already too large for best efficiency even at 40 megacycles. As the frequency increases smaller dimensions are necessary resulting in lower powers, whereas propagation conditions call for greater powers to produce the same signal intensity. For the present experimental television band of 42 to 86 megacycles, higher powers may be obtained over the lower portion of the band and lower powers over the upper portion. The present specific power limitations will be modified as the technique advances. However, the time when power in tens of kilowatts at frequencies over 100 megacycles will be practicable appears a long way off. Coupled with this is the uncertain practicability of a broadcast service of the present basic type above 100 megacycles in view of the higher attenuation in urban territory which may indicate impracticably high output powers. These higher frequencies appear more suited to point-to-point service than to broadcast service in urban areas.

CONCLUSIONS

From the foregoing it is concluded that the television band should start at a frequency between 40 and 45 megacycles. A frequency of 42 megacycles was recommended by Radio Manufacturers' Association as the lower limit, and is satisfactory from considerations of lack of sky wave, modulation with video frequency band, and propagation characteristics. The upper frequency limit is determined by the number of six megacycle channels required. A proposal of 42 to 90 megacycles has been made. This is satisfactory with respect to propagation, apparatus, and distribution of channels at reasonable distances.

PARTIAL SUPPRESSION OF ONE SIDE BAND IN TELEVISON RECEPTION

BY

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INTRODUCTION

EARLY television development followed the precedents established in sound broadcasting. A radio carrier was amplitude modulated by the video signals resulting from scanning and the transmission included both side bands. In the receivers the selectivity or bandwidth was made such as to pass both upper and lower side bands when the carrier was modulated with the highest desired modulating frequency. Progress in television development has been marked by a continual increase in the number of scanning lines and requiring, in turn, increases in the communication band. This race, as it became, between the terminal apparatus—ability to increase resolution, i.e., number of lines—and the communication portions of the system—ability to increase band width in the amplifiers and circuits exhibiting selectivity characteristics—first found one element in the lead and then the other. At times when the receiver band-pass characteristics were more limiting than other elements, it was early determined experimentally that a better picture was obtained when the receiver was slightly detuned. Thus, by detuning, the picture carrier was placed near one edge of the selectivity characteristic.

Later when this condition was more thoroughly appreciated, an analysis was made of its importance and usefulness. Suppose we deliberately design a receiver so the resulting intermediate frequency is placed near one edge of the intermediate-frequency circuit selectivity characteristic and so that carrier and all of one side band but only a small portion of the other side band is accepted, with the over-all selectivity being insufficient to remove entirely the second side band. We shall term this a selective side-band receiver. An immediate advantage is that we nearly double the modulation frequency range that the receiver will pass. This is of great importance where the band width for one side-band approaches the limits of circuit and tubes and where it is inadvisable to reduce gain or selectivity.

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It is a well-known fact that for circuits passing broad bands, the gain per stage is inversely proportional to the band width. This means that n intermediate-frequency amplifiers having the same number of stages, one for selective side-band and the other for double side-band operation, will have a difference in gain of 2^n, where n is the number of stages. For six stages this means a difference in gain of 64 to 1. If the gain per stage of the selective side-band receivers were 8, the double side-band receiver must have three additional stages to have the same over-all gain.

Before taking the important step of making this change in the receivers, it was thought necessary to make a further investigation of this problem. An experimental transmitter and receiver system, whose condition of operation could be controlled and upon which measurements could be easily made, was set up. This apparatus was arranged so that it would be used either as a double or a selective side-band system with a simple and quick changeover arrangement. It was also arranged so that part of the suppression of one side band was done in the transmitter, to determine whether this would introduce any special difficulties. The data taken on this system were also verified by a mathematical investigation.

Because of the profound influence selective side-band suppression is likely to have on practical systems of television, it is considered of interest and importance to describe these early tests and to outline the mathematical verification.

APPARATUS USED IN EXPERIMENTAL WORK

Fig. 1 is a block diagram of the transmitter and receiver equipment. The only adjustment necessary for changing from double side-band to selective side-band operation was to shift the master oscillator frequency from 4.25 to 4 megacycles. Suppose that the master oscillator was generating 4.25 megacycles, the condition necessary for normal double side-band operation. The modulator then delivered an 8.5-megacycle modulated carrier at the input of the transmitter intermediate-frequency amplifier. Care had been taken to make the modulation amplifier and the modulator itself with a fidelity characteristic flat to 1000 kilocycles. The output of the intermediate-frequency amplifier, still an 8.5-megacycle carrier but with side bands trimmed to 500 kilocycles on each side, was used to modulate another oscillator operating at 63.5 megacycles. Only the resulting lower side band was used. This was a carrier at 55 megacycles with side bands extending to 500 kilocycles on both sides. The receiver was also tuned in such a way that the incoming carrier was located in the center of the receiver selectivity characteristic, so that again both side bands were treated alike. The second detector and video frequency amplifier which were adjusted to have a fidelity characteristic good to 1000 kilocycles, brought the modulated signal to the grid of the "Kinescope.*"

Now suppose that the frequency of the master oscillator was shifted from 4.25 to 4 megacycles, the condition for selective side-band operation. The carrier output of the modulator doubler was now at 8 megacycles which brought the carrier to one edge of the transmitter intermediate-frequency pass-band characteristic. The output of this amplifier was still a carrier at 8 megacycles but with the upper side band extending to 1000 kilocycles and the lower side band greatly attenuated, except at low modulation frequencies. Similarly, in the receiver whose tuning adjustment had not been altered, the carrier was also moved to one edge of the selectivity characteristic, causing one side band to be reduced still more. At low video frequencies normal demodulation of a carrier and both side bands occurred at the second detector. At the higher video frequencies only the carrier and one sideband were present. In between was a range of frequencies in which one side-band was being rapidly attenuated. This problem of detection will be discussed in more detail later.

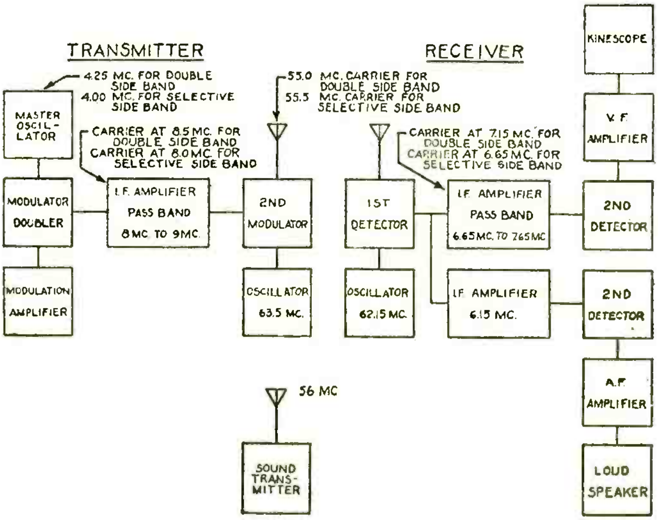

Fig. 1—Block diagram of the transmitter and receiver equipment.

The sound transmitter and the sound channel of the receiver which

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* Trade Mark Registered U. S. Patent Office.

had a sharp selectivity characteristic compared with that of the picture channel, were used to check the tuning of the receiver. The frequency spacing between picture and sound transmitters was checked by tuning a broadcast receiver to the difference frequency.

SELECTIVITY MEASUREMENTS

Figs. 2 and 3 show the selectivity characteristics of the transmitter and receiver intermediate frequency amplifiers. These were taken in the usual manner with a calibrated oscillator and vacuum tube voltmeter. Rejector circuits were used in both of these amplifiers which increased the attenuation of the unwanted side band. In the receiver, the rejector circuits were tuned to the sound intermediate frequency to prevent interference from the sound transmitter in the picture channel. Note that these curves show a generous 1000-kilocycle band width. An over-all selectivity measurement was not made but should correspond to the product of the two curves shown since the radio-frequency output circuit at the transmitter and the input system of the receiver did not have sufficient selectivity to affect the other curves.

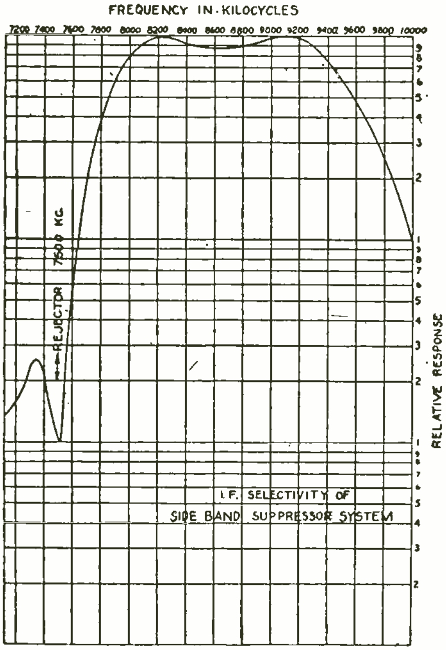

Fig. 2—IF selectivity of side band suppressor system.

MEASUREMENT OF FIDELITY AND PHASE CHARACTERISTICS

Measurements of fidelity and phase characteristics were made in the video frequency range between 10 and 1000 kilocycles since no effects due to suppressing one side band were found below 10 kilocycles. The fidelity characteristics were taken with a beat frequency oscillator and vacuum tube voltmeter having an upper frequency limit of 1000 kilocycles. A cathode-ray oscillograph also having a 1000-kilocycle frequency range was used in conjunction with the beat frequency oscillator to obtain the phase characteristics. This was done by the familiar method of connecting the output of the beat oscillator to the horizontal deflecting circuit of the oscillograph and the output voltage of the circuit being tested to the vertical deflecting circuit. From measurements of the resulting ellipse the phase angle between the input and output voltages can be calculated. To avoid wave shape errors, modulation on the transmitter was kept below about 25 per cent. The most desirable characteristics are, naturally, to have a flat frequency response and to have the phase shift proportional to frequency.

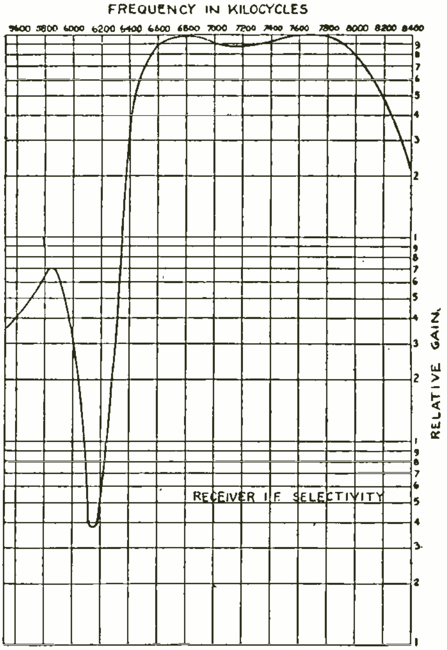

Fig. 3—Receiver IF selectivity.

Fig. 4 shows the resulting fidelity curves. The over-all curve for double side-band operation shows the expected loss in response above 500 kilocycles due to trimming of the side bands. The over-all curve for selective side-band operation is perhaps better than might be anticipated. Since at low modulation frequencies both side bands are present at the second detector and at the higher frequencies only one, we would expect the fidelity curve to drop down approximately 50 per cent at a fairly low frequency and then continue to about double the frequency limit for double side-band operation before dropping down again. This effect, however, is also dependent upon the exact position of the carrier on the edge of the selectivity curve. The farther down we put the carrier on the side of the curve, the less will be the first dip

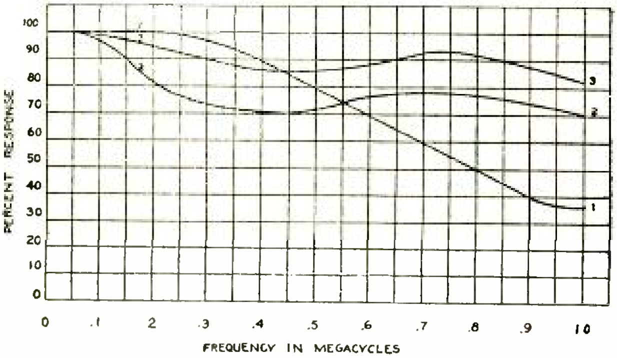

Fig. 4—Measured fidelity. 1. Over-all fidelity double side-band operation. 2. Over-all fidelity selective side-band operation. 3. Picture amplifier fidelity of receiver.

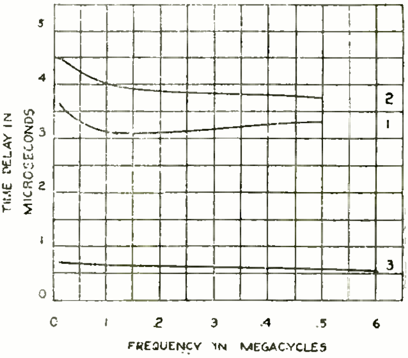

Fig. 5—Measured phase delay. 1. Over-all phase delay using double side-band transmitter. 2. Over-all phase delay using selective side-band transmitter. 3. Receiver picture amplifier alone.

downward in the response curve. It is possible, of course, to carry this procedure so far that the high-frequency response will actually be greater than the low-frequency response. In this particular case, the over-all selectivity curve of the system and the position of the carrier relative to it were such that the response curve shown in Fig. 4 was produced.

Fig. 5 shows the phase delay characteristics corresponding to the previous frequency characteristics. The phase shift, as measured by the ellipse method, was converted to phase delay by the following equation:

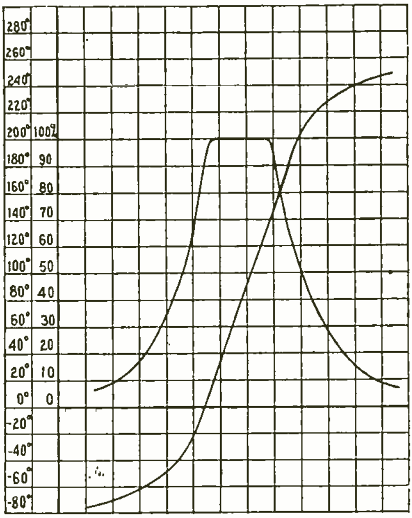

Fig. 6—Selectivity and phase of intermediate-frequency transformer.

$$\text{Phase delay} = \frac{\text{phase angle}}{360° \times \text{frequency}}.$$

This expression gives the actual time required for a cycle of a given frequency to go between input and output of the amplifier system being measured. Obviously, if this time is the same for all video-frequencies, there will be no phase distortion. This condition for a constant phase delay is equivalent to the previously mentioned condition for having the phase shift proportional to frequency. The variation in phase delay over the video frequency band may be taken as a measure of the phase distortion. Note that this variation is greatest for selective side-band operation but that the difference in variation between double side-band and selective side-band operation is not very great.

Fidelity and delay characteristics for conditions similar to those in this experimental work were also calculated and are given in the next section.

CALCULATION OF FIDELITY AND DELAY CHARACTERISTICS

In order to calculate these characteristics it is necessary to know the over-all selectivity and phase characteristics of the system. Accordingly, the selectivity and phase curves for one of the coupling transformers used in the intermediate-frequency system were calculated. These curves are shown in Fig. 6. Assuming no radio-frequency selectivity and that all the coupling circuits are identical, the selectivity and phase characteristics of the receiver or receiver and transmitter may be deducted from Fig. 6 by merely raising the ordinates of the selectivity curve to the *n*th power and multiplying the ordinates of the phase curve by *n*, where *n* is the number of identical coupling circuits used in the system. Fig. 7 shows the selectivity and phase characteristics for four intermediate-frequency coupling circuits is cascade as obtained from Fig. 6. These curves may be taken as the selectivity and phase characteristics of the receiver or transmitter alone.

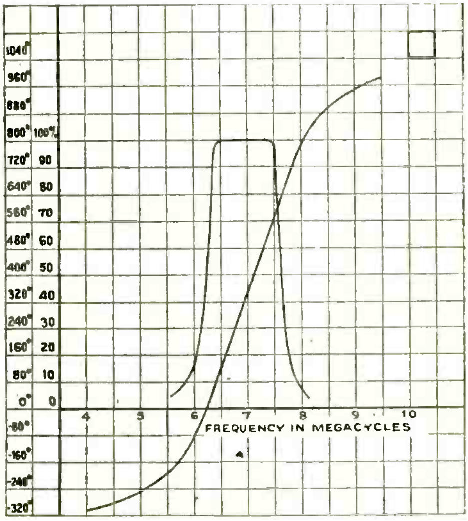

Fig. 7—Selectivity and phase characteristics of the intermediate-frequency amplifier.

Before proceeding with the calculation of the fidelity and delay characteristics as obtained from the selectivity and phase curves of the intermediate frequency, it is worth reviewing, for the sake of clarity, the action of the intermediate frequency and second dectector on a carrier modulated by a single frequency. For this purpose, consider the simple case of a receiver in which the input to the intermediate-frequency amplifier consists of a carrier of frequency f_0 modulated with the video frequency f_1. The input to the intermediate-frequency amplifier may then be written as

$$e = E \cos \omega_0 t + \frac{mE}{2} \cos (\omega_0 + \omega_1)t + \frac{mE}{2} \cos (\omega_0 - \omega_1)t \qquad (1)$$

where $\omega = 2\pi f$, E is the amplitude of the unmodulated carrier, and m is the percentage of modulation. After passing through the selective circuits of the intermediate-frequency amplifier, the voltage output becomes

$$v = E\left[A_c \cos (\omega_0 t + \phi_0) + \frac{mA_u}{2} \cos \left\{ (\omega_0 + \omega_1)t + \phi_u \right\} \right.$$
$$\left. + \frac{mA_L}{2} \cos \left\{ (\omega_0 - \omega_1)t + \phi_L \right\} \right] \qquad (2)$$

where A_c, A_u, and A_L are the amplitude ratios of output to input of the intermediate-frequency amplifier for the frequencies f_0, $f_0 + f_1$, and $f_0 - f_1$, respectively, and ϕ_0, ϕ_u, and ϕ_L are the phase shifts introduced by the selective circuits of the intermediate frequency for the respective frequencies.

Equation (2) gives the input to the second detector. The output of the second detector may be obtained by first determining the envelope of the modulated carrier given by (2). To determine the envelope at the input to the second detector it is but necessary to transform (2) into the form

$$v = V_e \cos (\omega_0 t + \phi)$$

and then gives the form of the envelope. Performing this transformation there results that

$$V_e = E\left[A_c^2 + \frac{m^2}{4} \left\{ A_u^2 + A_L^2 + 2A_u A_L \cos (2\omega_1 t + \phi_u - \phi_L \right\} \right.$$
$$\left. + mA_c \left\{ A_u \cos (\omega_1 t + \phi_u - \phi_0) + A_L \cos (\omega_1 t + \phi_0 - \phi_L) \right\} \right]^{1/2} \qquad (3)$$

Equation (3) thus gives the shape of the carrier envelope at the input to the second detector.

It is worth noting, in passing, that the phase of the modulated carrier, ϕ, is given by

$$\tan\phi = \frac{A_c \sin\phi_0 + \frac{mA_v}{2}\sin(\omega_1 t + \phi_u) - \frac{mA_L}{2}\sin(\omega_1 t - \phi_L)}{A_c \cos\phi_0 + \frac{mA_u}{2}\cos(\omega_1 t + \phi_u) + \frac{mA_L}{2}\cos(\omega_1 t - \phi_L)} \tag{4}$$

and that in general when one of the side bands is partially suppressed $\tan\phi$ is a function of time so that some phase modulation exists.

Referring to (3) it may be seen that for low percentages of modulation the output of an n-law detector* is given by

$$V_e^n = E^n\Big[A_c^n + \frac{nm}{2}A_c^{n-1}\{A_u\cos(\omega_1 t + \phi_u - \phi_0) + A_L\cos(\omega_1 t + \phi_0 - \phi_L)\}\Big] \tag{5}$$

Equation (5) shows that for small percentages of modulation the detector will reproduce only the original modulation frequencies. Assuming, therefore, a small percentage of modulation one may, with the aid of (5), calculate fidelity and delay characteristics from the selectivity and phase curves of the intermediate frequency. Thus the output of the second detector at the frequency f_1 is, by (5), proportional to

$$A_u\cos(2\pi f_1 t + \phi_u - \phi_0) + A_L\cos(2\pi f_1 t + \phi_0 - \phi_L)$$

where A_u and A_L are the ratios of output to input amplitudes for the frequencies $f_0 + f_1$ and $f_0 - f_1$, respectively, as obtained from a selectivity curve such as that shown in Fig. 7 and where ϕ_0 is the phase of the carrier and ϕ_u and ϕ_L are the phases for the frequencies $f_0 + f_1$ and $f_0 - f_1$, respectively, as obtained from the phase curve of Fig. 7. Adding the above two terms there results that

$$A_u\cos(2\pi f_1 t + \phi_u - \phi_0) + A_L\cos(2\pi f_1 t + \phi_0 - \phi_L) = Vf_1\cos(2\pi f_1 t - \theta)$$

where,

$$Vf_1 = \sqrt{A_u^2 + A_L^2 + 2A_uA_L\cos(\phi_u + \phi_L)} \tag{6}$$

and,

$$\tan\theta = \frac{A_u\sin(\phi_u - \phi_0) + A_L\sin(\phi_0 - \phi_L)}{A_u\cos(\phi_u - \phi_0) + A_L\cos(\phi_0 - \phi_L)}. \tag{7}$$

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* $n = 1$ for a linear detector, $n = 2$ for a square detector, etc.

The fidelity and phase characteristics may then be calculated by using (6) and (7) and the curves of Fig. 7. As was mentioned previously, the phase delay in seconds at any frequency f is $\theta/2\pi f$ where θ is in radians and f in cycles per second.

Fidelity and delay characteristics corresponding to various intermediate-frequency carrier frequencies were calculated with the aid of (6) and (7) and are shown in Fig. 8. These fidelity curves correspond to those of a receiver with no radio-frequency detector or video distortion and with the selectivity shown in Fig. 7. Curves (1), (2), (3), and (4) of Fig. 8 correspond to the fidelity of the receiver for intermediate-frequency carrier frequencies 6.9, 6.4, 6.2, and 5.6 megacycles, respectively.

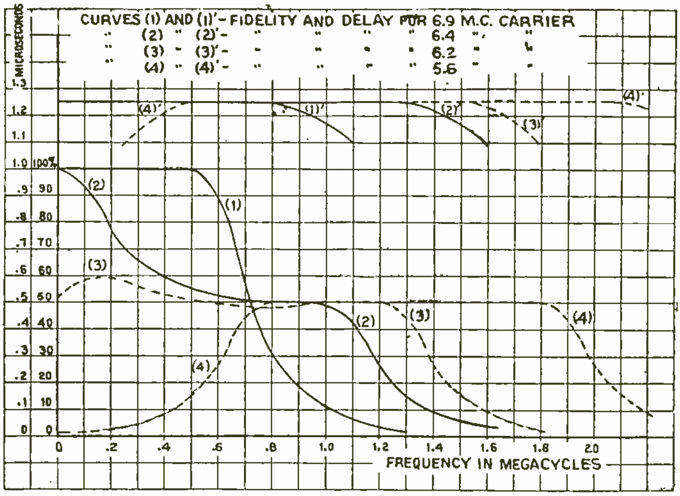

Fig. 8—Fidelity and delay characteristics.

In obtaining Fig. 8 it is assumed that the transmitter passes both side bands. If the transmitter partially suppresses one side band, it may still be assumed that the transmitter passes both side bands but that the receiver selectivity has been increased. Fig. 9 gives the selectivity and phase characteristics corresponding to those of receiver and transmitter. The fidelity characteristics for such a receiver calculated from Fig. 9 are shown in Fig. 10. Thus Fig. 10 gives the fidelity of a receiver having the selectivity shown in Fig. 1 when the transmitter has the same selectivity. Curves (1) and (2) of Fig. 10 correspond to a carrier at 6.4 and 6.25 megacycles, respectively.

Referring to Fig. 8 it is to be seen that: Curve (1), **corresponding**

to double side-band reception, is practically flat in the frequency range 0 to 0.6 megacycles. No phase distortion is present in the frequency range 0 to 0.8 megacycles. Curve (2), obtained with the carrier on one edge of the selectivity curve, emphasizes the lower frequencies more than the higher. No phase distortion is present in the frequency range 0 to 1.3 megacycles. Curve (3) is the best fidelity characteristic and is obtained when the carrier (with two side bands) is located halfway down the selectivity curve of Fig. 1. The delay characteristic given by

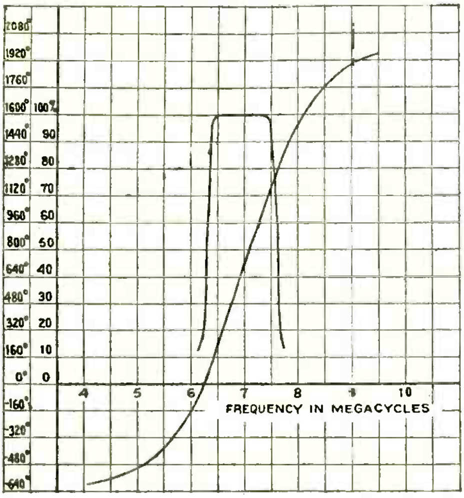

Fig. 9—Selectivity and phase equivalent to that of receiver and transmitter.

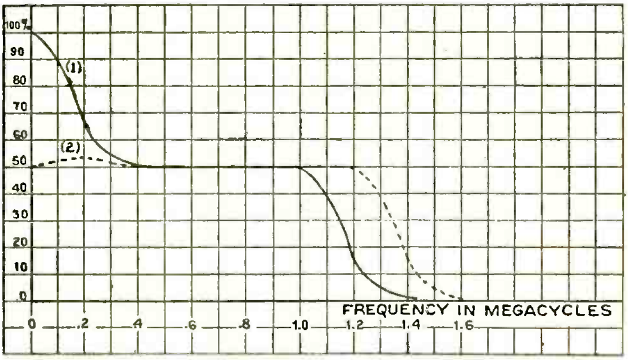

Fig. 10—Curve (1) fidelity for 6.4-megacycle carrier, obtained from figure. Curve (2) fidelity for 6.25-megacycle carrier, obtained from figure.

curve (3) of Fig. 8 is flat in the frequency range 0 to 1.5 megacycles, and hence there is no phase distortion, as all frequencies are delayed by the same time. The time of delay is seen to be about 1.25 microseconds. The characteristic is practically flat in the frequency range 0 to 1.3 megacycles. Curve (4) shows the low frequencies badly attenuated. Phase distortion exists for low and high frequencies.

The curves of Fig. 8, therefore, show that with the assumptions made and with the transmitter passing both side bands, it is best to tune in about halfway down on the selectivity curve in order to obtain the optimum fidelity curve with a given selectivity curve of the receiver.

The curves of Fig. 10 similarly show that with the transmitter partially suppressing one side band it is best to attenuate the carrier at the transmitter and receiver so that the total attenuation is down to 50 per cent. Thus if the transmitter attenuates the carrier to 71 per cent and the receiver to 71 per cent of this the result is about 50 per cent. However, as is shown by curve (4) of Fig. 8, the carrier should not be attenuated by transmitter or receiver any further than to 30 per cent, for at 30 per cent and below phase distortion appears. With phase distortion objectionable transients occur.

RESULTS WITH PICTURE MODULATION

Coming back to the experimental transmitter and receiver setup again, tests were made on the system using both double and selective side-band operation. The previous measurements and calculations should lead us to expect that with selective side-band operation, there should be much better detail due to the additional high-frequency response. At the time these measurements were made, the picture scanning equipment had an upper frequency limit of 500 kilocycles so that when pictures under both conditions of operation were compared, most observers agreed that there was very little difference between the two. Since that time the upper frequency limit of the picture pickup equipment has been increased and the expected increase in detail clearly demonstrated. Changing from double side-band to selective side-band operation, therefore, means an approximately two-to-one improvement in detail which results in a distinctly clearer and sharper picture.

SECOND-DETECTOR DISTORTION

The conclusions drawn from the calculated fidelity characteristics shown in Figs. 8 and 10 were based on the assumption that the detector distortion is negligible. This was shown to be true for any detector so long as the percentage of modulation is sufficiently small. The conclusions have to be modified when detector distortion with large percentages of modulation is considered.

Referring to (3) it may be seen that for double side-band reception where $A_u = A_L$ and $\phi_u - \phi_0 = \phi_0 - \phi_L$ the form of the carrier envelope becomes

$$V_e = E\left[A_c + mA_u \cos\left(\omega_1 t + \frac{\phi_u - \phi_L}{2}\right)\right] \tag{8}$$

so that a linear detector will introduce no distortion for any percentage of modulation. If one of the side bands, say the lower, is completely suppressed then $A_L = 0$ and (3) reduces to

$$V_e = E\left[A_c^2 + \frac{m^2}{4}A_u^2 + mA_cA_u \cos(\omega_1 t + \phi_u - \phi_0)\right]^{1/2} \tag{9}$$

Hence, the output of a square detector will be

$$V_e^2 = E^2\left[A_c^2 + \frac{m^2}{4}A_u^2 + mA_cA_u \cos(\omega_1 t + \phi_u - \phi_0)\right] \tag{10}$$

so that no distortion is introduced if a square detector is used. If one of the side bands is but partially suppressed then it follows from (3) that, for high percentages of modulation, there is, in general, no detector which will reproduce only the modulating frequency.

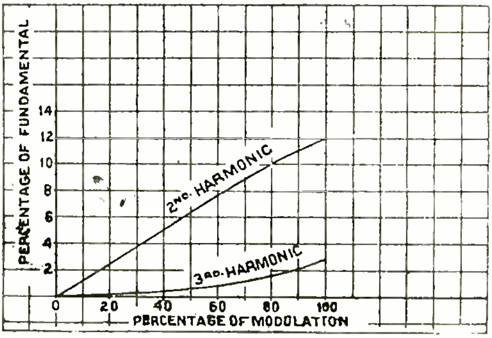

Fig. 11—Variation of harmonic distortion with percentage of modulation.

Some estimate of the second-detector distortion may be made by assuming that one of the side bands is totally suppressed and that a linear detector* is used on the envelope given by equation (9). Figure

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* 100 per cent modulation means a carrier modulated to 100 per cent with both side bands present.

10 gives the per cent of harmonics introduced by a linear detector as the percentage of modulation† is increased. It is seen that the introduction of these harmonics occurring at high percentages of modulation would be objectionable in the case of sound reception. However, in television it is not the frequency per se but rather the wave form of the signal that is important. The solid line of Fig. 11 shows a single side-band carrier envelope (the upper half of which is the output of a linear detector) and the dotted line shows the fundamental sine wave. In television reception the two wave forms would appear as practically identical.

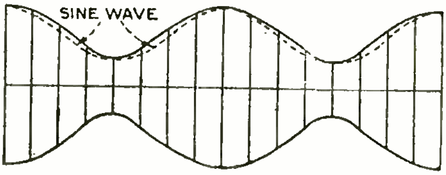

Fig. 12—Single side-band carrier envelope.

In discussing detector distortion for large percentages of modulation it is not sufficient to consider the envelope given by (3), but rather it is necessary to consider the envelope of a carrier modulated with any number of frequencies. By a method identical with that used in deducing (3) it may be deduced that the envelope of a carrier modulated with *n* frequencies is at the input to the second detector.

$$\begin{aligned}
V_e = E\Bigg[A_c{}^2 &+ \frac{m^2}{4}\sum_{i=1}^{n}(A_{L_i}{}^2 + A_{u_i}{}^2) \\
&+ \frac{m^2}{2}\sum_{i=1}^{n} A_{L_i}A_{u_i}\cos(2\omega_i t + \phi_0 - \phi_{L_i}) \\
&+ \frac{m^2}{4}\sum_{i=1}^{n}\sum_{\substack{j=1\\ i\neq j}}^{n}\Big\{A_{L_i}A_{L_j}\cos[(\omega_i - \omega_j)t + \phi_{L_j} - \phi_{L_i}] \\
&+ A_{u_i}A_{u_j}\cos[(\omega_i - \omega_j) + \phi_{u_i} - \phi_{u_j}] \\
&+ 2A_{L_i}A_{u_j}\cos[(\omega_i + \omega_j) + \phi_{u_j} - \phi_{L_i}]\Big\} \\
&+ mA_c\sum_{i=1}^{n}\Big\{A_{L_i}\cos(\omega_i t + \phi_0 - \phi_{L_i}) \\
&+ A_{u_i}\cos(\omega_i t + \phi_{u_i} - \phi_0)\Big\}\Bigg]^{1/2} \qquad (11)
\end{aligned}$$

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† Since a linear detector is usually used in practice.

It is to be noted that for large percentages of modulation any detector will reproduce not only the original modulation frequencies but also a great many others resulting from various combinations of the modulating frequencies.

With the effect of the second detector in mind, picture signal was again put on the experimental transmitter operating to suppress one side band and effects due to this type of distortion looked for. The picture modulation was increased to a value where saturation in the modulator began to be noticeable. All observers agreed that up to this value of modulation no difference in the picture compared to one at a lower value of modulation could be noticed. This supports the theory that distortion of this type causes no appreciable hurtful effect in the picture. It also indicates that the amount and type of distortion which can be tolerated in a picture signal is quite different than that in a sound signal.

LOCATION OF THE CARRIER ON THE SELECTIVITY CURVE

The calculated fidelity curves showed how the over-all frequency characteristic was greatly influenced by the exact position of the carrier at the edge of the selectivity curve. When the carrier was tuned at the 50 per cent response point of the over-all selectivity curve a very good over-all fidelity curve was obtained. At this point, however, the selectivity curve is quite steep and slight variations in tuning cause considerable changes in the over-all frequency characteristic. It also means that to obtain uniform results from a number of receivers their selectivity and tuning characteristics must be held to very close tolerances. We have found that a reasonable compromise is to have the carrier approximately 25 per cent down from maximum response. At this point the selectivity curve has not yet become very steep and the slight drop in high frequency response can be compensated for in the video frequency amplifier following the second detector.

TRANSMITTER CONSIDERATIONS

Since the time these measurements and calculations were made a moderate power test transmitter was installed in Camden to provide a signal at a receiver location a mile away. No attempt was made to suppress one side band in the transmitter but all the receivers used with it were of the selective side-band type. Excellent results were obtained with this system and the difference in detail between double side-band and selective side-band operation could be easily demonstrated by tuning from the center to the edge of the receiver selectivity curve. The suppression of one side band at the transmitter becomes a very difficult problem at the frequencies which are used for television. If this can be successfully done then the band width of one channel for television transmission can be considerably reduced. The power requirements of the transmitter are expected to be approximately the same, whether the double side-band or selective side-band operation is used. While the input signal may be thought of as being reduced due to the absence of one side band, the gain in the input circuits can be increased due to the smaller band width necessary. This increases the signal-to-noise ratio on the grid of the first tube which compensates for the loss of one side band.

CONCLUSIONS

This investigation has shown that no serious difficulties are encountered when a television system is operated with the carrier at one edge of the over-all selectivity curve. The necessity for fewer stages of amplification in the intermediate-frequency amplifier of the receiver makes it very desirable to adopt this system. In addition to this, if one side band can be suppressed at the transmitter there will be a considerable saving in channel requirements.

TELEVISION RADIO RELAY

BY

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***Summary.**—A general description of the 177 Mc television radio link between the RCA Building and the Empire State Building in New York City is given. The transmitter and receiver are described in detail along with results of tests on the circuit.*

WITH the installation of the new television transmitter in the Empire State Building, it became necessary to provide a connecting link to carry the video frequencies from the studios at Radio City to the transmitter. Both a coaxial cable and radio circuit are used for this link. This paper is devoted entirely to the radio circuit and its terminals.

The radio circuit is operating on a carrier frequency of 177 Mc which was chosen to be clear from harmonics of the picture and sound transmitters operating in close proximity to the relay receiver. A high frequency was chosen to be free from interference on existing radio services, to allow directive antennas to be used in which space was a limiting factor, and to take advantage of the lower man-made noise level encountered from sources such as elevator contractors, motors, etc. Vacuum tubes now available make operation above 200 Mc difficult. The air line distance from the transmitting antenna at Radio City to the receiving antenna at the Empire State Building is approximately 4600 feet. Ultra-high frequencies are particularly adaptable to distances of this sort, and to the wide modulation band required.

PROPAGATION TESTS

The video frequencies up to 1500 kc. to be transmitted require the radio circuit to carry a band of 3000 kc. with double side band transmission. Calculation showed that the combination of the direct and reflected rays at the receiving antenna could cause serious variations in transmission efficiency throughout the extremely wide band, depending upon the location of the points

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of reflection, and the intensity of the reflected ray or rays. To obtain more accurate information regarding this variation in transmission efficiency, propagation tests were carried out over the hand of 176 to 182 Mc. This work is described in a paper by P. S. Carter and G. S. Wickizer.[1] The results of these tests showed that a reasonably flat response could be obtained by using transmitting and receiving antennas having moderate horizontal directivity. Fig. 1, from the above paper, shows the response curve obtained with a directive transmitting antenna located at the 14th floor level of the RCA Building and a directive receiving antenna at the 85th floor of the Empire State Building. The antennas now in use at each end of the circuit are electrically equivalent to each other and consist of a one wavelength horizontal radiator, fed at the middle, located in front of a metal reflector. Fig. 2 is a photograph of the transmitting antenna now in use. These antennas are sufficiently broad to pass, without appreciable attenuation, the 3000 kc. band.

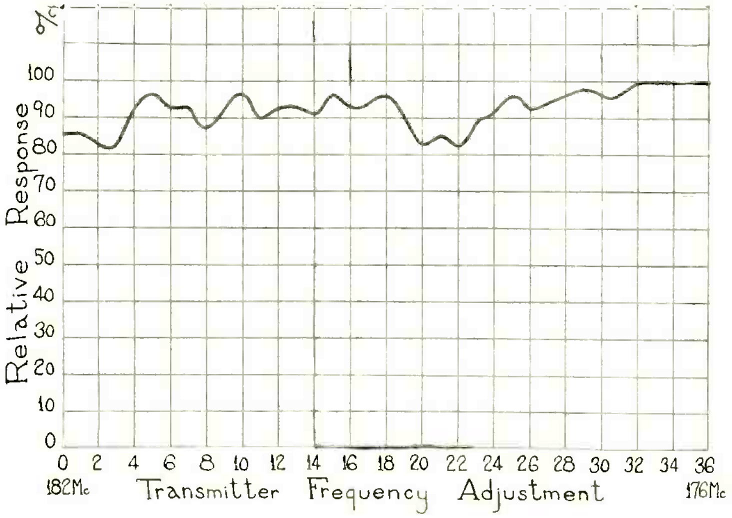

Fig. 1—Variation of received signal—horizontal one wavelength transmitting antenna at 14th floor level; receiving antenna, two horizontal half wave dipoles end to end spaced 1½ wavelengths between centers.

TRANSMITTER

The complete transmitter is mounted in a standard relay rack as shown in Fig. 3. The top unit contains the power amplifier, master oscillator, modulator and modulator amplifiers. This unit is mounted on rubber to protect the tubes and circuits from vibration. A peak voltmeter has been provided to measure the input level to the modulator amplifier and the output of the monitor rectifier. It is located just below the rubber mounted unit. Below the peak voltmeter panel is the d-c filament supply unit for the master oscillator. The bottom two units are plate supply rectifiers for the radio frequency stages and the video frequency stages. A schematic diagram for the transmitter is shown in Fig. 4.

The master oscillator, right hand compartment of Fig. 5, consists of two RCA-834 type tubes operating in push-pull at a frequency of 177 Mc. The frequency of the oscillator is determined by a low power factor, concentric resonator to which the grids are inductively coupled. The grid loops which are coupled to the frequency control circuit are in opposite polarity so that the phase of the grid voltages differ by 180°.[2] The ratio of the diameters of the concentric conductors of the frequency controlling circuit is 3.5.[3] A theoretical Q of 11,370 is obtained with an inside conductor diameter of 2.25 inches.[2,4] The inner member, which is .2 of a wavelength long, has one end silver soldered to an end plate of the outer sheath, and the other end connected to a four-inch diameter sylphon bellows one inch long. The free end of this bellows is screwed to an invar rod which is connected to the same end plate which supports the inner conductor. Since the temperature coefficient of expansion of invar is nearly zero the electrical length of the inner conductor is approximately constant with changes in temperature. Thus the resonant frequency

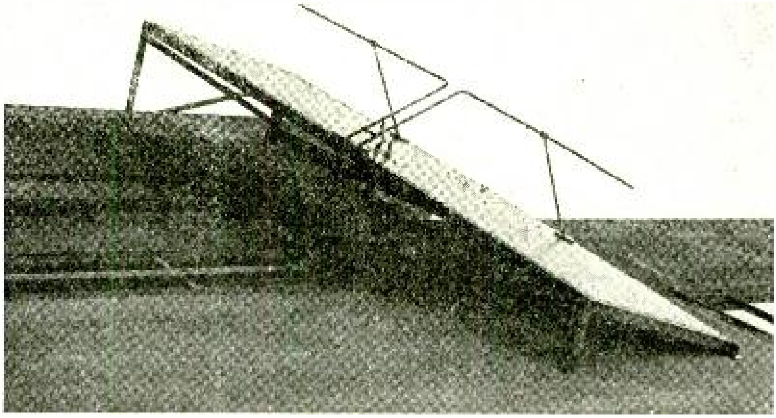

Fig. 2—Transmitting antenna at 14th floor level of RCA Building.

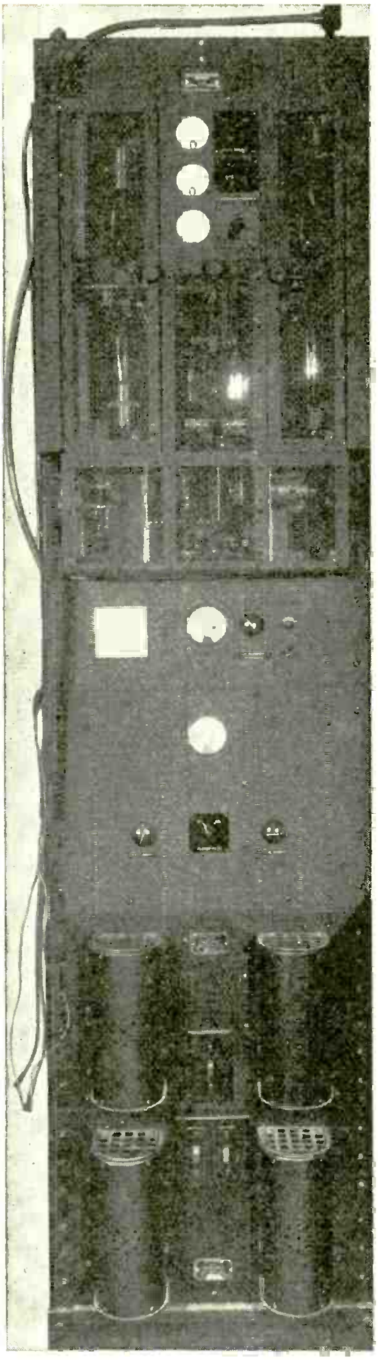

Fig. 3—177 Mc television radio relay transmitter.

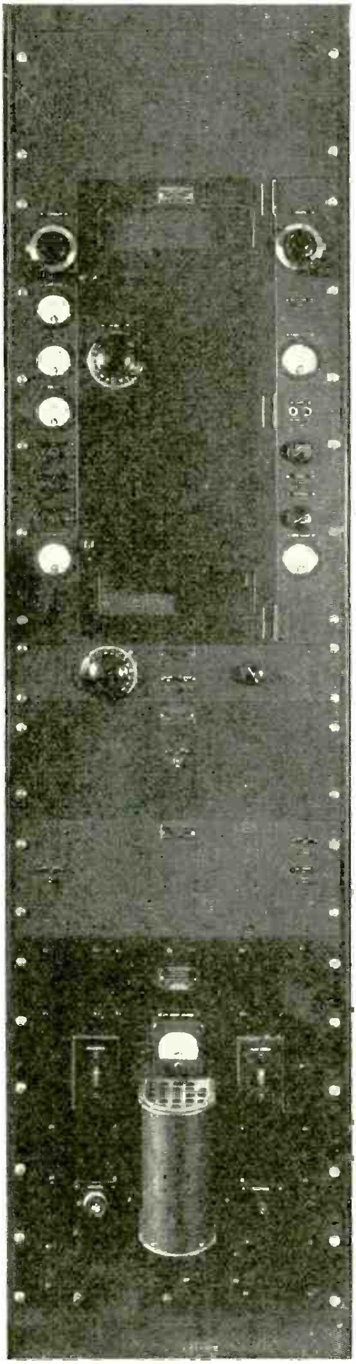

Fig. 7—177 Mc television radio relay receiver.

of the low power factor circuit is made substantially independent of temperature.

The master oscillator has adjustable impedances in its plate and filament circuits. The grid circuit reactance was adjusted to about the required value by a short wire connected from grid to grid. This wire is in parallel with the grid loops which couple to the low power factor circuit. The plate inductance is a concentric conductor line connected from plate to plate. At the neutral point on this line the inside conductor is exposed so the power amplifier grid coil may be inductively coupled to it. The photograph of Fig. 5 shows the master oscillator on the right hand side, the modulator in the center, and the power amplifier on the left. With such an arrangement the connection from the modulator to the power amplifier grid circuit is short and the modulator output capacitance is reduced. However, this makes the link from the master oscillator to the power amplifier rather long. This link is the master oscillator plate inductance and its maximum reactance is fixed by the tube inter-electrode capacities. The correct inductance was obtained by the proper choice of the conductor diameters. A small balanced condenser connected from plate to plate is used for fine adjustment of the master oscillator circuit. Plate voltage is supplied to each tube through an r-f choke.

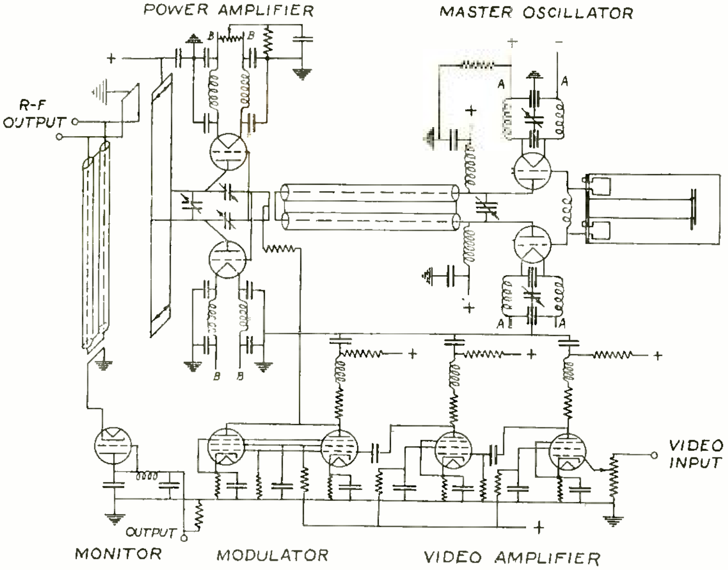

Fig. 4—Schematic diagram of television relay transmitter.

The r-f output stage is a conventional, push-pull, cross neutralized amplifier.[5] The tubes (two RCA-834's) are located as shown in Fig. 5 to make the length of the connections from the grid and plate tube prongs to the neutralizing condensers a minimum. This is necessary to prevent parasitic oscillations. The neutralizing condensers are the horizontal concentric cylinders at the center of the power amplifier compartment. The outside

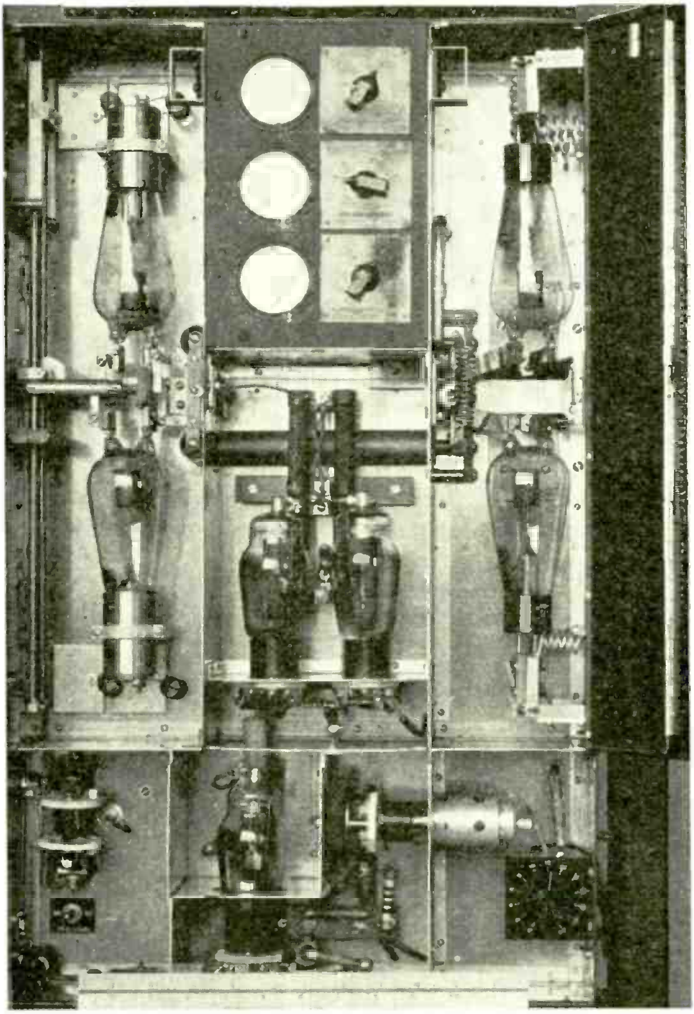

Fig. 5—Radio and video-frequency units of transmitter; left, power amplifier; right, master oscillator; center, modulator; lower left, monitor; lower right, modulator amplifiers.

cylinders are connected to the plates and are made up of two telescoping tubes for adjusting the neutralizing capacitance. The inside cylinders are connected to the grids. This arrangement reduces the stray capacity between the input and output circuits of the power amplifier.

The power amplifier grid circuit is an untuned inductance composed of a short brass strip connected from grid to grid, and closely coupled to the voltage nodal point of the master oscillator plate inductance. The center point of the grid inductance is directly connected to the modulator plates. By eliminating the blocking condenser between the modulator and the power amplifier the stray capacitance of the modulator output circuit to ground is reduced. Since the power amplifier grids are connected directly to the modulator plates they are maintained at a plus potential of 250 volts. To give proper operating bias the filaments are maintained at a plus potential of 400 volts by a filament return resistor.

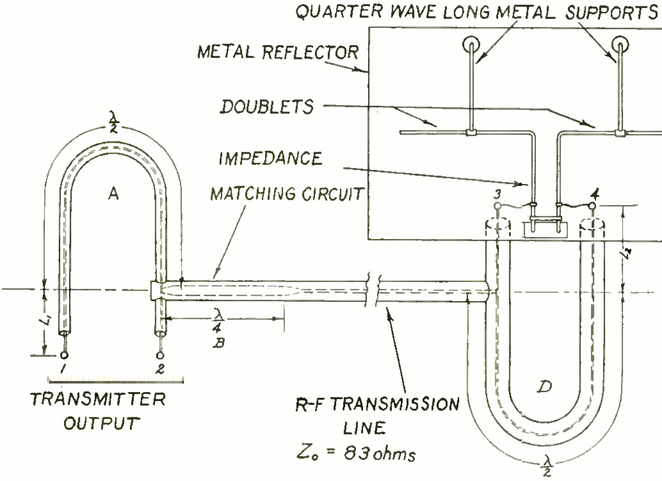

Fig. 6—Balanced to unbalanced transfer circuits, transmission line, and transmitting antenna.

To maintain the symmetry of the power amplifier output circuit the plate inductance is made of two balanced lines in parallel. Slides on these two wire lines are provided for approximate tuning of the power amplifier plate circuit, and a small two-plate variable condenser for the fine adjustment. One branch of the plate circuit is inductively coupled to a balanced 150-ohm load. The power amplifier will deliver to this load a 15-watt carrier.

The monitor step-down transformer is a concentric conductor line one half wavelength long connected across the output terminals of the power amplifier. At the center or voltage nodal point on this line a loop is inductively coupled to the inside conductor. This loop is connected to a rectifier which is used to monitor the transmitter r-f output.

The modulator uses two RCA-802's in parallel. The frequency response curve for each video frequency stage was made flat by using the system described by Messrs. Kell, Bedford and Trainer.[6] If the total output capacitive reactance is X_c at the highest frequency (1.5 megacycles) it is desired to transmit, then the plate load impedance at this frequency is made $1.13X + j\,.5X_c$ ohms. The phase shift produced by the resultant plate impedance is proportional to frequency over the transmission band and, hence, does not produce phase distortion. The attenuation and phase shift produced at the low frequencies by the interstage coupling and cathode by-pass condensers are compensated for by choosing a suitable value of plate supply by-pass capacitance. The plate supply of each stage has a series resistance or damped reactor to isolate it from the power supply.

The modulator amplifier consists of two stages, an RCA-802 and RCA-6C6. An input level of .45 volts r.m.s. is required to modulate the transmitter 85 per cent.

The possibility of transferring the balanced output at the transmitter to an unbalanced load suitable for feeding a single coaxial line was considered. The circuit shown in Fig. 6 proved to be satisfactory. A coaxial line A with a characteristic impedance of 75 ohms was made $2L_1 + \lambda/2$ meters long. L_1 may be any convenient length. When there is a traveling wave on A the proper impedance of 150 ohms will be presented to the transmitter output terminals 1 and 2. The voltages on terminals 1 and 2 differ in phase by 180 degrees. The path from terminal 1 to the quarter wavelength section of line B is one half wavelength longer than the path from terminal 2 to this junction. Hence, the wave that leaves terminal 1 arrives at B in phase with the wave from terminal 2. The section of line B which has a characteristic impedance of 55.8 ohms steps the 83-ohm transmission line down to 37.5 ohms, which will match the two sections of the loop A.[7] The r-f transmission line is made of a one-inch inside diameter copper pipe and a quarter-inch outside diameter copper tube. The quarter-inch tube is held concentric with the one-inch pipe with low-loss insulators. These insulators are spaced about every quarter wave to reduce the reflections produced by them. The length of the line is 100 feet and the efficiency about 90 per cent. At the antenna the unbalanced feed is transformed to a balanced feed of 332 ohms. The wave that leaves the transmission line and travels over the longer branch of D arrives at terminal 4, 180 degrees out of phase with the wave which travels over the shorter branch of D to Terminal 3. The concentric conductor D has a characteristic impedance of 166 ohms. The two branches in parallel will match the transmission line if the Terminals 3 and 4 are connected to a load of 332 ohms.

The impedance matching circuit shown is adjusted to step the antenna input load down to this value at 177 Mc. This is necessary to give maximum efficiency and flat frequency response over the band used.

RECEIVER

The receiving antenna on the north wall of the 85th floor of the Empire State Building is approximately 100 feet from the receiver location. The antenna feed line is composed of two 76-ohm, 13-gauge, coaxial cables, located in a conduit running from the receiver rack to the back of the antenna reflector. The use of two cables gives in effect a balanced, shielded, 152-ohm transmission line. Special tests were carried out to properly match the antenna to the feed line at 177 Mc to get the greatest overall efficiency and flatest response with frequency. The transmission line loss was estimated to be not more than 1.9 db. With all adjustments made the cables were sealed off, evacuated, and filled with dry nitrogen under pressure. This process insures the removal of moisture from the cables, and gauges permanently installed show whether the pressure is maintained. The sealed cables are thus impervious to weather conditions.

Fig. 7 on Page 154 is a photograph of the front of the receiving rack as installed in the Empire State Building.

Fig. 8 shows a schematic diagram of the receiver circuits. A balanced concentric line type band-pass transformer, receives 177 Mc energy from the balanced coaxial feed line. The transformer in turn feeds a balanced heterodyne detector consisting of two RCA 954 acorn tubes whose cathodes are excited by a concentric line type of local oscillator operating at 156 Mc. The intermediate frequency of 21 Mc appears push-pull in the output of the balanced detector stage and is coupled to a single ended 6-stage, band-pass amplifier using coupled circuit transformers. The overall flat band width is A Mc. The i-f amplifier is fed to a linear diode rectifier (RCA 955), which in turn feeds the RCA

42 output tube. Video frequencies are carried from the receiver over a coaxial cable to the transmitter line amplifier.

Automatic gain control of the i-f amplifier is accomplished by means of a d-c amplifier driven from a voltage divider across the diode load resistance. This circuit is arranged to feed variable negative control voltages to two tubes in the i-f amplifier. A switch is provided to allow the gain to be controlled manually.

A set of switches on the front panel allows the plate currents of the i-f amplifier tubes to be checked on one meter without interrupting the operation of the receiver. The other plate currents with the exception of the automatic gain control tube are shown continuously on individual meters.

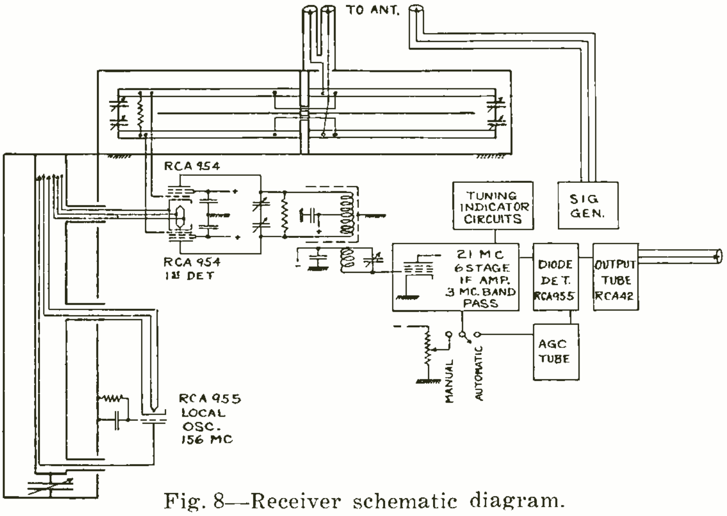

Fig. 8—Receiver schematic diagram.

Due to the extreme width of the i-f amplifier it is necessary to provide an indicator to show when the signal carrier is tuned to mid-band. This indicator allows the operator to easily find the correct setting of the local oscillator. A 0-1.5 ma. meter on the front panel shows the plate current of a biased triode detector, which is excited by a high C resonant circuit having fairly high Q. This resonant circuit is driven by an r-f pentode fed from the i-f amplifier. A push button is arranged to connect a small fixed capacity across part of the resonating inductor, and the resonant frequencies with the push button out and in are set to be equally spaced about the i-f mid-band. With such an arrangement the tuning indicator meter (0-1.5 ma) in the plate circuit of the biased detector will show no change with the push button out or in when the carrier is accurately tuned to mid-band.

A separate regulated power supply having an effective internal resistance of less than one ohm is used to supply power to the RCA 42 output tube. Thus, objectionable low frequency resonance often occurring in ordinary power filters is eliminated which permits a flat frequency response to be obtained down to 10 cycles or less with the output tube working into a load resistance of only 100 ohms.

In a receiver of this sort having a tuned band-pass input transformer at signal frequency, the problem of properly tuning these two circuits presents itself. The correct tuning to give a flat band pass is not necessarily that obtained by setting each dial for maximum response in the usual way. This problem is overcome by supplying in the receiver rack a shielded oscillator to supply energy over a single coaxial cable to a point on the antenna reflector. The cable termination near the antenna includes a damping resistance, a small radiating rod, and a shunt inductance all combining to produce a correct terminating impedance over the band of frequencies used. With this arrangement the operator can vary the oscillator frequency over the receiver pass band and observe the shape of the (antenna—feed line—receiver) characteristic on the output of the receiver. With a few trials the correct tuning of the input transformer can be obtained. These adjustments may be made when the 177 Mc television transmitter is off the air. These circuits once set require little attention thereafter.

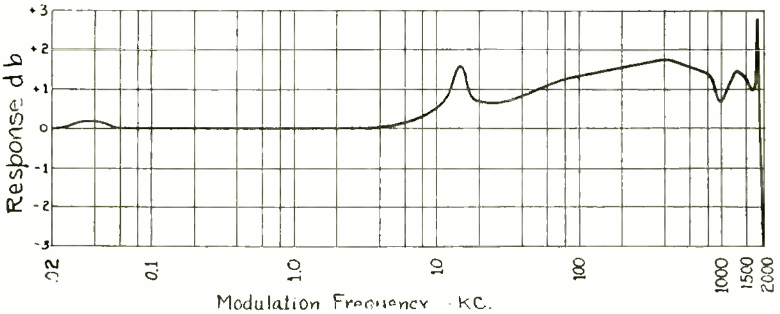

Fig. 9—Overall frequency characteristic of the radio relay.

RESULTS OF TESTS

As might be expected a signal of considerable intensity is received at the Empire State Building. Calculation shows that the transmitter power and antenna directivity used should result in a direct ray field strength of approximately 30 millivolts per meter at the receiving antenna. A strong signal is necessary to override local disturbing noises from elevator machinery, etc., which become more bothersome the wider the receiver band width. It might be mentioned that lightning flashes in the immediate vicinity give only moderate clicks in the receiver output.

Signal strength observations made so far show variations in intensity of only a few per cent, showing that variations in rays reflected from the ground are unimportant.

Overall frequency characteristic measurements have been made from the transmitter input to the receiver output over a range of from 20 cycles to 2000 kc. Fig. 9 shows the result of these tests. The irregularities in the curve from 100 to 1700 kc. are mostly caused by the propagation path as mentioned earlier. The peak at 1800 kc. is produced by an equalizing circuit in the receiver output. It will be observed that the maximum deviation over the desired band of 20 cycles to 1500 kc., is 1.8 db which occurs at 400 kc.

Signal to noise level measurements were made at the receiver using a measuring amplifier having an effective band width of 20 kc. These measurements showed a signal to noise level of 44 db with 85 per cent. modulation at the transmitter. The noise level was almost entirely 60 and 120-cycle power supply hum.

Although the receiver is located near the high power television broadcast transmitters no trouble is experienced from interference. Pictures have been transmitted over this circuit without altering their quality.

BIBLIOGRAPHY

(1) P. S. Carter and G. S. Wickizer, "Ultra-High Frequency Transmission Between the RCA Building and the Empire State Building in New York City," presented at the joint meeting of the International Radio Union and the Institute of Radio Engineers, at Washington, D. C., May 1, 1936; Proc. I.R.E., Vol. 24, pp. 1082-1094, August 1936; and published in TELEVISION, RCA Institutes Technical Press, July 1936.

(2) Clarence W. Hansell and Philip S. Carter, "Frequency Control by Low Power Factor Line Circuits," Proc. I.R.E., Vol. 24, pp. 597-619, April 1936.

(3) U. S. Patent No. 1,937,559.

(4) F. E. Terman, "Resonant Line in Radio Circuits," Electrical Engineering, Vol. 53, pp. 1046-1061, July 1934.

(5) U. S. Patents No. 1,334,118 and 1,560,332.

(6) R. D. Kell, A. V. Bedford and M. A. Trainer, "An Experimental Television System," Proc. I.R.E., Vol. 23, pp. 1246-1265, November 1934.

(7) Sterba and Feldman, "Transmission Lines for Short Wave Rado Systems," Proc. I.R.E., Vol. 20, pp. 1163-1202, July 1932.

EXPERIMENTAL STUDIO FACILITIES FOR TELEVISION

By

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Introduction

In May 1935, David Sarnoff, President of the Radio Corporation of America, announced extremely significant television plans. Mr. Sarnoff reported to the stockholders that television had advanced to a point where a conclusive field test was both necessary and expedient. A $1,000,000 expenditure was recommended to construct and install a complete operating plant for experimental television. The plan included a three point schedule:

1. The existing audio and video transmitters in the Empire State Tower were to be remodeled.
2. A number of experimental receivers were to be manufactured and distributed to engineers for test purposes.
3. Studio facilities—the subject of this discussion—were to be designed and provided for experimenting with the actual production of programs, both direct pickup and film.

Since this field test was to approximate actual operating conditions, the problem of providing adequate studio facilities became more complex. The requirements for producing interesting television programs were known to be exacting, for television programs, like radio programs, must be continuous. It is not possible to shoot each scene individually and later combine a number of scenes into a prolonged sequence as is now common motion picture practice. Each television program involves instantaneous switching from long shots to closeups with no break in the continuity. Or, as is often the case, there may be switching from one studio to another, all in a split second. In order to achieve the desired flexibility, the utmost care was required in planning the design of the television studios and associated apparatus. It was necessary to provide sufficient space for a direct pickup studio, as well as a studio for televising motion picture film, which is also an important element in television programming.

One of the first considerations in planning the studios was the matter of a suitable location. It was decided that Radio City offered several

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distinct advantages. Here were the most modern broadcasting studios in the world, some of which were of sufficient size to serve as a proving ground for a television service. Moreover, the selection of one of these would immediately eliminate the need for extensive sound proofing and acoustical alteration inasmuch as the treatment applied to these radio studios is also peculiarly adapted to the needs of television sound pickup, at the present stage of the development.

Radio City offered other advantages no less important. The severe air conditioning load, contributed by lighting in a direct pickup studio, could be carried by the existing NBC conditioning system. Furthermore, by locating television studios in the same building with the NBC and RCA executive offices, television experimentation would be under closer supervision by executives. Programming, also, would be simplified through the use of NBC artists, conveniently available through routine programs and the NBC Artists Service.

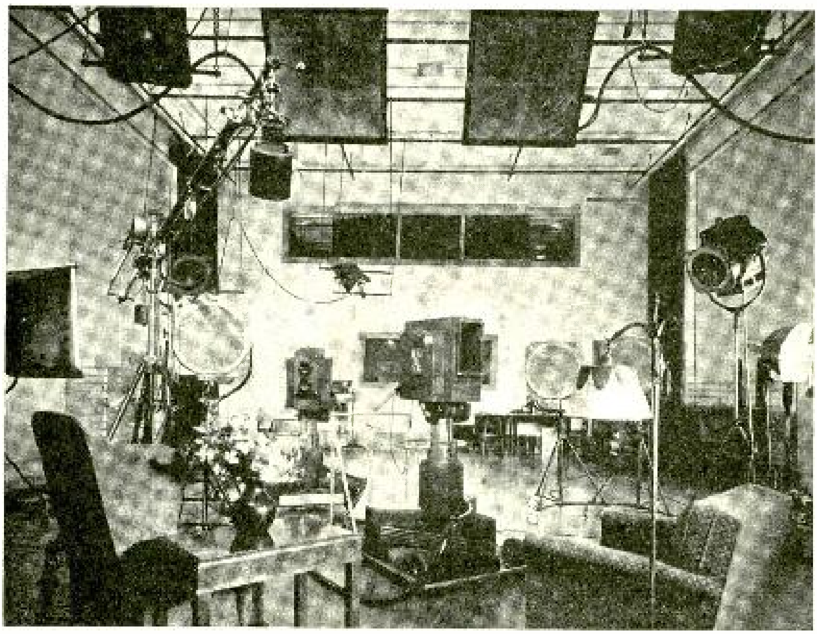

Fig. 1—Direct pickup studio.

These advantages far outweighed possible difficulties, the principal limitation being the lack of convenient outdoor facilities suitable for program settings. Other limitations were minor and consequently a direct pickup studio was selected on the third floor of the NBC quarters. A film studio had already been anticipated when Radio City was planned, and base facilities were thus available on the fifth floor.

FACTORS INFLUENCING THE DESIGN OF A DIRECT PICKUP STUDIO

There are a number of factors concerning the operation of apparatus in a television studio which must be carefully considered in planning adequate studios. For example the "Iconoscope"* pickup tube in the television camera is one of the determining elements in studio length. This tube is a gourd-shaped glass envelope enclosing, at the enlarged spherical end, a photosensitive mosaic plate which is so placed within the glass envelope that an electron beam, generated in the elongated section of the tube, is free to sweep across the plate. The distance between this plate and the glass envelope enclosing it is about 4½ inches, at present at a minimum consistent with the structural strength of the tube and the proper physical relationship of component parts. This distance, then, constitutes the absolute minimum focal length for any lens system used in connection with the Iconoscope cameras. In practice, lenses with a focal length of approximately 6½ inches and an angle of 37 degrees are found to be best suited to requirements just mentioned. However cameras equipped with lenses with this rather narrow viewing angle must be operated at a considerable distance from the wider studio sets if complete accommodation is desired. Studio length must be sufficient to permit such camera technique.

The studio length should also allow for ample distance between the back of the studio set and any projection apparatus used for producing background effects. Here again lenses are a controlling factor. The narrow angle lenses (not more than 30 degrees) are vastly more efficient in light transmission than wider angle lenses, but require longer projection distances which in turn increase the necessary length of the television studio. Studio width is of course determined by the width of the largest scenes desired, with allowance for passageway on either side.

Studio height is influenced by several other elements. In order to relieve congestion on the floor, key lighting units for set illumination are better suspended from a ceiling of considerable height and structural strength. Control booth facilities should be elevated also to permit engineers and production men to have an unobstructed view of the entire studio floor area. Furthermore, the use of scenic backdrops and the familiar scenery flats require a rather high ceiling.

The overall cubic volume of the studio, as governed by the area and height, is an equally important factor. The acoustics of a studio have an important relationship to the cubic volume enclosed. The sound pickup associated with television transmission serves to complete the illusion created by the image and must be faithfully reproduced. Studio volume is also closely related to air conditioning problems which will

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* Reg. trade mark, R C A Mfg. Co., Inc.

be discussed in more detail later. All these considerations are vital to the operating success of a studio installation for television.

DIRECT PICKUP STUDIO

The direct pickup studio at Radio City is 50 feet long and 30 feet wide with a ceiling height of about 18 feet, a size which conforms, to a large extent, with the requirements just mentioned. Figure 1 shows a view of this studio looking toward the control booth from the approximate location of the main studio set. Two of the studio cameras and several of the lighting units are clearly visible. The camera at the left utilizes a narrow angle lens system with a focal length of eighteen inches for televising closeups, whereas, the camera in the foreground is used for semi-closeups and long shots. Sound is picked up by a standard velocity microphone equipped with a wind shield and attached to the familiar boom, seen at the left of the picture.

Fig. 2—Television control booth.

Studio walls and ceiling are surfaced with perforated transite backed with rock wool, to eliminate discrete sound reflections and generally, to provide the studio with acceptable acoustical conditions. Three of the studio walls are coated with aluminum paint. The fourth wall is painted black to increase light absorption and thereby eliminate interference with the operation of background projection apparatus which is located in a booth at this end of the studio. A network of pipe is hung from the ceiling for use in suspending key lighting units and stage backdrops. Automatic sprinklers and a special rate of temperature rise fire alarm device are also installed on the ceiling of the studio as are the air conditioning ducts. For a floor surface, a light gray linoleum was chosen.

The studio is arranged to accommodate one large scene and at least one additional smaller one. There is no fixed size of set, the arrangement purposely being flexible to fit the varied requirements of experimental television programs. Thus far, the largest set used was about 22 feet in width and included a section of a fully equipped kitchen plus a complete dining room with tables, chairs and the usual accessories.

Control Booth and Equipment

The control equipment for the direct pickup studio, both audio and video, is located in a booth on the second floor level at one end of the studio. (See Figure 1.) This elevated position permits a clear view of all action on any of the studio sets. The main set is placed at the opposite end of the studio about 15 feet from the back wall in such a way that control room occupants and the men operating the Iconoscope cameras view the action from the same direction. This arrangement is most desirable because stage illumination is then directed away from the control booth and does not produce a direct glare which would interfere with monitoring the televised images.

A soundproof glass partition separates the control booth from the studio proper, extending practically the full width of the studio, and is of such height that seated control booth occupants may comfortably view nearly the entire studio floor area. This window is partially covered with a dark green transparent cellulose material which effectively attenuates reflected light from the studio, further aiding video monitoring.

Those operating controls which require more or less constant attention are centrally located on a long console in the control booth as shown in Figure 2. Audio controls, including the volume indicator meter and gain adjustors are clearly visible in the foreground. The engineer at this control position also has the responsibility for switching from one studio to another.

All scenes televised by the Iconoscope cameras appear on two image tubes known as "Kinescopes"*. These are located just above the window partition in front of the video engineer and the production man who sits between video and audio control. The video control setup is shown clearly in Figure 3. Brightness and video gain controls for the three studio camera chains are grouped on the panel directly in front

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of the operator. The operator is shown adjusting these dials for the best relationship between contrast and brightness in the image. Electrical focusing of the Iconoscopes in the studio cameras is controlled by the three dials at the left of the operator's hands. Pushbuttons for controlling camera switching relays are visible on the console immediately under the associated signal lights. The group of dials at the right is used to vary "shading" of the transmitted image. By regulating these controls, voltages having special wave forms are added to the video impulses in the amplifiers for balancing out unwanted dark or light areas in the image. Note the Kinescope monitors and the associated cathode ray oscilloscopes. These latter provide a wave picture of the television image and are to television what the volume indicator meter is to sound broadcasting.

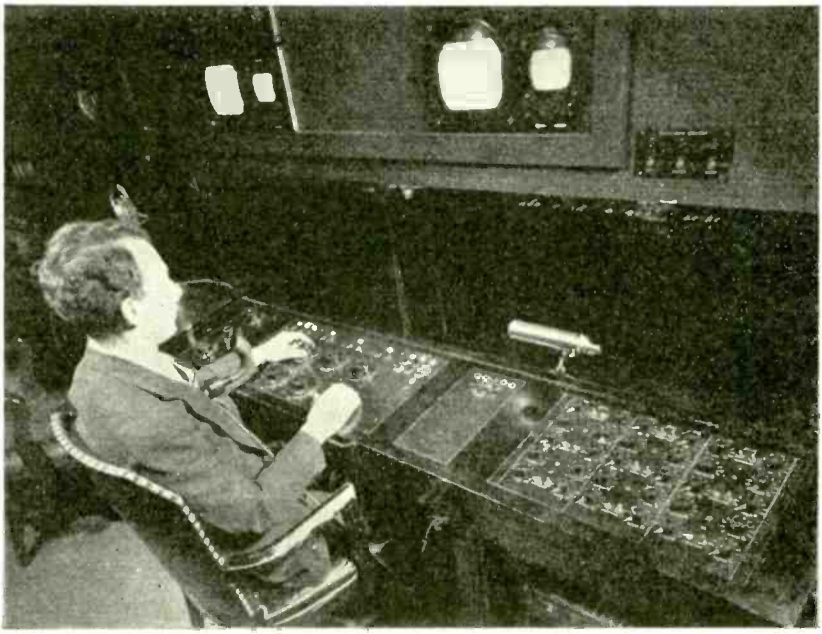

Fig. 3—Video control setup.

Amplifying equipment for video signals and for the horizontal and vertical deflection potentials, together with rectifiers for supplying the Iconoscope beam potentials, are mounted on several equipment racks easily accessible for repair and maintenance. Since video circuits are required to pass a wide band of frequency extending from 60 cycles per second to extremely high frequencies of the order of 4 million cycles per second, it was necessary to wire these equipment racks with coaxial cable. Special shielded blocks were designed to terminate such cables and to act as distribution centers to other remotely located equipment (See Figure 4). Several types of coaxial cable were used in this installation, the type being selected according to circuit requirements. Special care was exercised to avoid cross-talk between circuits in the band passed by the equipment.

Power requirements for operating the television system include both alternating and direct current supplies. Video amplifiers operate on direct current supplied from a central battery source on the fifth floor of the NBC plant. Alternating current is distributed from a circuit breaker panel in the control room, such circuits being isolated from the remainder of the wiring and routed through separate conduits. High potential circuits are protected by sheet steel boxes with interlock switches which automatically turn off the power when the covers are removed.

STUDIO LIGHTING

Television at present requires somewhat more light than is needed for motion picture production. The present limits of sensitivity of the Iconoscope tube necessitates an incident light intensity on a set of about 1000 to 2000 foot candles. To provide this illumination, the studio is equipped with incandescent lamps of various types, having a total power consumption of over 50 kw, the amount in use at any one time depending upon the size of the set. Rifles, floods, and focusing spots with ratings of between 2 and 5 kw each, are most numerous, although there are several larger units of special design. Key lighting and back lighting units are suspended from the ceiling; modeling lights are operated on the studio floor. These latter are mounted on mobile standards which require considerable floor area for effective operation. At present, studio lighting is operated on direct current obtained from the generators at Radio City. Alternating current is also available for use when desired.

The selection of incandescent illumination represents months of experimenting with practically every known source of high intensity light which would meet the requirements of quiet operation and dependability. Measurements were made of the spectral characteristics, lumen output per watt, useful life, and changes in color temperature. These tests indicated incandescent lamps, with high lumen output, to be the most satisfactory of any light source commercially available at this time. Some small scale experiments have been conducted using high pressure mercury vapor lamps which indicated promise for the future.

Incandescent lamps, like most other types, radiate a considerable amount of heat. When a battery of such lights is focused on a relatively small set, a serious heat problem is created. This difficulty was partially alleviated by placing heat filters in front of the various light units to reduce the radiant heat in the beam. Here again many types were tested before serviceable filters were found which would absorb a large part of this heat energy without undue reduction in the amount of incident light. Those now in use are a special glass, cut in strips to relieve internal stresses in the glass caused by the high temperature. Their performance is quite satisfactory; the actual reduction in effective heat is of the order of 2 to 1.

In addition to the heat filters, diffusing screens are used on several light units for reducing the glare and equalizing light distribution. By this method the intrinsic brilliance of the incident light is considerably reduced without subtracting materially from the net illumination on the set. This method has the effect of making the high intensity light flux less apparent to performers whose comfort must be considered if a satisfactory performance is expected. For further comfort it is also desirable to cool the sets by concentrating freshly conditioned air into the action areas.

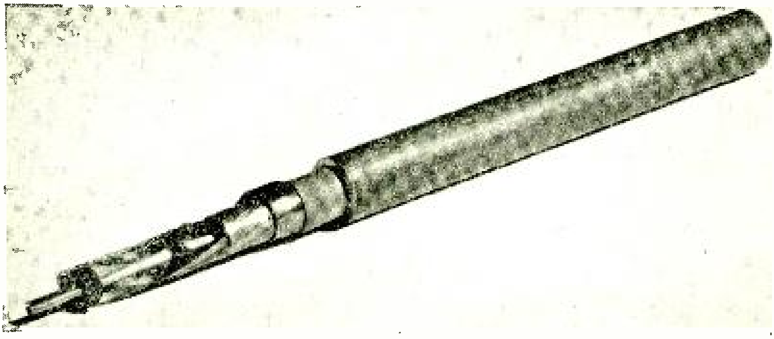

Fig. 4—Coaxial cable.

Radiant heat absorbed by the filters is of course eliminated from the light beam and hence from the set, but is necessarily redistributed by the filter to the surrounding atmosphere. Thus there is no change in the overall heat load which must be carried by the air conditioning system. In this respect, extensive tests were conducted to determine means for eliminating not only the heat concentration on the set, but also means for maintaining comfortable effective temperatures throughout the studio. At the outset, the handling of an internal sensible heat load so great in proportion to the volume of the studio requires a combination of high cooling-temperature differentials and rapid air change. Extremes of either of these factors must, of course, be avoided. In the present system, refrigerated supply air in large volumes is handled at temperature differentials approximating 30 degrees. In this manner, the heavy internal heat load is absorbed at reasonable room temperature.

ACOUSTICS

The sound accompanying the television program is a necessary complement to the video signal to complete the illusion of the transmission of the performance taking place in the studio. The acoustical design of the studio and the microphone technique employed are important considerations and supplementary problems in the television project.

The present television studio was previously used for sound broadcasting and has a volume of about 25,000 cubic feet. The adapting of this studio to television requirements necessitated structural modifications, but the acoustical changes were relatively small because of the provision for adjustment of acoustical conditions in the original design. The ceiling and end walls (except for the wainscot) are treated entirely over the available area with rock wool covered with perforated transite. The side walls are equipped with sliding panels which are acoustically treated with rock wool covered by perforated metal. These panels are arranged in pairs, three pairs on each side wall. Each pair of panels is approximately 10 feet wide and 15 feet high. Sheet metal pilasters, backed by cork to avoid resonance, are so arranged that when the panels are opened they slide behind these pilasters and their acoustic absorption is effectively removed from the room. It is possible by opening all of the panels to effect an increase in reverberation time of almost 100 per cent over a greater part of the frequency spectrum. The pilaster wall surfaces exposed and those of the pilasters (which are not acoustically treated) are "Vee'd" to avoid discrete reflections or "flutter" and effectively disperse incident sound. The reverberation time at 1000 cycles with the panels exposed is about .4 seconds.

The change in reverberation time can be varied continuously over the available range as the remote-control hydraulically-operated panels may be opened any desired amount. In certain cases where the acoustical effect of very reverberant spaces must be simulated the "echo" chambers developed for and used so successfully in radio broadcasting may be used when the required change is greater than can be accommodated by the panels.

The microphone technique employed in television differs from that in radio mainly with regard to the respective locations of the microphone and performers. In radio the performers may change their location to suit the one chosen for the microphone while in television the microphone must be moved to the location of the performer. It is further desirable to correlate the acoustical "pick-up" with the video—that is, a "close-up" should sound like a "close-up" and a distant "shot" should sound distant. It is the change in ratio of reflected to direct sound that creates this impression of proximity of distance.

A majority of the "pick-ups" have been made with the velocity microphone, equipped with wind shield, and suspended from a boom which traverses the scene of action. Provision has been made for the use of parabolic reflector microphones which will be suitable for many types of pickup and will not require the careful manipulation necessary with the "boom microphone".

It is apparent thus far, that the studios should be less reverberant than those of equivalent size used for broadcasting, but that the fundamental principle of the provision of uniform acoustical conditions throughout the studio should be retained.

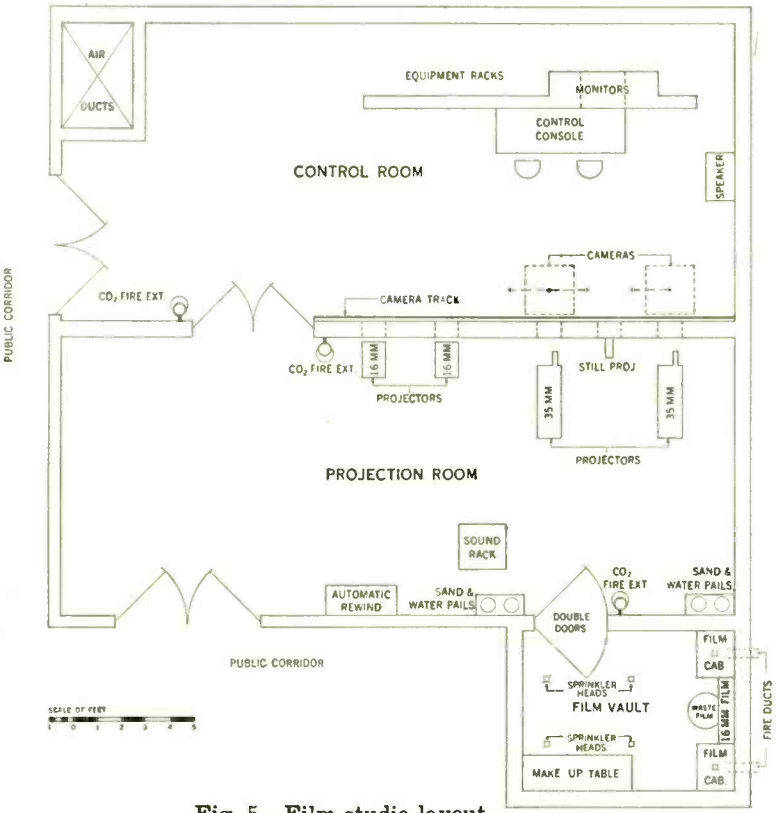

Fig. 5—Film studio layout.

THE FILM SCANNING ROOM

The transmission of motion picture film used in the project is handled in a specially designed film scanning room on the fifth floor of the NBC Radio City plant. Any standard 35mm or 16mm motion picture film can be used and many of these films provide interesting entertainment. Such features as comedies, topical films, and news reels have already proved to be extremely valuable as program material.

Structurally, any television film studio must comply with municipal building and fire regulations prescribed for rooms where nitrate film is handled. Basic construction for this studio was provided for in the original plans for Radio City. Of particular interest is the film storage vault, constructed of heavy masonry walls, and provided with fireproof doors. The vault is equipped with sprinklers and drains, and ventilated directly out of doors in compliance with City regulations. Film storage cabinets are themselves fireproof and internally sprinkled, with connecting ducts to the outside atmosphere. At various points in the studio there are fire extinguishers and sand pails conveniently located for emergency use (See Figure 5).

Although adherence to the building and fire codes is compulsory, compliance with these provisions must be accomplished without impairing operating efficiency. The continuous nature of a television transmission requires that equipment be flexible in use. Instantaneous switching from one film projector to another without interruption is necessary, and was so arranged in this installation. The layout also was designed to facilitate rapid substitution or replacement of various units.

The actual layout of the film studio is shown in Figure 5. There are two adjacent rooms and a film vault. One room houses all projection apparatus and supplementary equipment, the other being reserved for the video apparatus and control facilities. In the projection room are four motion picture projectors, two 35mm projectors with sound heads and two 16mm machines without sound. There are also two small still projectors for test patterns and film slides. The 35mm projectors operate at the regular rate of 24 frames per second and are provided with a high-speed shutter and a modified intermittent system. This ingenious arrangement makes it possible to use standard motion picture film, operating at the normal projection rate, with a television pickup at a higher picture frequency. If such a device were not used the wealth of film entertainment already available on standard film could not be used in television since operation of standard film at 30 frames per second would obviously distort the action and sound far beyond reasonable tolerance. The 16mm machines are also provided with a high speed shutter, but in this case film is projected at a rate of 30 frames per second. This higher rate is taken into account in the making of the films.

The power requirements of this projection equipment make the use of oversize driving motors necessary. These must be of the synchronous type in order that they remain in step with the video system. This is accomplished by supplying these motors from the same alternating current supply which feeds the video synchronizing apparatus about which more will be mentioned later.

All projection machines operate through standard glass ports, focusing images directly on the plates of Iconoscope tubes encased in two cameras mounted on the opposite side of the wall in the control room. These cameras are so mounted on a track that they can be moved into place in front of any projector quickly and accurately.

The video apparatus for film television is centralized on a group of equipment racks in the control room as shown in Figure 5. Operating controls are grouped on a control console that is affixed to the equipment racks on which are mounted the two Kinescope monitoring screens. The arrangement of controls is quite similar to the installation in the direct pickup studio. In Figure 6, the control console and three of the equipment racks are shown. Audio controls and inter-studio switching arrangements are mounted on the panel in the foreground. To the right are the Kinescopes and associated cathode ray oscilloscopes; controls

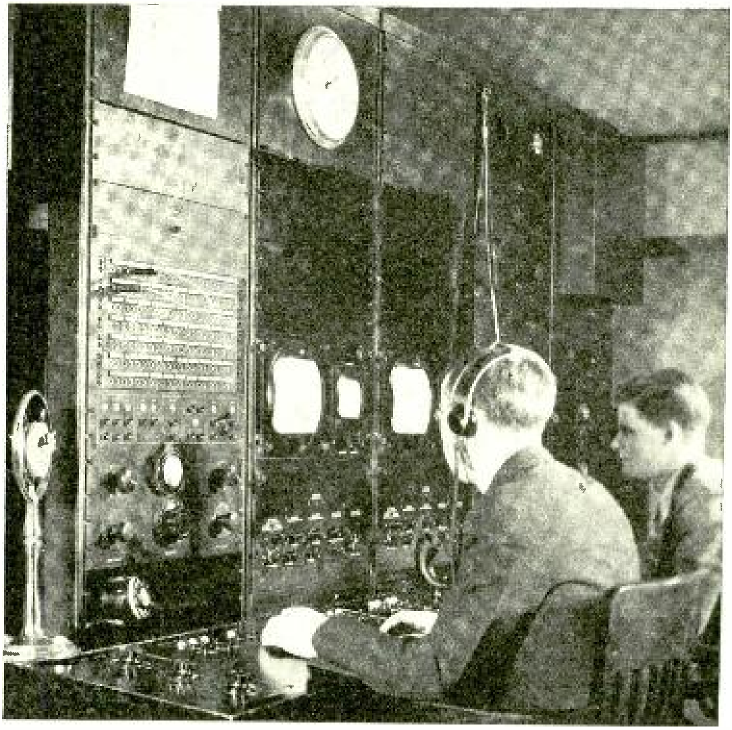

Fig. 6—Control console and equipment racks with audio controls, interstudio switching, Kinescopes and associated cathode-ray oscilloscopes.

for these are immediately below. The console controls include Iconoscope electrical focusing, camera switching relay push-buttons, motor and framing controls for the projectors, video gain and brightness, and shading. The microphone in the foreground is used to communicate instructions to the projectionist in the next room. An observation port is also provided for this purpose.

To the left of the operating position, not visible in the picture are two equipment racks on which are mounted video amplifiers and horizontal and vertical deflection amplifiers, as well as the beam power supply for the Iconoscopes. High potential circuits and switches are centralized on the miscellaneous equipment rack to the right of the installation. There is sufficient room in back of all equipment racks to permit easy maintenance and repair.

MAIN EQUIPMENT ROOM

Iconoscopes and Kinescopes are dependent for their operation upon deflection and blanking impulses which are generated by special equipment installed in the Main Equipment Room. Figure 7 shows this installation. The equipments mounted on the first and third panels from the left are the synchronizing generators, complete electrical units which produce all blanking and deflection impulses for the apparatus in the Film Scanning Room and the Direct Pickup Studio. These signals are amplified by the apparatus on the rack between the generators and are then distributed by coaxial cable to the television studio equipment. To guarantee maximum stability, these generators are operated continuously twenty-four hours a day, and either one may be instantaneously switched into service, the other acting as a standby. These generators also produce a fifth impulse known as the locking frequency, so named because it synchronizes receivers with the transmitter. This latter impulse is added to the video signal at the input to the line amplifiers, which are mounted on a rack at the right in the photograph. Here the studio signals are given a final boost before distribution to the television transmitters in the Empire State Tower, or to remote monitoring points in the NBC headquarters. Again there is a provision against failure. Three line amplifiers are available, any one of which may be selected for use. Video signals from either the film studio or the direct pickup studio feed inputs of these amplifiers through remotely controlled switching relays. The channel method of distribution such as is used for sound broadcasting, has been followed in the video switching arrangements. Present interlocking relays allow instantaneous switching from either originating studio to the input of the line amplifiers. Audio and video channels are switched simultaneously by one operation.

Two methods have been provided to transmit the picture signals to the transmitter on the Empire State Tower:

1—By coaxial cable.

2—By ultra high frequency radio circuit.

A special experimental coaxial cable is provided for conducting signals directly from the main equipment room to the Empire State transmitter, or the signal may be routed to a special ultra high frequency transmitter on the 10th floor of the NBC plant (See Figure 8).

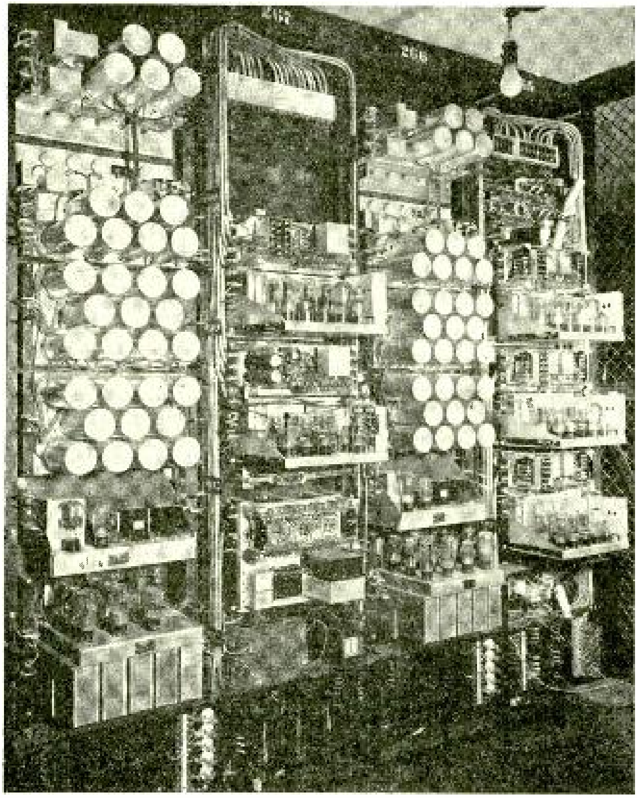

Fig. 7—Synchronizing generators and associated equipment.

This link transmitter operates on a frequency of 177 megacycles. The antenna of this transmitter is aimed at a similar array on the 85th Floor of the Empire State Tower where the signals are received for retransmission. The equipment at the left in Figure 8 is a radio frequency monitor which operates directly from the antenna circuit of this transmitter, thus providing a final check as the picture leaves the link transmitter. This equipment is provided with the usual Kinescope monitoring screen and associated apparatus.

CONCLUSIONS

From the above discussion it may be readily appreciated that the ramifications of studio planning for television are many. Numerous fields of scientific endeavor contribute to the general technology of television. To mention but a few it would be necessary to include optics, electronics, lighting, motion pictures, radio engineering, acoustics, air conditioning and photography, etc. The coordination of these sciences and the development of techniques which are applicable to television is a continuing process. The television field can only be briefly surveyed at this time, but from present knowledge there is ample reason to anticipate a public service of stupendous proportions, a medium with new engineering techniques, new program ideas new talent and new commercial application. Experience will undoubtedly result in changes and improvements in existing apparatus as the progress of television is advanced toward the ultimate goal of a comprehensive program service.

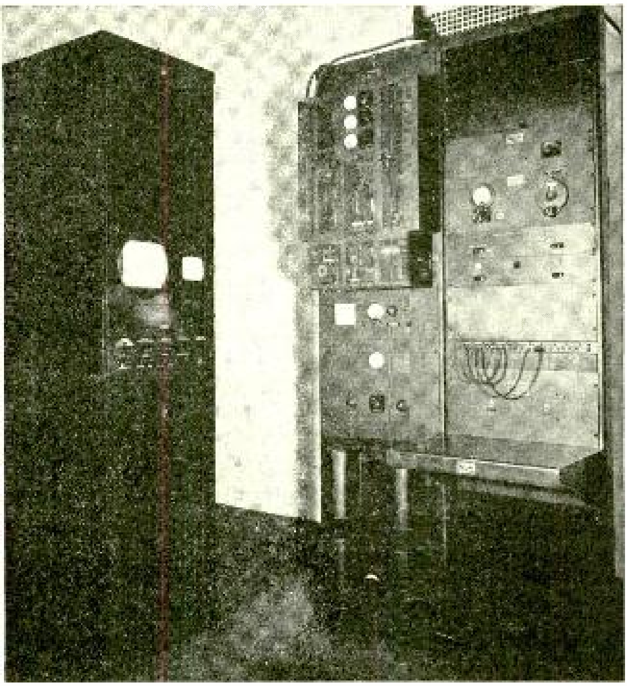

Fig. 8—Special ultra-high frequency link transmitter.

Television covers a vast field of various subjects too numerous to consider in a single article such as this, however succeeding issues of the RCA REVIEW will contain one or more papers dealing with other aspects of the problem of Television.

TELEVISION STUDIO DESIGN

BY

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OVER a period of years the RCA policy with regard to the development of television has been characterized by a continuous program of laboratory research coupled with field demonstrations at suitable intervals to test the apparatus and circuit developments under operating conditions. The progress of this work has been recorded from time to time in a series of technical papers by various engineers of RCA companies.

Early in 1935 television apparatus had been developed, as a result of laboratory research, which showed considerable promise on small-scale demonstrations. It was therefore decided that another field test was not only appropriate, but essential to further progress toward a public television service. It was also agreed that this field test must be sufficiently comprehensive in nature to provide a representative indication of audience reaction, furnish information on the problems of program production and distribution, and test the fundamental, technical principles and reliability of the system under conditions approximating those which might obtain in actual public service.

Accordingly a field demonstration was inaugurated, involving the co-ordinated efforts of all of the associated companies of RCA. The general plans of this project and a brief description of the facilities employed have been given in a paper by Mr. R. R. Beal.*

In a more recent paper by Mr. O. B. Hanson†, the planning of the television studios employed in this field test was discussed. It is the purpose of this present paper to discuss, from the viewpoint of the operating company, the engineering problems involved in the design of a plant for originating television broadcast programs.

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* RCA REVIEW, January 1937, "Equipment Used in the Current RCA Television Field Tests."

† RCA REVIEW, April 1937, "Experimental Studio Facilities for Television."

Reprinted from *RCA Review*, July, 1937.

When design of the present television plant in Radio City was started a little more than two years ago, the model used as a starting point was a set of television equipment in the research laboratory in Camden. That layout consisted of one direct-pickup camera chain and one film camera chain operating on a basis of 343 lines interlaced and 30 picture frames per second. The studio was relatively small and the equipment was all located in three adjoining rooms so that problems such as would arise in a practical installation were relatively nonexistent. From the fundamental system exemplified by this apparatus, it was necessary to design a television plan comprising a direct-pickup, live-talent studio equipped with three camera chains and a film studio having two projectors and camera chains, together with all necessary appurtenant apparatus such as synchronizing generators, video line amplifiers, etc. These facilities were to be installed in the Radio City plant of the National Broadcasting Company. Considerations governing the choice of this location and the general layout have been given in the paper by Mr. Hanson to which previous reference has been made.

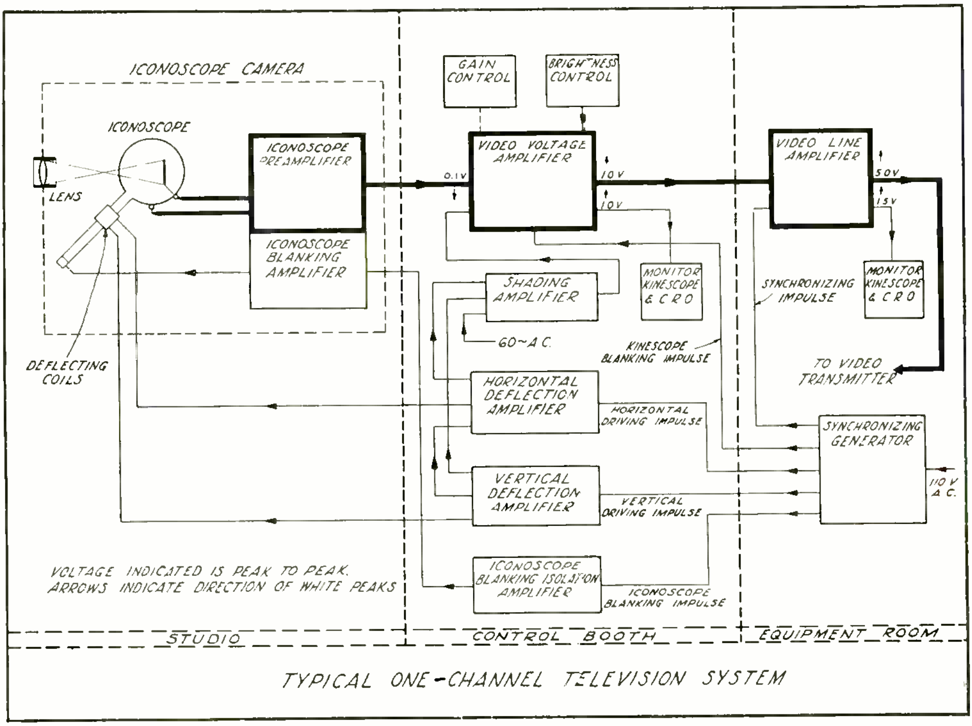

Fig. 1—Diagram showing elements of one video channel.

The fundamental elements of a typical camera chain are shown in Figure 1. At each significant point in the circuit the polarity of the signal is shown by an arrow and the approximate peak-to-peak value of voltage is also given. It will be appreciated that only the bare essentials of a single video camera chain are indicated in this figure. The video signal generated in the "Iconoscope" is fed into a pre-amplifier located in the camera. In this amplifier the signal is built up to a value suitable for transmission from the camera to the video voltage amplifier in the studio control booth where it is amplified still further before being transmitted to the video line amplifier in the main equipment room. The main output of the line amplifier feeds either a coaxial cable or a link transmitter for transmission to the main video-broadcast transmitter. Average brightness and contrast (gain) of the picture are controlled in the video voltage amplifier. In addition to the main amplifier chain for the video signal, horizontal and vertical deflection systems must be provided for scanning both the "Iconoscope"* and the monitoring "Kinescopes,"* and a synchronizing generator must be provided to supply the various impulses required for synchronizing the scanning and blanking operations at the "Iconoscope" with those at the "Kinescopes" in the receivers. Monitors must be provided for viewing the transmitted picture just as monitoring loudspeakers are used in sound-broadcast operation. Shading amplifiers and controls are necessary to provide adjustment of relative light values in the various areas of the picture.

In expanding this relatively simple, fundamental television layout into a larger plant capable of producing programs under conditions suitable for a limited public service, a number of new problems arose. Decisions had to be made as to the location of the various pieces of video apparatus associated with the plant. Consistent with NBC experience in broadcast-plant design it was thought desirable to place as much of this equipment as possible in a centrally located main equipment room—the same equipment room in this case as was used for the sound-broadcast equipment. Study of the situation, however, indicated that because of the greater number and complexity of controls associated with video equipment, it would be necessary for most of the video equipment to be located in the studio control booths. In audio-broadcast-plant design, usual practice provides a number of microphones in the studio with individual preamplifiers which feed into a mixing system followed by one main amplifier which is placed in the equipment room. In video-plant design this plan is not at the present time considered feasible for several reasons. In the first place, sev-

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* Trade Mark Registered U. S. Patent Office.

eral control operations take place in the amplifier which follows the preamplifier. Another important consideration has to do with the difficulty of feeding and switching video circuits, particularly at low levels. The fact that a complete chain of amplifiers and deflection and power circuits must be provided for each camera means that a relatively large amount of apparatus must be installed in the control booth.

Controls necessary to the proper operation of a camera chain may be grouped under two classifications: those normally requiring adjustment but once at the beginning of a program, and those requiring adjustment during normal operation. In the first group are included those controls which regulate the amplitude of horizontal and vertical scanning for the "Iconoscope," keystone correction, focus and several others. Those controls which the operator must adjust frequently include gain control (contrast), blanking pedestal (brightness) control, and those controls which regulate shading of the transmitted picture.

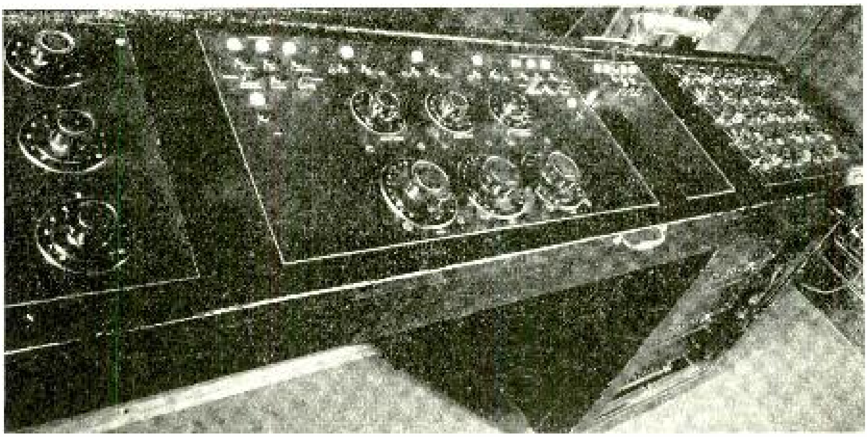


Fig. 2—Video console in Studio 3H, Radio City.

The physical layout of these controls is shown in the photograph of Figure 2. This is a view of the top of the video-engineer's console located in the control booth of the direct-pickup studio. The three large knobs on the extreme left control electrical focus of the electron beams in the "Iconoscopes" of each of the three cameras. The three vertical groups of large knobs in the center control average brightness and contrast for the three cameras and the three panels of controls on the extreme right (ten knobs and six switches in each group) regulate shading. The shading amplifiers are mounted beneath the shading control panels. Push-buttons for switching cameras are located above the brightness controls, and those for switching the two monitors are in the upper left and right hand corners of this panel. On the small panel to the right are located signal lights and "stand-by" keys for the camera positions. The console in the film studio has the same general arrangement, with controls for only two instead of three cameras. It has in addition controls for four film projectors. The photograph of Figure 3 shows the top of this console.

A unique feature of the video-gain or contrast controls used on both consoles is shown in Figure 4. The control knobs on the console are attached to the shafts of Selsyn motors through suitable reduction gears. The other motor of each pair is built into the video voltage amplifier and connected to a potentiometer gain control. Rotation of the control knob and its associated motor causes an equivalent rotation of the other motor and its potentiometer. In this way control of amplification is effected with no compromise as to frequency response characteristics or convenience of operation. This method was selected after careful consideration of several ways of accomplishing this important function.

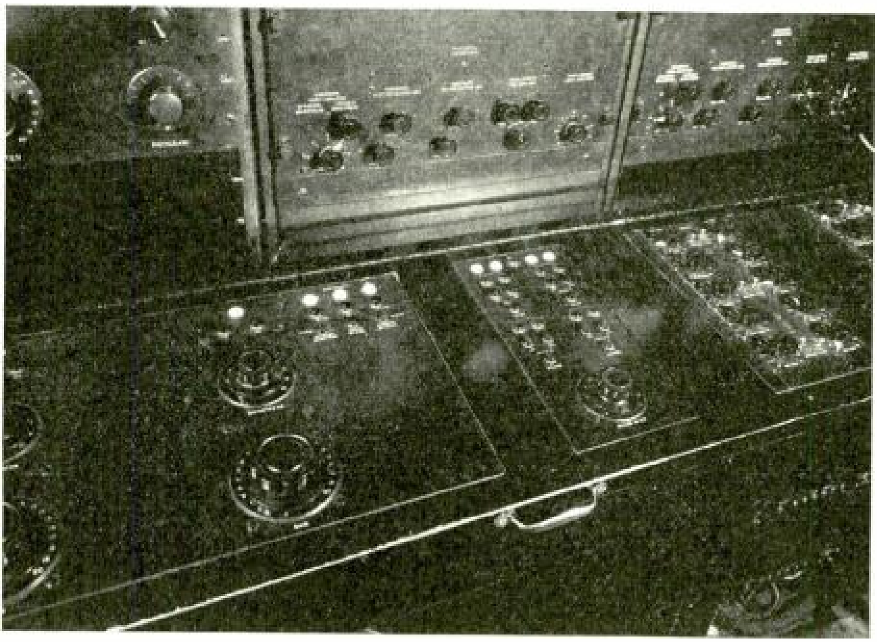


Fig. 3—Video console in film studio 5A, Radio City.

Monitoring of the output of the various video voltage amplifiers and video line amplifiers is afforded by a combination "Kinescope" and oscilloscope monitor unit shown in Figure 5. This complete unit combines a 9-inch "Kinescope," a 5-inch oscilloscope tube, video amplifiers for each capable of operation from a minimum level of 0.5 volt peak-to-peak, a 250-volt regulated power supply, and a high-voltage power supply. The amplifiers must be located immediately adjacent to the tube panel to reduce capacity on video leads. The power supplies may, however, be conveniently located in a near-by auxiliary cabinet rack. In transmitting a normal program requiring frequent switching from one camera to another it is necessary to have at least two of these monitor units. This provides one monitor at all times on the outgoing picture and another which may be used for preliminary viewing of the other cameras. It also provides a spare monitor essential in case of failure during a television production. With the additional monitor the engineer can be sure that the camera which he is about to switch to the outgoing channel is properly focused and adjusted for signal level and brightness. Flexible relay switching is provided for these monitors which makes it possible to connect either or both to any of the camera chains in the studio. An automatic-switching arrangement may be cut in on either monitor so that this monitor will follow camera switching and always be connected to the chain transmitting the outgoing picture.

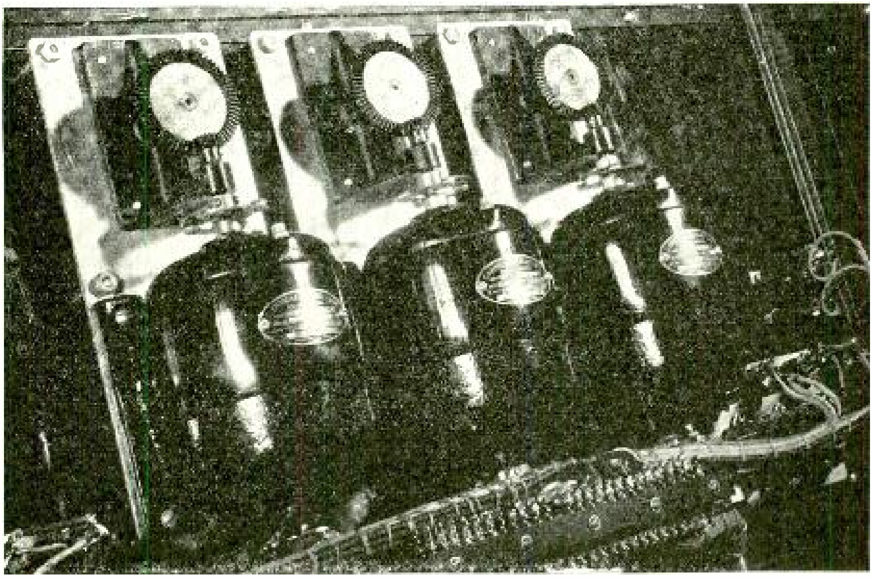


Fig. 4—Selsyn motor used for video gain control.

In addition to switching arrangements for the monitors it is necessary that provision be made to switch the various cameras onto the outgoing line and also to switch between the direct pick-up studio and the film studio. Since both audio and video circuits must be simultaneously transferred when changing studios, the two control circuits are so interlocked that one push-button operation effects the switching of both. Remotely controlled relays are used for both video and audio switching.

The relays used for video switching must meet special requirements not imposed upon relays used for other purposes. The capacity to ground and capacity between springs of the relay must be as low as possible consistent with reliable mechanical design. The relays used in the Radio City installation employ two sets of contacts in series with an auxiliary contact for grounding the central springs when the circuit is open, thus obtaining electrostatic shielding between the incoming and outgoing video circuits. The camera-switching relays are interlocked in such a manner that dropping one camera and picking up another is accomplished by merely pressing one push-button. To provide smooth-switching action, these video relays must be so adjusted

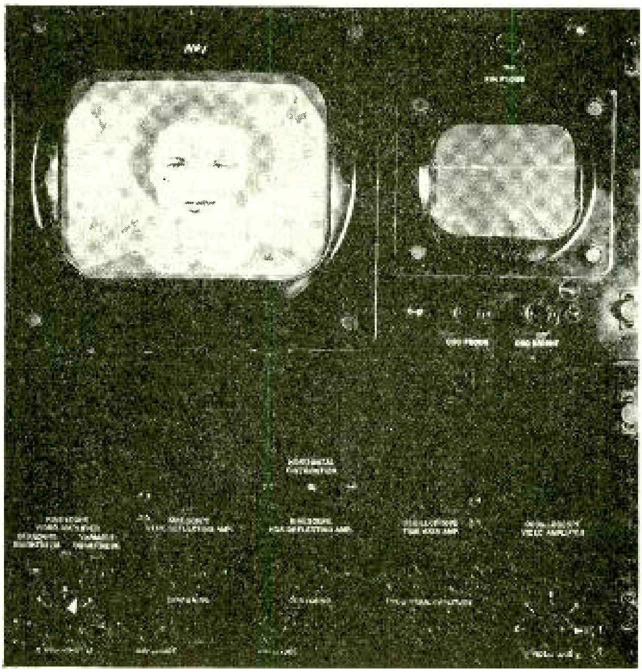
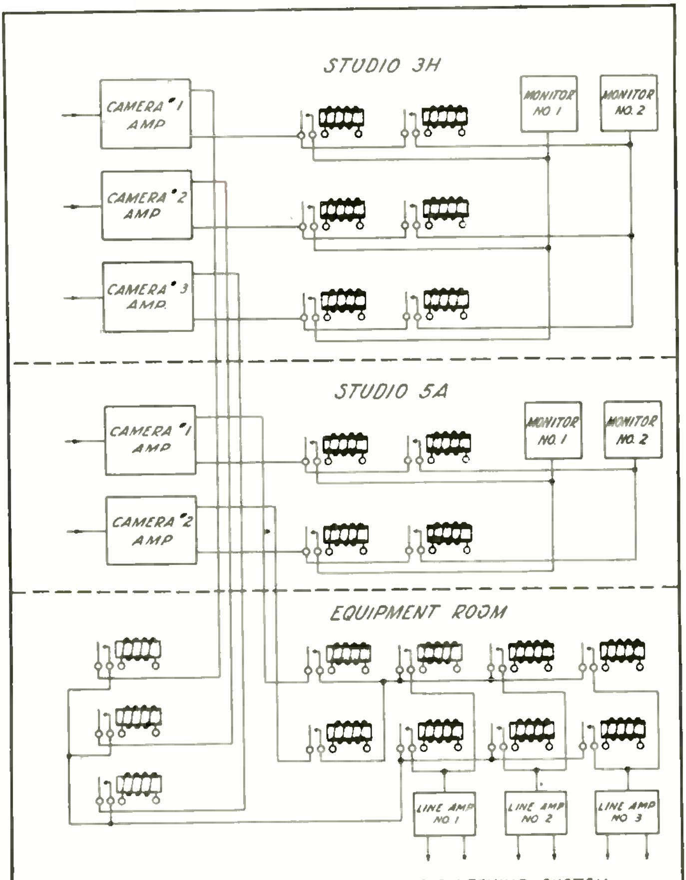


Fig. 5—Monitor showing "Kinescope" and oscilloscope in normal operation.

that the proper make-break sequence is obtained in order to prevent surges from being transmitted which would momentarily upset receiver synchronization. Improper adjustment of the relays results in a very annoying surge in picture brightness and often will cause the receiver to slip a frame every time cameras are switched. The schematic arrangement of video relays used in Radio City is shown in Figure 6.



SCHEMATIC OF TELEVISION RELAY-SWITCHING SYSTEM
RADIO CITY

Fig. 6

In addition to the normal switching facilities provided by the relays, it is desirable to have convenient means of connecting and disconnecting various units of the video system. To accomplish this, coaxial patch cords and jacks are provided in some circuits. The photograph in Figure 7 shows a coaxial jack strip. These patch cords and jacks make possible the convenient changing of circuits without the introduction of an impedance irregularity in the 75-ohm coaxial conductors.

The design of a multiple studio plant for originating television programs is attended by many engineering difficulties of the same kind that are encountered in laying out a comparable plant for sound broadcasting. In addition there are many special problems which arise, due to the nature of the television signal. The extremely wide band of frequencies, extending from the lower audio frequencies to several million cycles per second, imposes severe limitations upon not only the amplifiers themselves, but also upon the circuits used to connect them and the equipment used for monitoring, switching, and testing. At the present time, so far as we are aware, no transformers are available for handling satisfactorily the entire band of video frequencies required for a high-definition 441-line television picture. This means that rather severe mismatches of impedance must be tolerated between amplifier output tubes and the low-impedance coaxial cables which they feed, with the attendant loss of amplification made up by high gain in other stages of the amplifier chain.

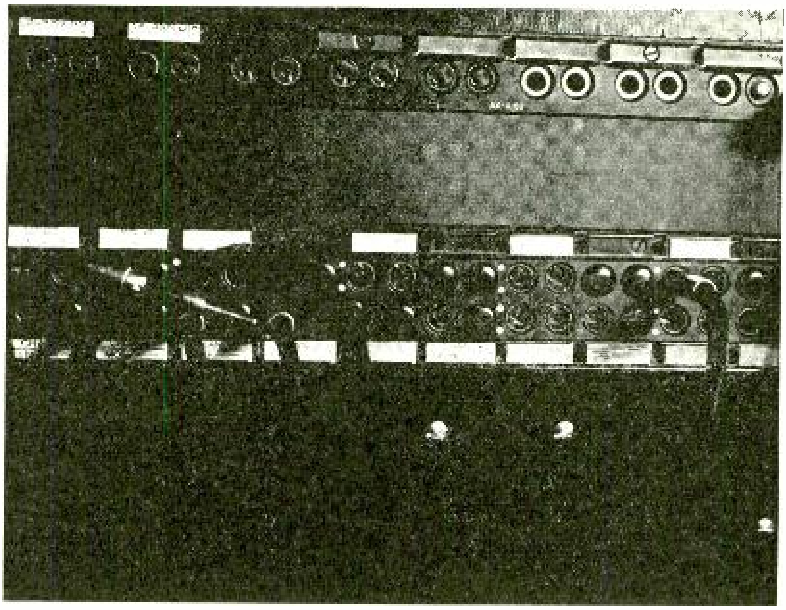
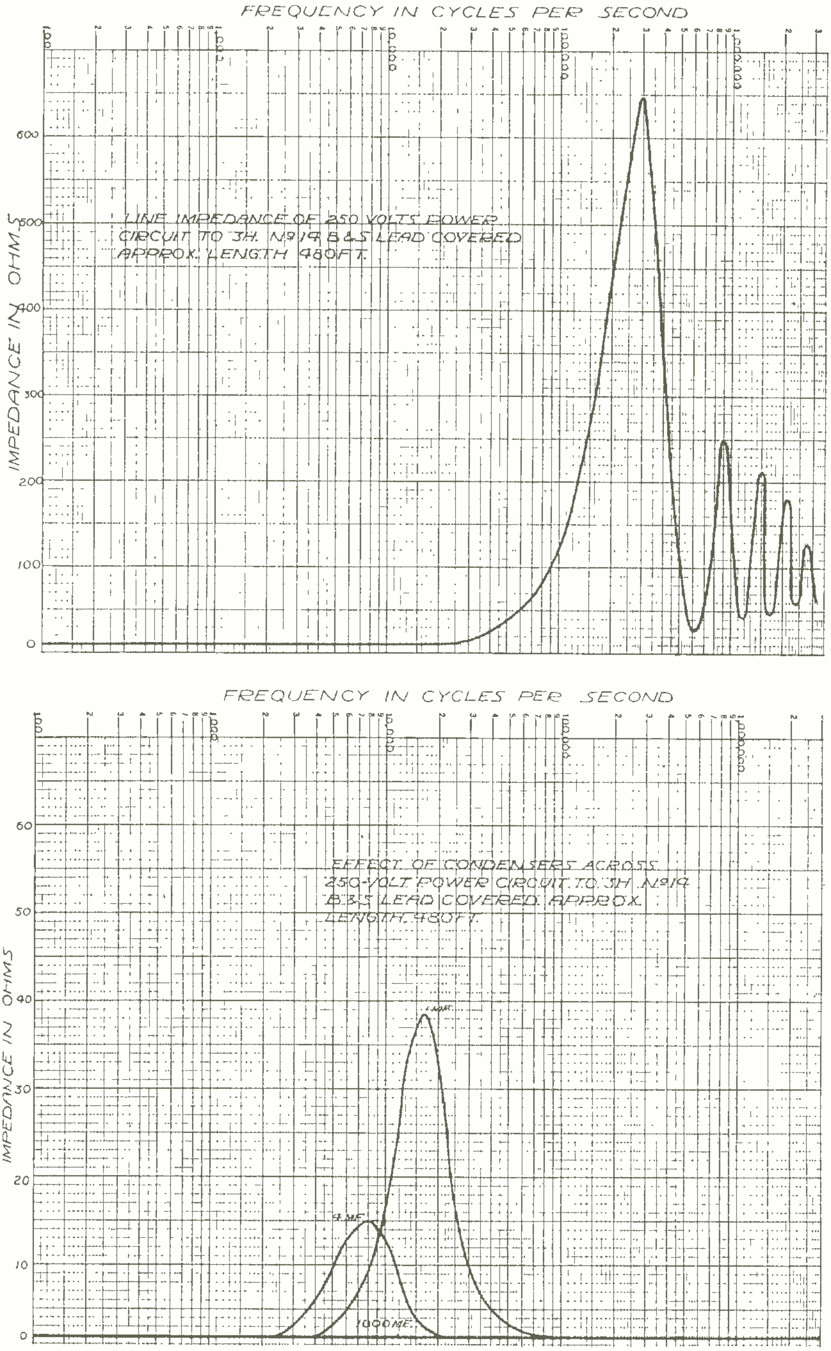


Fig. 7—Coaxial-cable jack panel and patch cord.

One of the problems which arose in the design of this television plant which had not given serious trouble in previous installations was the difficulty caused by the length of coaxial-cable circuits for the video signal between various groups of apparatus. Any appreciable mismatch of impedance at the receiving end of these cables produced reflections which in many cases have sufficient delay to produce objectionable multiple images. In those cases where switching relays were placed on the ends of such cables the low impedance at the higher video frequencies caused by the capacity-to-ground of several relays in parallel was found to produce serious reflections. In order to overcome this, it was necessary in some instances to provide isolating amplifiers between the resistance termination for these cables and the switching relays. In this connection it is pointed out that the attenuation of high frequencies produced by a shunt capacity such as this may be overcome in other amplifier circuits by suitable peaking of the high frequencies, but this correction will not compensate for the reflections.

All video amplifiers used in this project are of the resistance-capacity-coupled type with suitable corrective networks to obtain the wide-frequency response required. Amplifiers of this kind are usually susceptible to low-frequency interference arising in power-supply circuits, particularly those having stages which have low-impedance circuits where the power-supply impedance may be comparable to the load impedance. This may seem to be a condition which is unlikely to obtain in practice, especially where a large central storage battery is the source of plate supply. However, such a source of plate power together with the necessary lengthy wiring produces a sufficiently high impedance looking back from the amplifier into the power supply to cause "motorboating" of a video chain. This is not due to the resistance of the battery or wiring, but to the reactance of the line connecting the equipment to the battery. With no by-pass condensers and a nominal run of 100 to 200 feet the impedance can rise to over a thousand ohms in the frequency range of a video amplifier. By-passing with a moderate-size condenser to ground will eliminate this condition, but will raise the impedance above its previous value at some lower frequency. The question then resolves itself into putting on a sufficiently large condenser to lower the impedance at all frequencies in the video range below the value necessary for stable operation. The impedance can usually be reduced to a workable value by applying condensers of approximately 2000 μf at the equipment end. Figures 8A and 8B show the measured impedance of the 250-volt circuit in Studio 3H and the effect of several sizes of condensers connected across the equipment end of the circuit. Any circuit-breaker impedance, particularly from the inductive-type overload breakers, must be eliminated from the circuit. Fuses have thus far been found superior to circuit breakers from this standpoint.



Figs. 8A and 8B—Impedance of power circuit used with video amplifiers as a function of frequency for various values of by-pass condenser.

Some of the problems involved in the wiring of a television plant such as this one have already been indicated in their relation to other problems. In order to provide low-loss circuits with good shielding for the high frequencies involved and with a minimum of impedance irregularity it was decided that coaxial cable would be used for all video-signal transmission circuits and also for all circuits carrying synchronizing and blanking impulses from the centrally-located synchronizing generator to the studios. The coaxial cable constitutes an unbalanced load to ground at its input terminal and is therefore suitable for direct connection to unbalanced amplifiers (i.e., amplifiers of the "single-ended" type as distinguished from those of the push-pull type). Because it is unbalanced the cable is subject to interference from stray ground currents flowing in its outer conductor. The intensity of this interference is of course dependent upon the length of the run and the difference in "ground" potentials at the two terminals. We have found that it is not serious under the conditions encountered in this installation.

In order to minimize cross-over between circuits and to guard against impedance irregularities, a specially shielded terminal block was developed for use with the coaxial cables. Each single-circuit compartment in the block is separately shielded on all sides by solid walls of copper. The heavy copper block is cadmium plated to facilitate good electrical contact at all points.

The production of a television program differs from the production of a motion-picture film in several important respects. Once the television program is started, the action is continuous until the end. There can be no retakes, no pauses, no correction of errors, and no re-editing. All equipment used in the studio must be extremely flexible and quiet in operation. Lighting must be altered, cameras moved and switched, and microphone positions changed without the television observer being aware of these activities throughout the entire production. This necessitates that the "Iconoscope" camera be extremely maneuverable and easily adjusted by properly and conveniently located controls.

The camera, which houses the "Iconoscope" with its lens system, an "Iconoscope"-blanking amplifier, and a video preamplifier, is mounted on a movable pedestal or a motion-picture type dolly. The pedestal has three rubber-tired wheels which are locked together with a chain drive and which may be steered with a conveniently located lever. The pedestal head contains pin jacks which connect the circuits to the camera proper. This head contains the mechanism for "panoraming" ("panning") and tilting, and either operation may be independently locked. Connections to the pin jacks are made from a corkscrew spiral cable which is mounted within the telescopic elevating tubes of the pedestal. The other end of this corkscrew cable terminates in a 36-conductor flexible cable 60 feet long and approximately 2 inches in diameter. Elevation is accomplished by means of an electric motor which operates a windlass and a system of pulleys. In operating this type of pedestal, the engineer stands on the floor, and pushes the camera about as desired. A pair of shafts protrude from the rear of the camera and the engineer raises or lowers the camera by rotating the shaft on the left, and focuses by rotating the shaft on the right. These two shafts also serve as a means of "panning" and tilting the camera during operation. Signal lights on the front and rear of the camera indicate "stand-by" or "on the air". A headphone jack is also mounted on the camera so that the video engineer in the control booth may communicate with the engineer at the camera. When using the motion-picture type dolly the camera is removed from the pedestal and remounted. An assistant propels and steers this vehicle so that the camera engineer may devote his attention to more important duties.

In order to make it possible for the camera operator to follow moving action from varying camera angles and keep the scene always properly in focus, it is essential that a reliable "finder" be provided on the camera. In early television cameras a mirror was provided which made it possible for the operator to see directly the image focused upon the mosaic of the "Iconoscope". This had the disadvantage of low brilliance, since the mosaic surface is not a good reflector of light, and there was also some danger that light from the studio might reach the mosaic through this "finder". On the present cameras two identical lenses are used on each camera—one for focusing the image upon the mosaic and the other for focusing a duplicate image upon a ground glass for viewing by the camera engineer. The position of the ground glass is adjusted so that it is in an identical plane with the mosiac of the "Iconoscope," and thus adjustment of the focusing control to obtain sharp focus of the image on the ground glass also results in proper focus of the image on the mosaic. An advantage of this type of finder is that the lens used for the finder may be operated "wide open" for critical focusing regardless of the stop setting on the main lens.

Interchangeable lenses with focal lengths of 6½, 14, and 18 inches are provided for use with these cameras. They are mounted in pairs upon demountable lens plates so that lens combinations on the camera may be changed conveniently. The advantage of using long focal length lenses in studio work is that one camera utilizing wide-angle (short-focal-length) lenses may be employed to cover a large area of the set, while telephoto (long-focal-length) lenses are used on another camera to obtain close-up shots without having the camera so close to the action that it would be within the viewing angle of the other camera.

In a system of the kind used in this project, it is essential that adequate communication channels be provided between the various engineers to maintain smooth program continuity. In a typical television program, two or more scenes in the direct pickup studio will be interspersed with several film scenes. The most pleasing effect is obtained if a smooth continuous performance is given with no interruptions when switching between various portions of the program. To achieve this the operators in the two studios must be in close contact with one another so that the studio show can begin the instant the film is ended or vice versa. The switch from the direct-pickup studio to the film studio is the more difficult of the two, since the film projectors must be started, brought up to speed, and the picture "framed" properly, within the proper number of seconds before the studio act is completed so that the start of the film will appear on the screen the moment the circuits are switched to the film studio. If the projectors are started too early the first part of the film will be lost, and if they are started too late, there will be an interval during which the screen will be dark. A thorough knowledge of the proper operating technique on the part of the operators is of course essential, but even with this, good continuity would not be assured without proper communication circuits. Figure 9 is a simplified diagram showing the several telephone and studio address systems employed to provide the desired co-ordination. A private-line telephone system is used to connect the control booths of the film studio, the direct-pickup studio, and the control room of the Empire State transmitter. This telephone circuit is connected prior to the start of the program and is monitored continuously throughout the duration of the program by one of the engineers at each location. It is over this circuit that "standby" warnings and switching cues are given. An independent one-way telephone circuit is provided between the video-control operator and each of the cameras in the direct-pickup studio. Over this circuit the video-control operator can give instructions to the camera man regarding location and adjustment of the camera while the show is on the air without interfering with the audio pickup. This circuit is also connected to the rear-projection booth. There is a studio address system provided for giving instructions from the control booth to personnel and actors in the studio during rehearsals. This system is automatically cut out when the studio goes on the air to prevent accidental interference with the audio pickup. A microphone-loudspeaker address system is provided from the control booth of the film studio to the projection room so that the control operator can give instructions to the projectionist. A microphone is also provided in the projection booth so that the projectionist can warn the control operator of any emergency. Both of these loudspeakers are normally used for audio monitoring, except when operated as an address system. Each studio control booth also has a branch on the Engineering Interphone system which connects the various studios and operating control points in the NBC plant. A Program Interphone is provided in the direct-pickup studio for use by the Program Department.

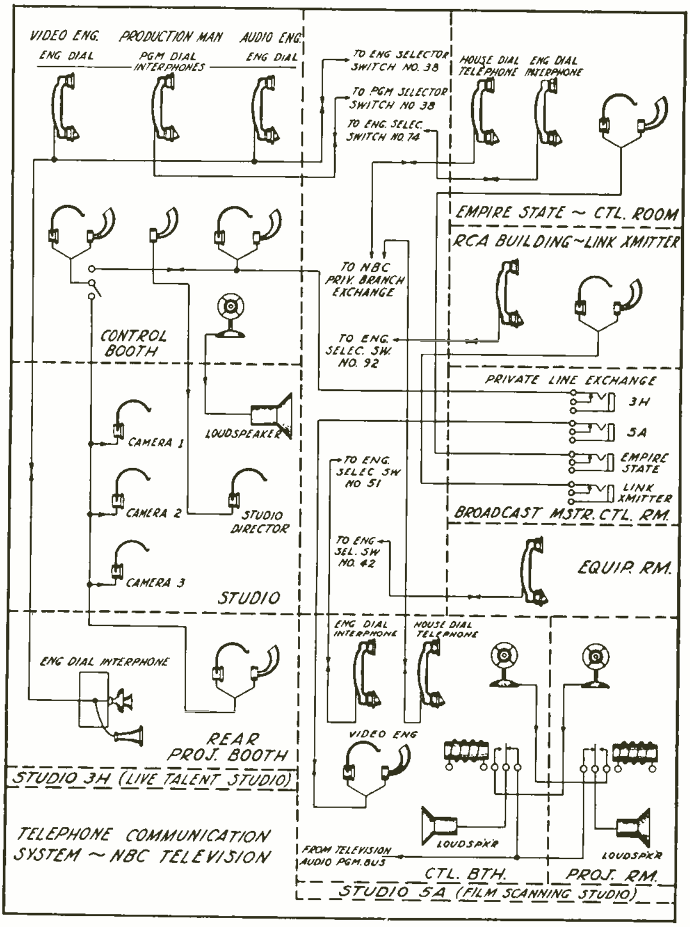


Fig. 9—Schematic of communications system used in conjunction with Radio City Television Studios.

A separate telephone circuit is provided between the control booth and the direct-pickup studio so that the program production man can communicate with his assistant in the studio while the show is on the air. House phones which may receive outside calls are available at the Empire State transmitter and at the film-scanning room. These are used to correlate information with the field receivers. In addition to the telephone communication circuits, other signal systems are provided. These include the two sets of signal lights on each camera mentioned previously, as well as the usual signal lights associated with the push-buttons which are used for camera and monitor switching.

The introduction of video apparatus into the broadcast plant brought with it an increased problem in the matter of safeguarding personnel. The voltages used for the "Iconoscopes" and "Kinescopes" while not extremely dangerous, since very low current is used, might, if direct contact were established, lead to a severe shock. Adequate protection against accidental contact with these voltages is obtained by a complete system of interlocking. All covers and doors giving access to voltages over 500 volts are equipped with interlocks which automatically remove the power when the covers or doors are opened. The studio cameras are equipped with manual keys and locks in addition to interlocks. When it is necessary for engineers to work on equipment, grounding sticks are available and used, and heavy rubber mats prevent standing on grounded equipment.

Additional interlocking is used to protect the "Iconoscope" tube since if either the horizontal or vertical deflection voltages or both are removed, the mosaic would be burned by the intensification of the electronic bombardment. To prevent this, protective relays are installed which apply a cut-off bias to the "Iconoscope" grid if either or both of the deflecting voltages are removed.

This paper has attempted to outline some of the major technical problems encountered in the design and operation of a multi-studio television plant and the solutions which have thus far been found most feasible. In general, it has been attempted whenever possible to carry over and incorporate into this new field those operational and design practices which experience in broadcasting has shown to be sound, modified where necessary by the new factors introduced by television.

TELEVISION AND THE ELECTRON

BY

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A FEW months ago the R.M.A. decided upon a set of standards to be applied to commercial television receivers. Among the requirements specified were those that the system should produce a 441-line picture with a picture frequency equivalent to 30 per second. These standards were accepted by the television engineering world with the utmost complacency.

If such a set of standards had been announced a few years ago it would have been instantly branded as quixotic idealism by almost every worker in the field. When it is realized that television research has been actively carried on for the past quarter of a century, this rapid advance in the last few years takes on real significance.

The cause of this extremely rapid advance which has changed television from a laboratory plaything into a practical engineering accomplishment was primarily a change from mechanical methods of picture transmission and reception to cathode ray systems.

Pioneering work in the field of cathode ray television had been carried on by a few isolated workers for a number of years previous to its general recognition by the major research laboratories. The work of these men served to illustrate to the world that the basis of cathode ray television was sound, and that electronic methods offered a solution to such problems as those of obtaining sufficient illumination on the viewing screen, of inertialess scanning required to obtain high definiton, and sufficient sensitivity for the successful transmission of pictures under ordinary conditions of illumination.

Once the way had been pointed out, a number of the more farsighted of the television research laboratories initiated a program of intensive research along this line. This work has been going on for the past five years and has led not only to refining

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Reprinted from *Short Wave and Television*, April, 1937.

the basic principles advanced by the pioneers but also to the discovery and adaptation of a great number of new principles. As a consequence of this effort, both the television transmitter and receiver have become a practical reality.

The television receiver as it is today—using the *Kinescope** —resembles, in appearance and size, a console radio receiver. The reproduced picture is sufficiently brilliant to watch without strain in a moderately lighted room and is in size about a page of this magazine. Thus, while such a reproducing device is a long way from ideal, it nevertheless is capable of bringing to the observer a picture that has high entertainment value, one which is both pleasing and informative.

The pickup camera employing the *Iconoscope** is but little larger than a commercial 35 mm. moving picture camera, and since it contains no moving parts can easily be made portable. At its present stage of development its sensitivity is sufficient to enable the transmission of an out-door scene under almost all conditions of lighting, or a studio picture when bright but not uncomfortable lighting is used.

The picture signal from this and accompanying sound pick-up is carried to the main ultra-short wave transmitter through cable or radio relay, and from there it is transmitted on a carrier of 5 or 6 meter wavelength. Such a transmitter is capable of servicing a radius of from 30 to 50 miles, depending upon the topography of the terrain.

Of course, it must be recognized that the problems of covering the country with a network of television transmitters, of manufacturing a reasonably priced receiver, and those involved in organizing and producing suitable programs are enormous. These problems are ones that must and will be met by the manufacturer, the production engineer and the technician. This solution is only a matter of time.

Even if some inconceivable law should come into existence that prevented the application of any new principles or developments to the cathode ray television system as it stands today, I am convinced that it would still become a commercial reality, that the system is amply capable of producing a picture which would satisfy a real economic demand.

However, this is equivalent to saying that the automobile of 1910 was a commercial reality. Certainly it was a mode of transportation which met a definite demand, and if all development

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* Registered Trademark of the RCA Manufacturing Co., Inc.

had ceased at that date the automobile would still be extensively used today. Just as the useful but crude vehicle of 1910 has evolved into the luxurious motor car of today, which in its turn will be supplanted by an even better vehicle in the future, so the application of the laboratory research which is going on today must inevitably lead to improvements in the cathode ray television system.

Of course, the statement that marked advances in cathode ray television can be made is not proof that this progress is possible. However, research which is being carried out in the laboratory gives ample evidence of the improvements that may be expected as our knowledge increases. To give a concrete example, recent advances in electron optics makes it possible to produce an electron copy of a visible image and secondary emission, which has only just begun to be seriously studied, makes it possible to intensify this copy. These two new principles have been applied to laboratory models of the Iconoscope with a consequent manyfold increase in sensitivity. Another example that might be cited is that of the viewing tube. The size of the present television picture is limited because it is viewed directly on the fluorescent screen of the Kinescope and, consequently, is dependent on the physical size of the tube. *Laboratory experiments indicate that there is every reason to believe that it will be possible to build tubes giving a small picture of sufficient brilliancy to be projected upon a large viewing screen.* Experimental models of this type of projection tube have been made which very nearly meet the requirements of television. Continued improvements in the electron gun and in fluorescent material will unquestionably make this type of Kinescope entirely practical.

These are only two of the many examples that might be given of the progress that may be expected. Next year and the year after, examples which do not exist today can be given. In other words, the electron system has not yet even emerged from early childhood. Only the most incorrigible pessimist, the man who has an honest doubt about the sun's rising tomorrow, believes the cathode ray television is a closed field, that all is known about it that can be known.

Assuming that the system as it stands today can produce a fairly satisfactory picture and that there is every reason to look for marked improvements in the near future, lest us ask what will be required of television if it is to become popular in the sense that radio broadcast is popular.

Considering first the receiver, the entertainment supplied by the receiver must be such that it can be made incidental to the normal household activities. In other words, television is not and should not be intended to take the place of the observer's going in person to see an event in which he is intensely interested. The sport fan will still go to the baseball field, the football game or the boxing arena, the theatre lover will still go in person to see the plays in which he is interested, television or no television. However, to the individual who is not sufficiently interested in an event to expend the time and effort to become an eye witness, television will bring a summary of what is taking place. This means that the receiver must be small enough so that it will not be objectionable as a piece of furniture. It must be simple in operation and arranged so that it does not require setting up of viewing screens or any other elaborate preparation. The picture should be bright enough so that it can be readily seen in a moderately lighted room, and small enough not to be too obtrusive, perhaps one-and-a-half by two feet in size. In a sense, the receiver might be considered as a window through which the individual may, in the course of conversation or reading, glance to see what is going on in the world around him.

The television pickup device, to be completely satisfactory, must be sufficiently sensitive not only to reproduce scenes of average illumination but should also be operative at very low light levels. Imagine the feelings of the spectators looking at a football game if the last few minutes' play cannot be transmitted due to insufficient light. The Iconoscope of today, while it will suffice for ordinary weather conditions, would not be operative in the semi-darkness of late afternoon in November. However, as was pointed out above, there is every reason to expect a continuous improvement in the *sensitivity* of the Iconoscope as time goes by. Eventually, the Iconoscope may equal or even exceed the photographic camera in sensitivity.

Perhaps the most difficult to attain is a satisfactory *network of transmitters.* At present, the range of an individual transmitter is limited to the visual horizon as seen from its antenna. This means that the area serviced by a transmitter is relatively small, and that each urban center must have its own television transmitters. It is obviously necessary, in a completely satisfactory system, to be able to chain these transmitters in such a way that events can be broadcast nation-wide. These chains will be formed by inter-connecting the stations with means of *concentric cable* and by the use of *radio-relay links.*

This ideal system will eventually exist, but only after years of television broadcasting experience. In the meantime, we will have to be content with a much less perfect system. All the units for satisfactory television are ready and now await commercialization by those responsible for the economic and production aspects of the problem. But, as warning to those who are unduly optimistic, the problem of assembling these elements is almost as formidable as that of developing cathode ray television. Universal television in the home will not be an accomplished fact for a number of years to come but, on the other hand, it is absolutely assured that home reception of pictures will eventually be commonplace.

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.

Reprinted from *Proc. I.R.E.*, August, 1937.

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 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.

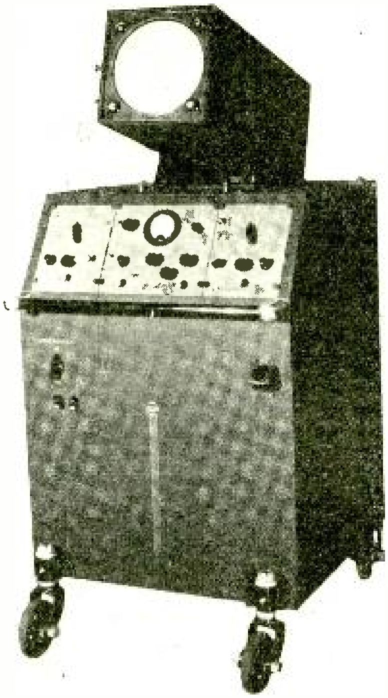

Fig. 1—Front view of cathode-ray oscillograph.

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 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

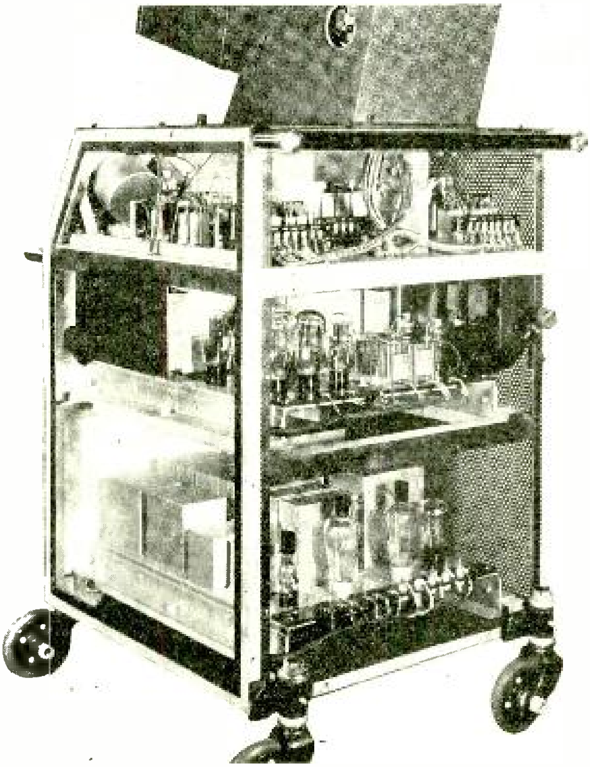

Fig. 2—Back view of cathode-ray oscillograph.

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-inductor 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 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

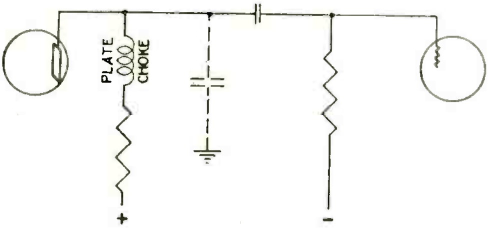

Fig. 3—Basic circuit for correction of initial transient response.

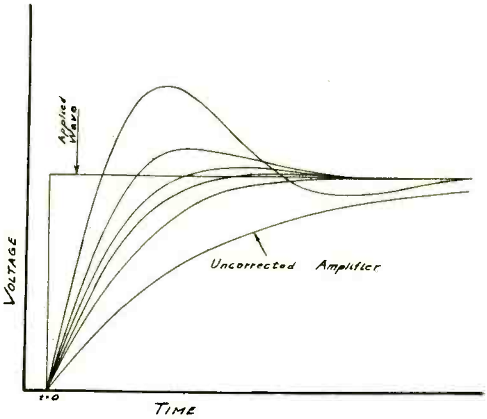

Fig. 4—Response to initial transient. Amplifier uncorrected and with varying degrees of correction.

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 relaxation 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.

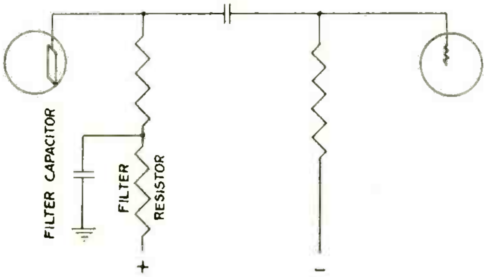

Fig. 5—Basic circuit for correction of relaxation transient.

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-

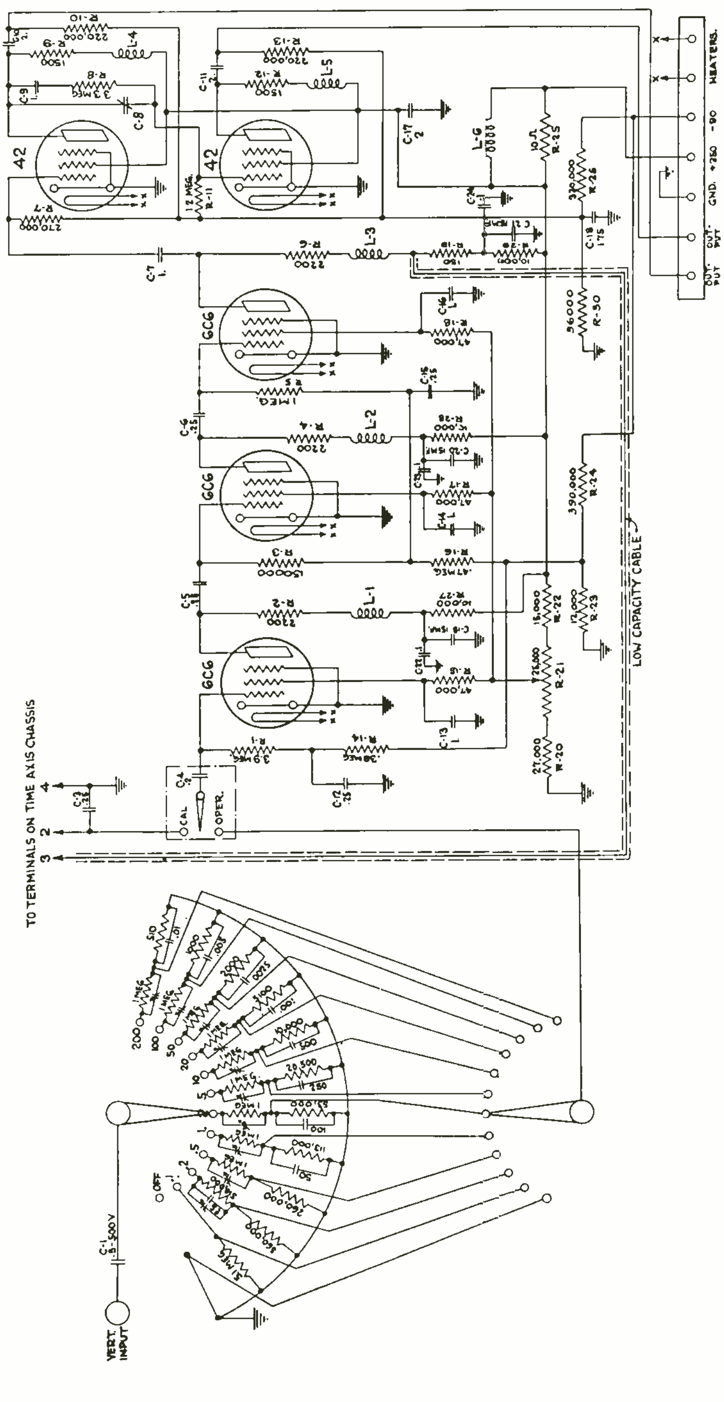

Fig. 6—Schematic diagram—vertical amplifier of cathode-ray oscillograph.

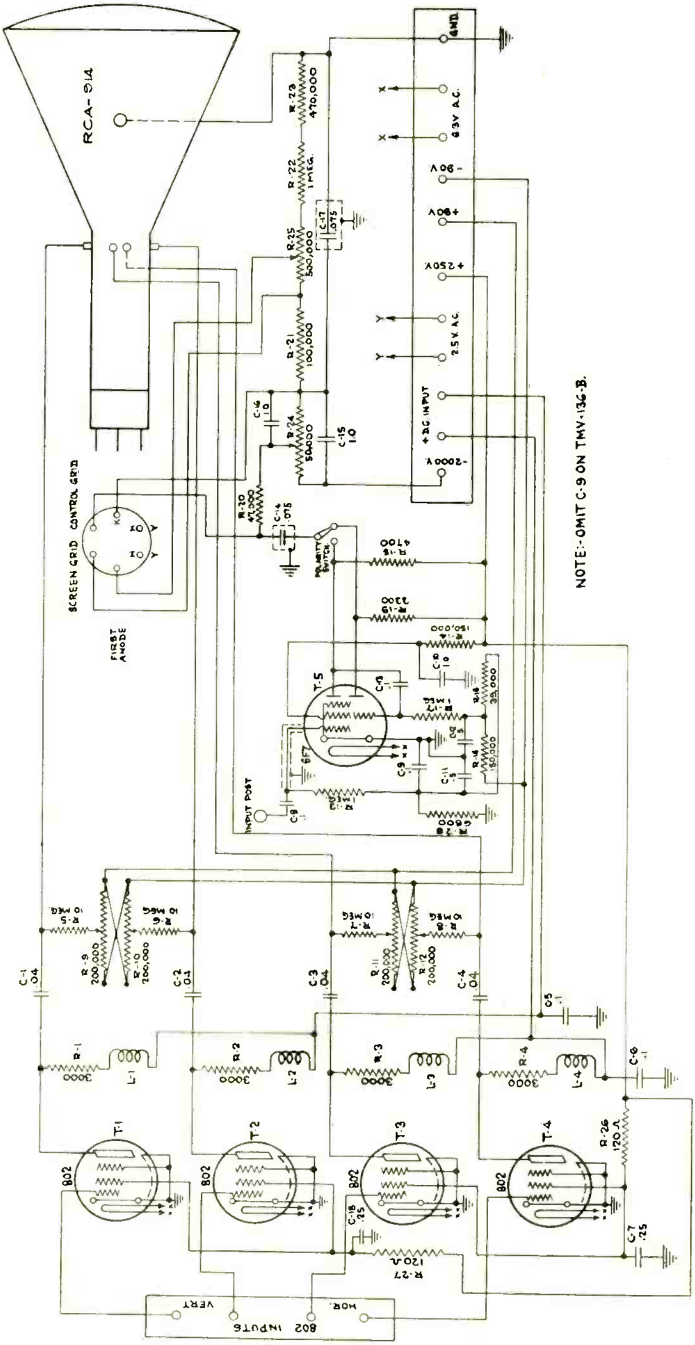

Fig. 7—Schematic diagram—oscilloscope mount of cathode-ray oscillograph.

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

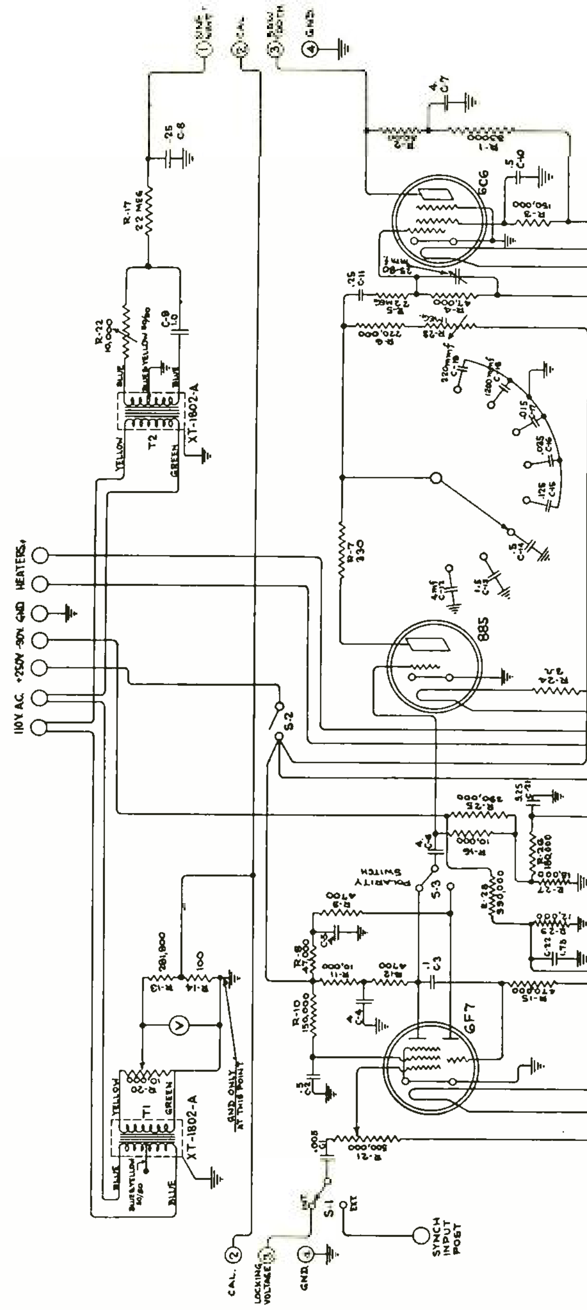

Fig. 8—Schematic diagram—reference axis supply of cathode-ray oscillograph.

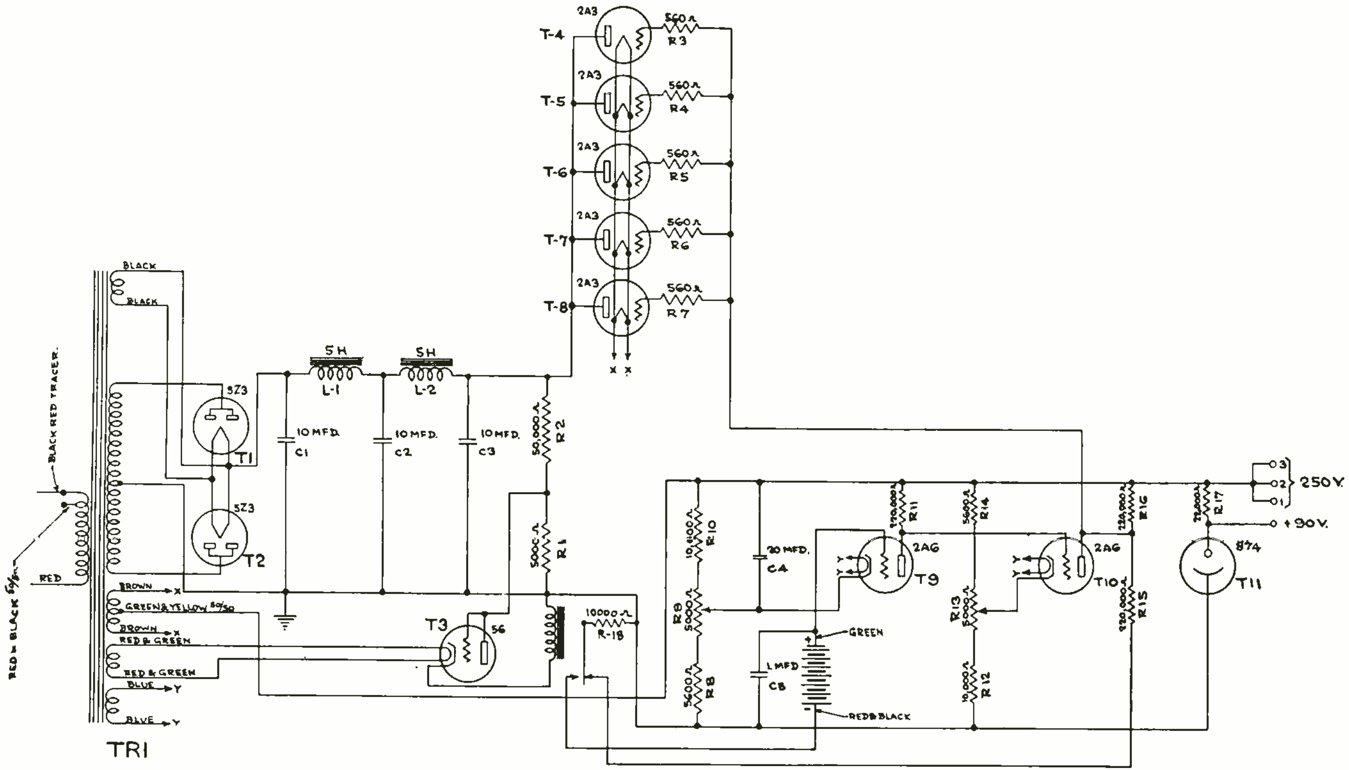

Fig. 9—Schematic diagram—regulated power supply of cathode-ray oscillograph.

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

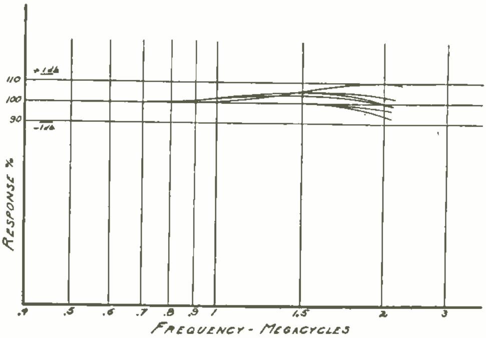

Fig. 10—Composite frequency versus response curve first twelve amplifiers in production.

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

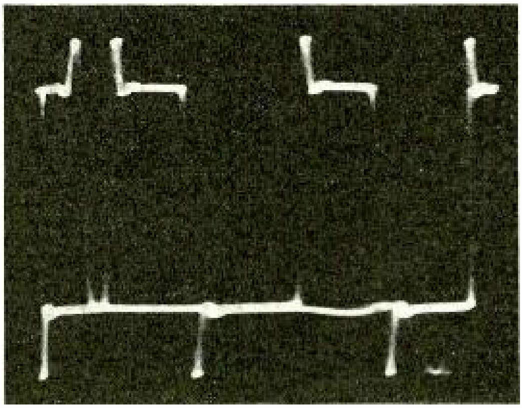

Fig. 11—Response to a square wave of 250 kilocycles fundamental.

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 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.

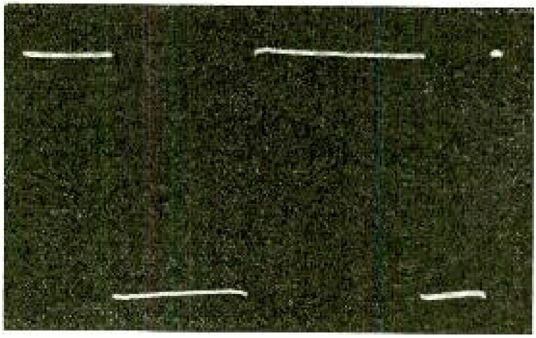

Fig. 12—Square-wave, ten-kilocycle fundamental. Output of square-wave generator used as test signal for all attenuator adjustments.

For adjusting the circuit elements controlling the low-frequency response there is no choice of test method; square waves provide the only test known at present that predicts the performance of the unit in service. The waves for this test have a fundamental frequency of thirty cycles and are obtained by commutating a direct-current circuit with a vacuum tube controlled relay. Five per cent tolerance is

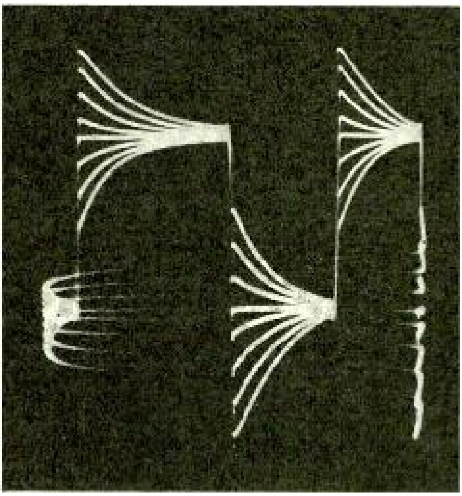

Fig. 13—Wave shapes obtainable during adjustment of attenuators. Final adjustment shown by square wave near center of range.

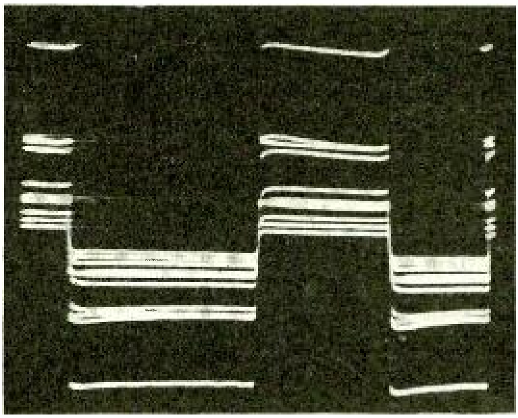

Fig. 14—Agreement of attenuator steps. One exposure on each step. Input voltage range shown, about sixty decibels.

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.

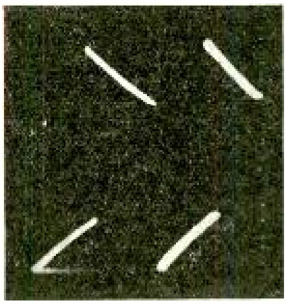

Fig. 15—Response to thirty-cycle square wave. The response characteristic of this amplifier was two per cent low at thirty cycles.

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 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

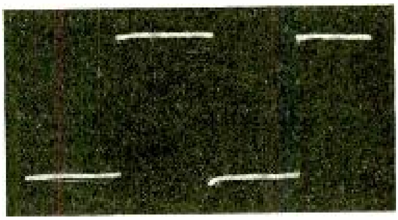

Fig. 16—Response of the described instrument to a thirty-cycle square wave.

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.

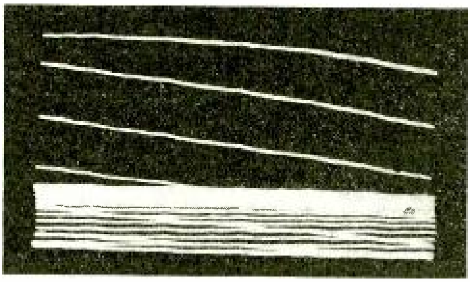

Fig. 17—Response to application of a direct potential.

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 amplifiers 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.

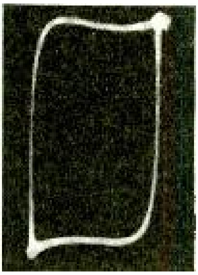

Fig. 18—Demonstration of time of transmission. Vertical deflection—input, wave shape as shown in Fig. 11. Horizontal deflection output.

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.

A CIRCUIT FOR STUDYING KINESCOPE RESOLUTION

By

C. E. Burnett

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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.

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

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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

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[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 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.

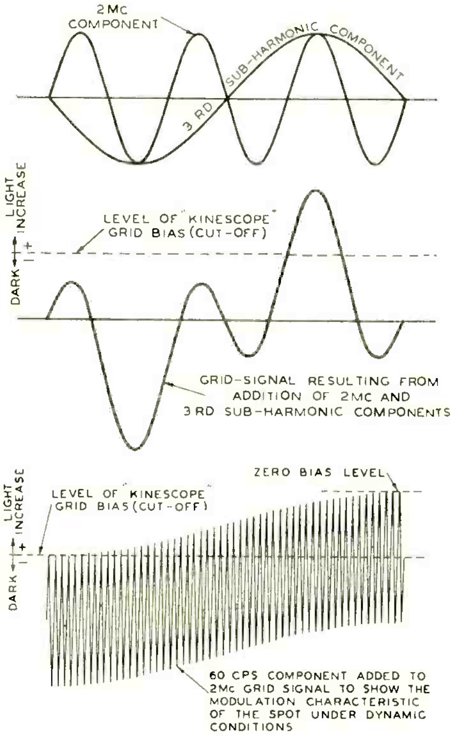

Fig. 1—Grid-signal components.

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:

$$f_2 = \frac{L_1 R f_1}{L_2 \pi} \qquad (1)$$

$$= \frac{R f_1}{\pi} \text{ if } L_1 = L_2 \qquad (2)$$

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 special 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.

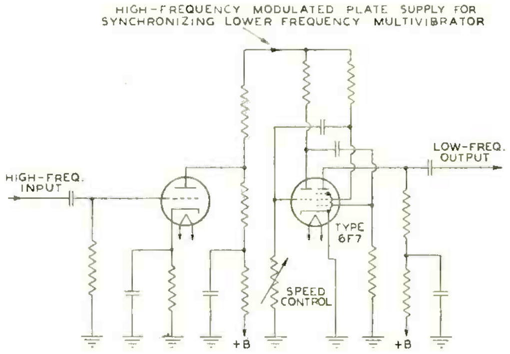

Fig. 2—Circuit showing type 6F7 as multivibrator arranged to synchronize on subharmonic of higher frequency supplied through another tube.

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-

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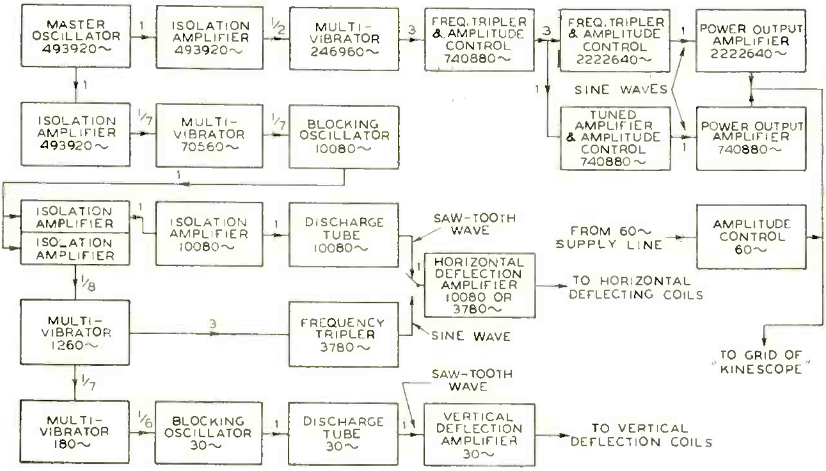
[3] For explanation of the blocking oscillator see R. S. Holmes, W. L. Carlson, and W. A. Tolson, "An experimental television system," Proc. I.R.E., vol. 22, p. 1277; November, (1934).

[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.



NOTE: NUMERALS BETWEEN BLOCKS DESIGNATE RATIO OF FREQUENCIES

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 $493{,}920/2 = 246{,}960$ 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 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

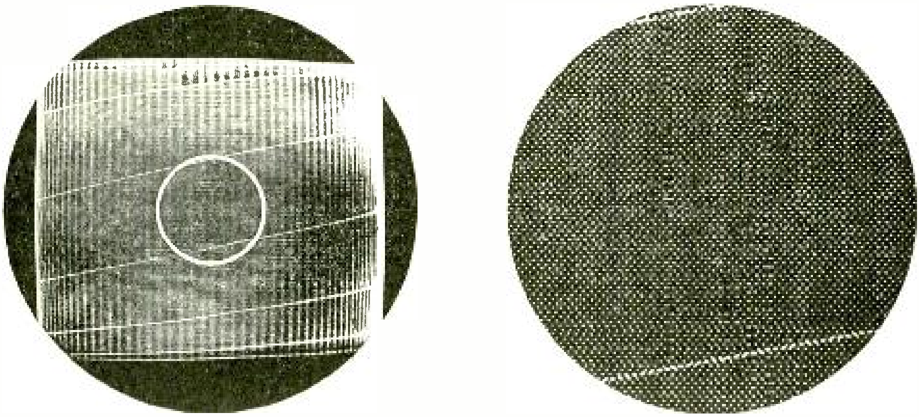


Fig. 4

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

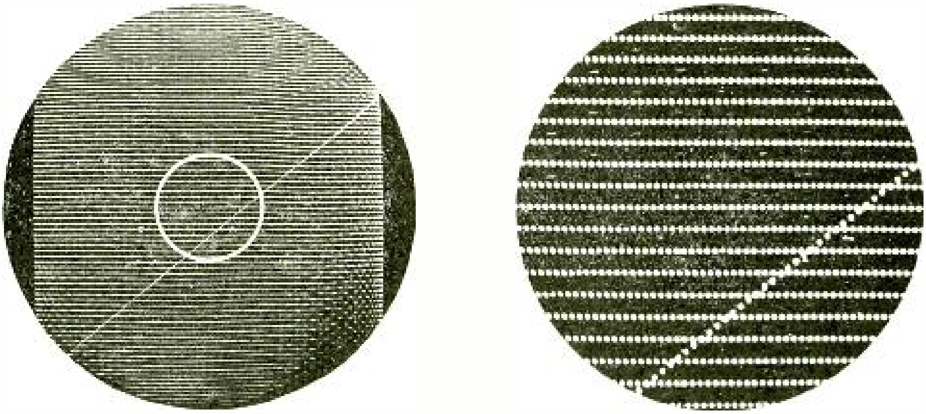


Fig. 5

(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.

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 approximately 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

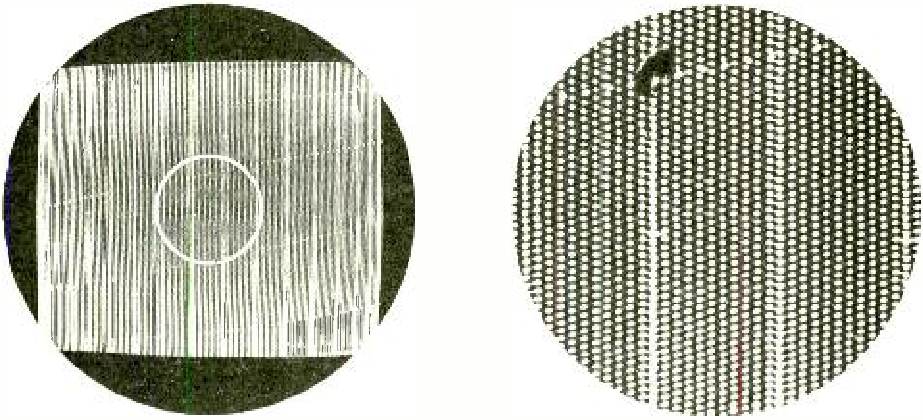


Fig. 6

(Left)—Same test pattern as shown in Fig. 4 except that two thirds of white elements are removed.

(Right)—Area within white circle on shownabove pattern enlarged four times to show detail.

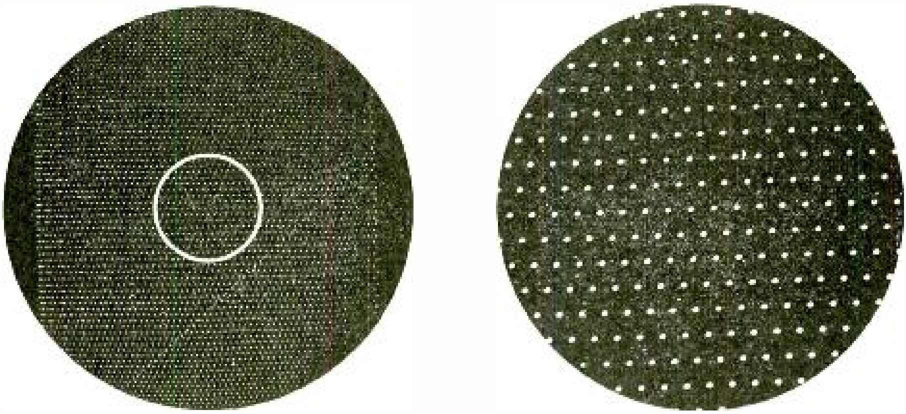


Fig. 7

(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.

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 that there is a small amount of irregularity in the checkerboard formation. This results from a small amount of pickup in the horizontal de-

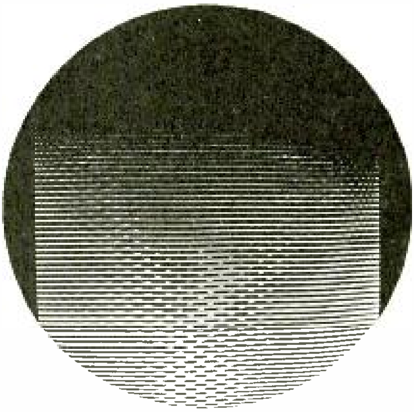


Fig. 8

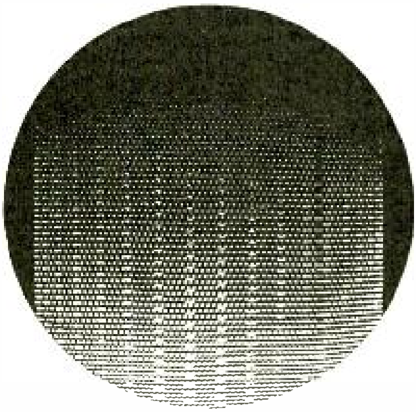


Fig. 9

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.

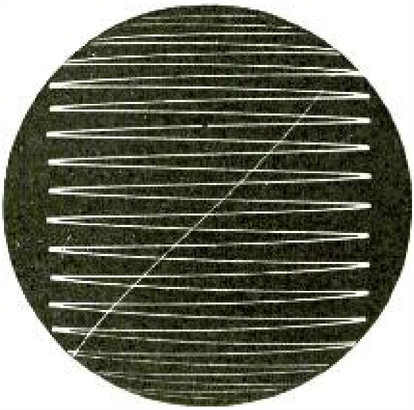


Fig. 10

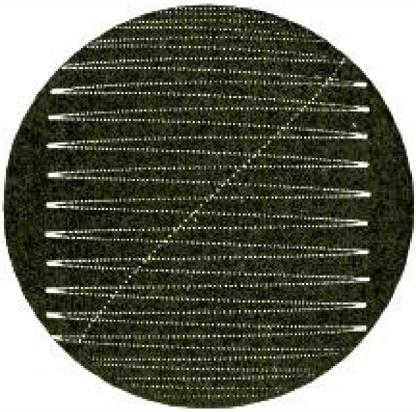


Fig. 11

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.

flection 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 saw-tooth 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 pictures 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.

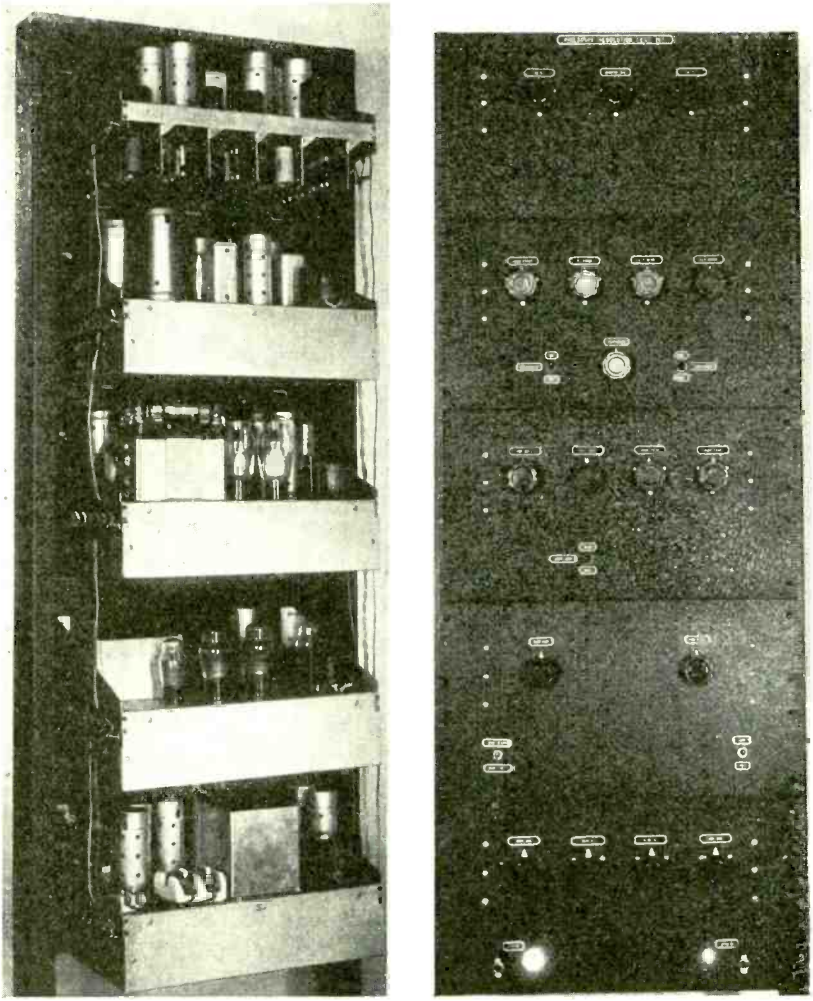


Fig. 12—Rear and front views of test equipment for studying Kinescope resolution.

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

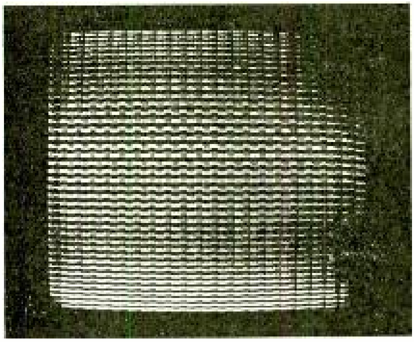


Fig. 1

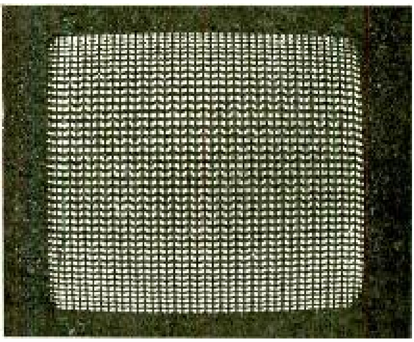


Fig. 2

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

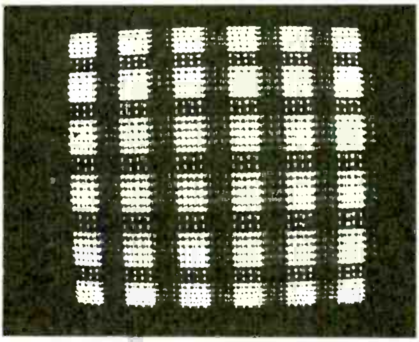


Fig. 3

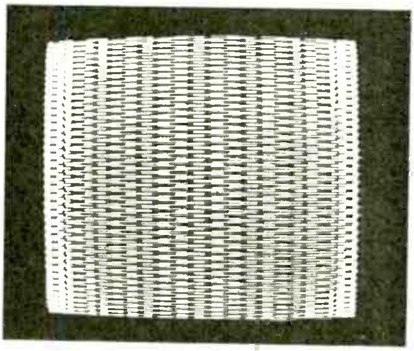


Fig. 4

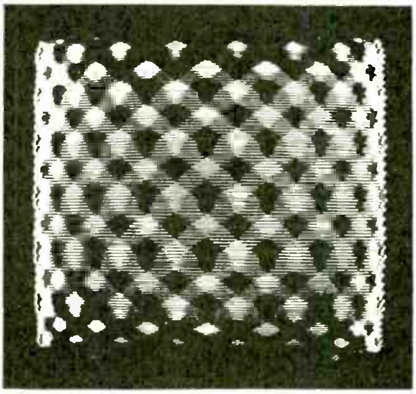


Fig. 5

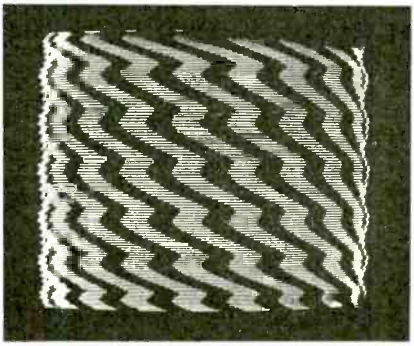


Fig. 6

Fig. 7

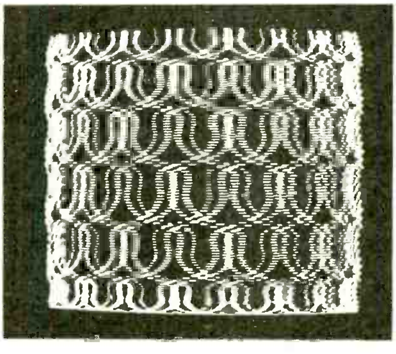


Fig. 8

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

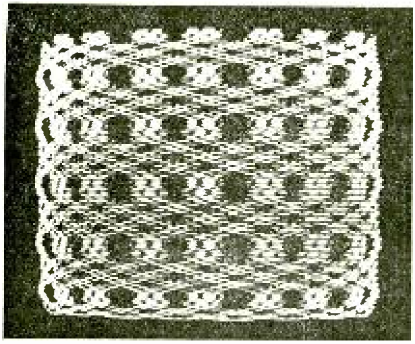


Fig. 9

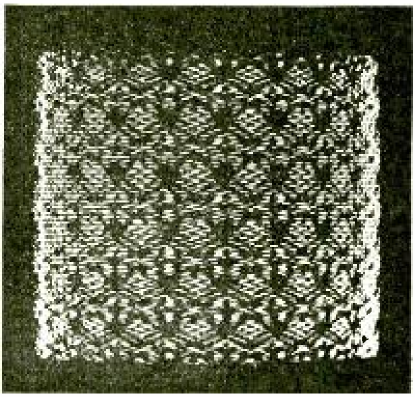


Fig. 10

ANALYSIS AND DESIGN OF VIDEO AMPLIFIERS

BY

S. W. SEELEY AND C. N. KIMBALL

License Laboratory, Radio Corporation of America

NATURE OF THE PROBLEM

THE amplification of the wide band of frequencies which constitute the video modulating signals in television transmission presents a special problem in amplifier design, since the requirements differ considerably from those encountered in audio amplifiers, in which only flat frequency response and freedom from harmonic generation are usually sought. Video amplifiers must be designed with particular reference to the maintenance of constant gain over the entire video frequency band, and attention must also be given to phase characteristics as affecting the time delay in transmission of the signals through the amplifier.

The high frequencies involved and the necessity for the maintenance of definite time-delay characteristics are the factors which require the most attention, and we propose to indicate means for attaining the desired amplifier characteristics through expedients which are easily applied in practice.

The present RMA standards of 441-line interlaced scanning, with a field frequency of 60 cps. and a frame frequency of 30 cps., impose severe requirements on the video amplifiers used in television receivers. The amplifiers must be capable of passing, with constant gain, all frequencies from 60 cycles to at least 2.5 megacycles, and the time delay must be substantially independent of frequency.

The necessity for constant time delay over the video band may be explained from consideration of the effect upon picture detail of using a video amplifier with phase characteristics which cause the high-frequency end of the video band to be delayed with respect to the low-frequency end in transmission through the amplifier. (This is generally the manner in which the time delay

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* Trade Mark Registered U. S. Patent Office.

varies as a function of frequency in typical video amplifiers.) With 441-line scanning and a twelve-inch tube (ten-inch picture) the spot on the "Kinescope"* screen moves at a rate of approximately 1.5×10^5 inches per second, that is, it takes about 7 microseconds to move one inch horizontally. (These figures are based on a return time in the horizontal sweep of ten percent of a scanning cycle.) Thus, consider the situation existing when the transmitted picture consists of a pattern half white and half black, with the vertical center line of the screen separating the two halves. The video signal is a square wave, containing a fundamental frequency of 13,230 cycles per second (441 lines and 30 frames), and all its odd harmonics. The maintenance of this wave form in transmission through the video amplifier requires that the time delay be constant for all frequencies. If the delay decreases with frequency, the higher harmonics of the square wave will be retarded less than the lower frequencies, and the resulting pattern on the "Kinescope" screen will not have the sharp line of demarcation between black and white as contained in the original picture. A difference in time delay of one microsecond between the high and low ends of the video band will cause a horizontal shift in the higher frequency components of the picture of about .14 inches with respect to the low-frequency components.

Similar results are obtained from an analysis of the situation on a phase shift basis, since the total time delay at any frequency is equal to the quotient of the total phase delay in the amplifier and the angular frequency. (Note that the phase reversal of 180 degrees which occurs in each stage of the amplifier due to tube action does not constitute a phase delay. We are concerned here only with the phase and time delays due to the presence of reactance in the plate circuit loads, and shall confine our remarks to these quantities.) The square wave generated by scanning the pattern described above may be expressed in a Fourier series of sines and cosines of the fundamental frequency (13,230 cycles) and its harmonics. The maintenance of the square-wave form requires that the total phase delay in the video amplifier vary linearly with frequency (as can be seen by analysis), and linearity of the phase characteristic implies a constant time delay.

Generally the patterns scanned by the "Iconoscope"* beam are not as geometrically precise as that used here for discussion of the video amplifier requirements, but are made up of random

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* Trade Mark Registered U. S. Patent Office.

variations of light and dark shading. The necessity for constant time delay is no less important in this case, for the picture will be distorted in the event of non-uniform time delay, especially if the pattern contains considerable detail.

It follows, then, that both constant time delay and flat frequency response are equally important in video amplifiers, and that anything done to bring about correction of one should not affect the other adversely. It is assumed here that the signal input will be held below the level which causes harmonic generation in the amplifier, so that harmonic distortion need not be discussed further.

ANALYSIS

In a well designed resistance-coupled amplifier, the top frequency which can be amplified without material loss in gain is determined by the effect of the reactance of the tube and circuit capacitances in shunting the resistive plate load.

Obviously the upper limiting frequency may be extended in any case by using a low value of plate-load resistor, so that the reactance of the shunting load-circuit capacitance is large in comparison with that load resistance. It is seen that the frequency range may be increased extensively if the load resistance is made sufficiently small, but the gain drops off at all frequencies as R_L is decreased.

One way to diminish the shunting effect of the load circuit capacitances is to insert a properly proportioned choke in series with the output-load resistor. This causes the plate-circuit load of the stage to have very nearly constant impedance over a wide band of frequencies, the top frequency being determined by R. L and the total capacitance C from plate to ground.

The compensated stage, with its constant impedance load circuit, as shown in Figure 1, has a gain which is approximately constant and equal to $g_m R$ at all frequencies up to and including f_o, the top frequency which the stage must amplify. (See Appendix I for derivation.)

R and L for a given value of f_o are determined by the load-circuit capacitance C. To fulfill this condition R must be made equal to the reactance of this load capacitance at the top frequency, f_o, that is, $R = \dfrac{1}{2\pi f_o C,}$, and the reactance of the compensating choke at f_o must be equal to half the load resistance,

i.e. $2\pi f_o L = \frac{R}{2}$

The gain of $g_m R$ per stage due to the use of this compensated load circuit is equal to the gain which would be experienced with zero load-circuit capacitance and no compensating choke; hence, the compensation for flat-frequency response is seen to be adequate.

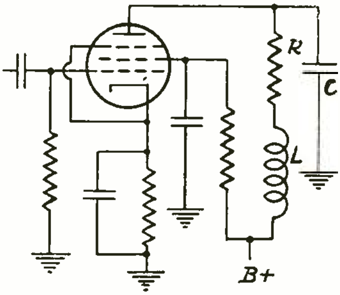

Fig. 1

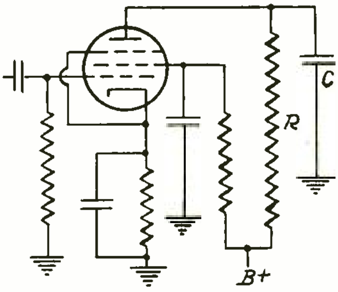

Fig. 2

With only R and C in the load circuit, and with no compensating choke, the gain is equal to

$$\frac{g_m R}{\sqrt{1 + C^2\omega^2 R^2}} = \frac{g_m R}{\sqrt{1 + f^2/f_o^2}} \quad \text{if } R = \frac{1}{2\pi f_o C}$$

Here the gain at the top frequency f_o is only .707 $g_m R$, a loss of approximately 30 per cent with respect to the gain of the compensated stage.

It is seen that, even in a compensated stage, the limiting frequency f_o can not be increased indefinitely, for the output-load resistance must be decreased as f_o is increased. Since the gain falls off inversely with f_o (gain $= g_m R = \frac{g_m}{2\pi f_o C}$) the limiting frequency is reached when $\frac{g_m}{2\pi f_o C} = 1$. At frequencies higher than $f_o = \frac{g_m}{2\pi C}$ the amplifying properties of the stage disappear, and the output voltage becomes less than the input voltage.

There is a simple method for determining the load-circuit capacitance of each stage in the video amplifier, which depends upon the fact that the gain of an uncompensated stage falls to 70.7 per cent of its low-frequency value at the frequency f' for which $R_L' = \frac{1}{2\pi f'C}$. (Here R_L' is the output-load resistance and C is the load-circuit capacitance to be measured.) The procedure is as follows: In the plate circuit of the first stage of the amplifier insert a load resistor of about 3000-5000 ohms. Place a fixed bias on the grid of the second tube just sufficient to produce cathode current cut-off. Apply a low-frequency signal (about 10 kc) to the grid of the first tube and adjust its magnitude to produce a second-tube cathode current of some predetermined value, say .1 ma. Now determine the frequency f' at which the input voltage to the first tube must be increased to $\sqrt{2}$ times its low-frequency value to maintain the cathode current of the second tube at .1 ma (i.e., f' is the frequency at which the stage gain is down 30 per cent).

This frequency f' is used to calculate C by $C = \frac{1}{2\pi f'R'_L}$. (Note that this value of C includes all the tube and circuit capacitances effective during operation of the amplifier.) This frequency f' will generally be lower than the top frequency which the compensated stage is intended to amplify. With this value of C next determine R_L (to be used in the compensated circuit) to satisfy the equation $R_L = \frac{1}{2\pi f_o C}$ where f_o is the top frequency to be passed by the amplifier. The compensating choke to be inserted in series with R_L should have a reactance at this top frequency f_o of half the value of the load resistance, that is $2\pi f_o L = \frac{R_L}{2}$.

This procedure can be repeated stage by stage throughout the entire amplifier, by connecting, in each case, the signal generator to the grid of the stage whose load-circuit capacitance is desired, and by using the following tube as a vacuum-tube voltmeter.

The determination of C for the last stage may be made in this manner by utilizing the "Kinescope" as a vacuum-tube voltmeter. Bias its control grid back to a point which permits the cathode-ray tube to act as a plate-circuit detector, and repeat the procedure previously outlined. The use of the "Kinescope" in this manner permits the measurement of C for the last tube under actual operating conditions, and C therefore includes the input capacitance of the Kinescope control grid.

PHASE AND TIME DELAY

I. *Uncompensated video amplifier stage:* The gain is equal to $g_m R / \sqrt{1 + \left(\frac{f}{f_o}\right)^2}$ if $R = \frac{1}{2\pi f_o C}$. The phase shift due to passage through the stage of a signal of frequency f is $\phi = -\tan^{-1} 2\pi f C R = -\tan^{-1} \frac{f}{f_o}$. (See Appendix II for derivation), where the negative sign means a greater phase *delay* for the higher frequencies than for the lower ones.

Note that this delay is due only to the presence of reactance in the plate-circuit load. There is no delay in the tube at these frequencies, for the tube merely reverses the phase of its input voltage.

The actual time delay in seconds corresponding to a frequency f is $\Delta t = \frac{\text{phase delay in radians}}{2\pi \times \text{frequency in cycles/second}}$

The phase shift and time delay for several stages in a video amplifier are additive; three similar stages cause three times the time delay of a single stage, whereas the gain of a three-stage amplifier is the product of the individual stage gains.

Figure 3 shows curves of phase delay and gain vs. $\frac{f}{f_o}$ for a single uncompensated stage. Note that the phase delay does not increase linearly with frequency, hence the time delay is not constant over the frequency band.

The quantitative effect of non-uniform time delay will be discussed in detail in the section dealing with compensated video amplifiers.

II. Choke compensated amplifier stage: As noted previously, the condition for flat-frequency response to a frequency

$$f_o \text{ is } R = \frac{1}{2\pi f_o C} = 4\pi f_c L$$

The phase delay for a single compensated stage is

$$\phi = + \tan^{-1} 1/4 \left[\left(\frac{f}{f_o} \right)^3 + 2 \left(\frac{f}{f_o} \right) \right]$$

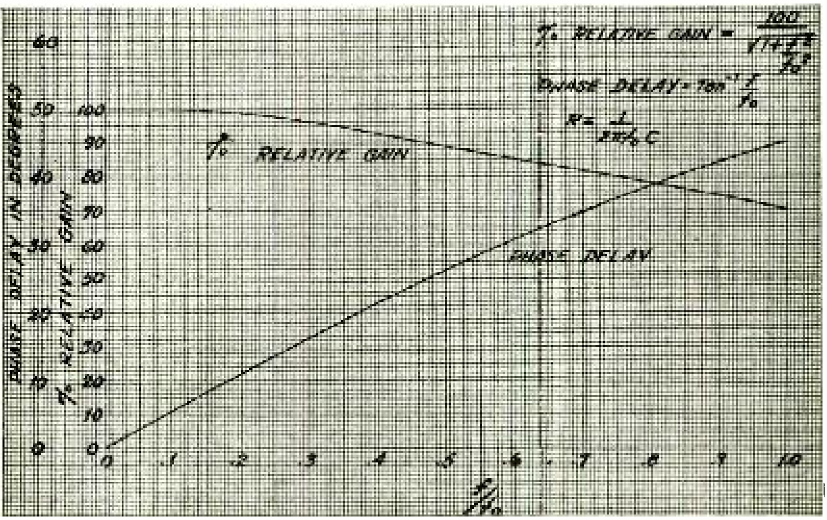

Fig. 3—Uncompensated stage of video amplifier.

and the time delay in seconds is

$$\triangle t = + \frac{1}{2\pi f} \tan^{-1} 1/4 \left[\left(\frac{f}{f_o} \right)^3 + 2 \left(\frac{f}{f_o} \right) \right]$$

(see Appendix I for derivation of these expressions). Note that the phase and time delays for a given frequency f are dependent only upon f and the top frequency f_o, regardless of the numerical values of R, L and C which are used to attain flat-frequency response out to a frequency f_o. Here, again, the total phase and time delay for several stages is equal to the algebraic sum of individual stage delays.

The phase delay of a compensated stage is plotted vs. f/f_o

in Figure 4 and it is seen that the non-linear phase characteristic will result in a non-uniform time-delay curve.

The elements in the load circuit of a video-amplifier stage can be proportioned to produce a constant time delay throughout the video band but this generally results in a non-uniform gain characteristic.

As a quantitative indication of the magnitude of anticipated time delay and its effect upon the displacement of picture elements on the "Kinescope" screen, there is plotted in Figure 5 the total time delay due to a three-stage video amplifier compensated for constant gain to a frequency of 2.5 megacycles, and a curve of the actual horizontal displacement of picture elements corresponding to the different frequencies in the video band is shown. Since the video-detector load will generally be compensated for constant impedance to f_o, its contribution to the total time delay has been included. Therefore, the net time delay is equivalent to that of a four-stage video amplifier fed from an uncompensated detector load. The calculations of element displacement are based on 441-line horizontal scanning, a ten-inch picture on a twelve-inch tube, and ten percent return time in the horizontal sweep.

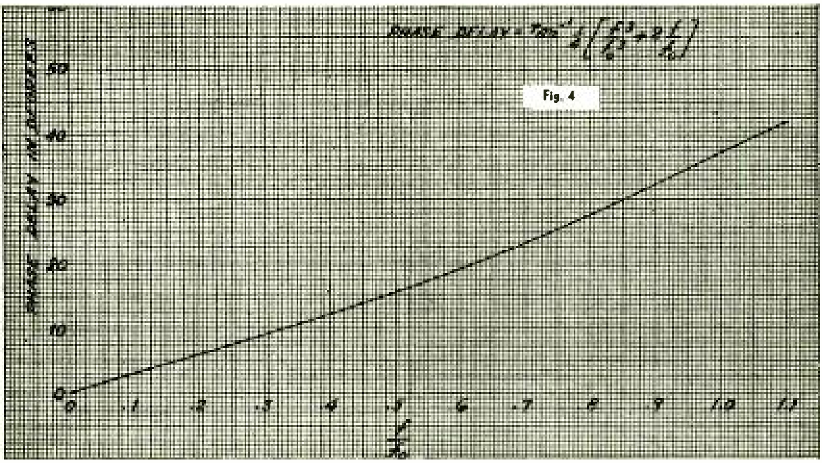

Fig. 4—One compensated stage of video amplifier.

Figure 5 shows that the delay increases with frequency. The total time delay is not significant, as it is the difference in time delays for the various frequencies in the video band with which we are concerned. These differences are the cause of the relative displacements of the various frequency components in the picture. Constant time delay would result in all the picture elements being displaced by the same amount, regardless of the video frequency with which they are associated, and no picture distortion would result. As it is, the curve of displacement vs. frequency shows that picture elements corresponding to the two extremes of the video band (60 cycles and 2.5 megacycles) will be displaced by approximately .019″ at the low end and .024″ at the top end. The relative displacement, or the effect which causes the relative shift in picture elements and the corresponding distortion, is only .005″, and this is small in relation to the width of a scanning line.

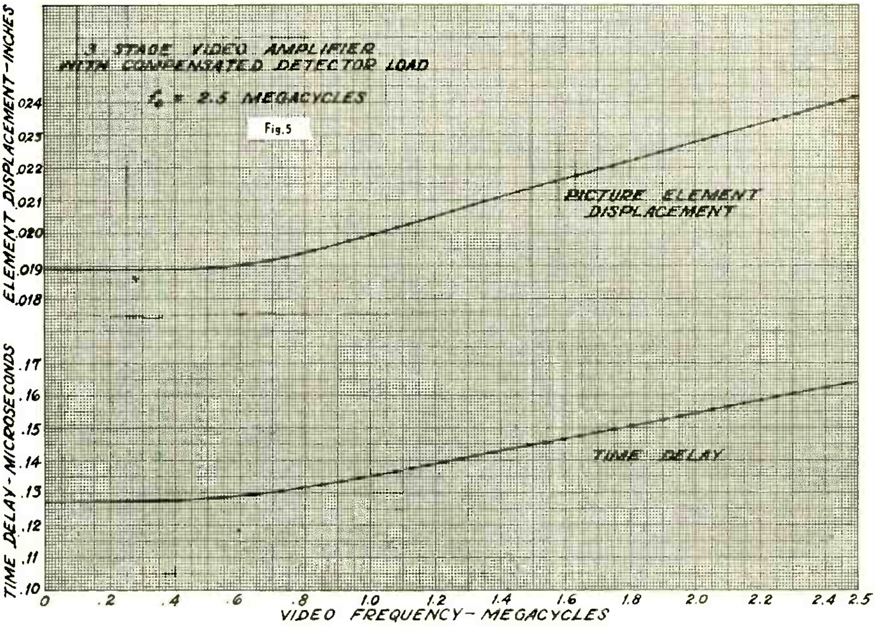

Fig. 5—Three-stage video amplifier with compensated detector load.

NUMBER OF STAGES

The choice of an even or odd number of stages in the video amplifier depends upon the video detector circuit and the method of transmission. With negative modulation, as specified in the current RMA standards, a positive pulse of modulation on the television carrier occurs when the scanning beam in the "Iconoscope" passes through a black portion of the picture. With any type of detector circuit in which the cathode end of its load resistor becomes positive for the video signal during modulation peaks, it requires an even number of tubes in the amplifier to reproduce on the "Kinescope" screen the same polarity of shading as that in the transmitted picture. This is true when the detector cathode is grounded. If the negative end of the detector load is grounded an odd number of amplifier tubes is required; this connection may not be so favorable to uniform video-frequency response in an uncompensated detector-load circuit because of the shunting effect on the detector load of the heater-cathode capacitance of the detector tube.

LOW FREQUENCY CONSIDERATIONS

The maintenance of the proper gain and phase-delay characteristics at the low-frequency end of the video band (60 cycles) requires that attention be given to the coupling circuits between successive stages, since the cause of non-uniform characteristics in this part of the band will generally be due to insufficient interstage coupling.

An extremely small departure from linearity in the phase delay vs. frequency characteristic at very low frequencies can be quite serious. One degree at sixty cycles corresponds to 46.2 microseconds, and a .1 $\mu fd.$ coupling condenser in conjunction with one-megohm grid leak produces a phase shift of 1.5 degrees or 69.3 microseconds. Consideration of the reproduced pattern under these conditions shows that if a solid white screen were being transmitted a 1.5 per cent change in intensity from top to bottom for each such coupling unit would result.

For this reason the low-frequency characteristic of each stage must be compensated by the use of a plate circuit-load impedance which becomes capacitive at low frequencies. This is accomplished by including a second load-circuit resistance at the low (v.f.) potential end of the main resistor. This additional resistor is by-passed by a condenser such that the phase delay in the total load circuit (at low frequencies) just compensates for the phase advance caused by the preceding grid-coupling circuit.

The tendency toward motor-boating in video amplifiers is sometimes prominent because of the maintenance of normal gain at low frequencies. This is best avoided by using as small a coupling condenser as possible, consistent with proper 60-cycle performance, and by maintaining the output impedance of the power supply at a very low level for frequencies at which motor-boating is liable to occur (10-30 cycles). Separation of the screen supplies for the different amplifier tubes by means of high inductance (500-henry) chokes and heavy by-passing of all screen leads with 8 $\mu fd.$ electrolytic condensers generally suppresses all tendency toward motor-boating.

MEASUREMENT OF GAIN AND PHASE DELAY

The gain characteristic under actual operating conditions is best determined by utilizing the "Kinescope" as a vacuum-tube voltmeter, since the input capacitance of its control grid is then present across the output circuit of the last stage in the video amplifier. The tube should be biased back to act as a plate-circuit detector, and the gain characteristic is determined from measurements of the input voltage to the amplifier required to maintain the cathode current of the "Kinescope" at some constant value.

The phase-delay characteristic of a compensated video amplifier can be determined directly from calculation or from the curve of Figure 4 if it is known that the gain is constant for all frequencies up to the frequency which represents the top of the desired video band. If, however, the gain is not constant, due possibly to intentional over-compensation to produce an increase in high frequency gain, the phase-delay characteristic is not as easily calculated, and may best be determined experimentally.

This measurement is most effectively made with the aid of an oscilloscope whose horizontal and vertical amplifiers are identical and capable of amplifying at least up to 2.5 megacycles. The application of this instrument to the measurement of phase delay makes use of the fact that two voltages of the same frequency, applied to the separate pairs of deflecting plates in the cathode-ray tube (through amplifiers, if the voltage level is so low as to preclude direct application of the voltages to the plates), cause the trace on the oscilloscope screen to assume a definite pattern, dependent upon the relative amplitudes and the phase relation of the voltages under observation. The oscilloscope trace is linear when the voltages are 0 degrees or 180 degrees out of phase, and becomes a circle with 90 degrees phase angle and equality of amplitude of the voltages.

Any other phase relation causes the trace to be elliptical, and the desired phase angle can be determined graphically from measurements on the screen of the major and minor diameters of the ellipse, or, more accurately, by employing *R-C* circuits to shift the phase of one of the voltages until a linear trace is made to appear. The unknown angle is then computed from ω and *R* and *C* of the phase-shifting network.

The presence of capacitive reactance in the plate circuits of the video amplifier causes the output voltage to lag the input voltage in time phase; hence the *R-C* circuits used for phase shifting in the phase-angle measurements must be so arranged as to cause the phase of the input voltage to be delayed before it is applied to the oscilloscope, or, conversely to advance the phase of the output voltage. Figures 6 and 7 show typical circuits for use in this work. A linear trace is obtained when the phase shift in the *R-C* network is equal to the phase shift in the video amplifier. As noted above $\phi = (90° - \theta)$, where θ is the angle between e_{gen} and *i* through *R* and *C*. Note that *C* must include the additional capacitance occasioned by connection to the oscilloscope; i.e., either the input capacitance of the horizontal amplifier or the capacitance between horizontal deflecting plates, depending upon whether or not the voltage is applied directly to the plates. The input capacitance of the vertical-deflection system will also add to the output capacitance of the video amplifier, and this must be taken into account in determining overall performance.

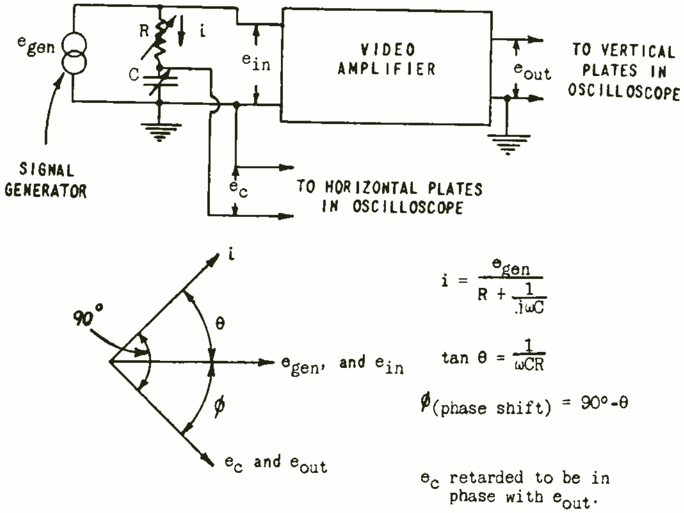

Fig. 6

The necessity for the horizontal and vertical amplifiers to be identical applies only to their phase characteristics, which may have any arbitrary shape so long as they are the same. Similar gain characteristics are not necessary.

An alternative arrangement for phase-angle measurement is shown in Figure 7.

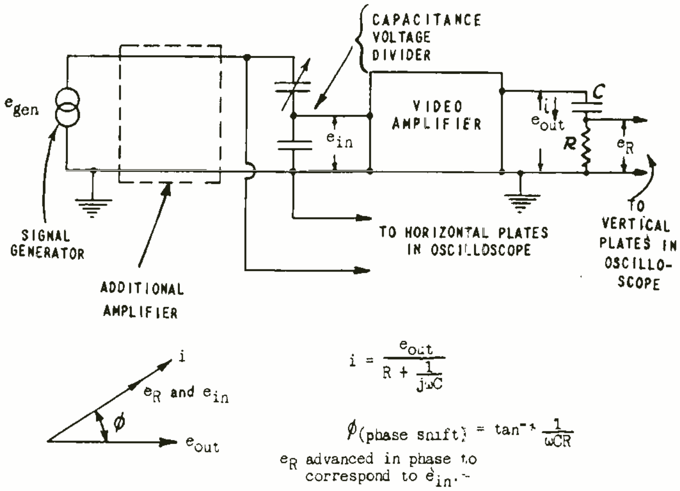

Fig. 7

The measurement is facilitated considerably, and no doubt is left as to the relative phase characteristics of the two oscilloscope amplifiers, if an additional amplifier (whose phase and gain characteristics are arbitrary) is interposed between the signal source and the input to the video amplifier. A capacitance attenuator may be used to prevent overloading due to excessive input to the video amplifier, and the voltage derived from the phase-shifting network may be used for direct application to one pair of plates, while the video amplifier's output voltage is applied directly to the other pair.

APPENDIX I.

Gain, phase and time delay of a compensated stage in a video amplifier.

Let $r_p >> Z_L$, hence the gain $= g_m Z_L$ and the phase shift is equal in degrees to the phase angle of the complex impedance $Z_L = R_L \pm jX_L$.

$$Z_L = \frac{(R + S\omega L)\,\dfrac{1}{S\omega C}}{R + S\left(L\omega - \dfrac{1}{\omega C}\right)} = \frac{R + S\,(L\omega - L^2C\omega^3 - R^2C\omega)}{R^2C^2\omega^2 + (LC\omega^2 - 1)^2}$$

Substituting $R = 2L\omega_0 = \dfrac{1}{C\omega_0}$ as the condition for constant gain to $\dfrac{\omega_0}{2\pi}$ cycles.

$$Z_L = \frac{R\left[1 - \dfrac{j}{4}\left(\dfrac{f^3}{f_0^3} + 2\dfrac{f}{f_0}\right)\right]}{\left(\dfrac{f}{f_o}\right)^2 + \left(\dfrac{f^2}{2f_o^2} - 1\right)^2} \quad \text{gain} = \frac{g_mR\sqrt{1 + \left(\frac{1}{4}\dfrac{f^3}{f_o^3} + \frac{1}{2}\dfrac{f}{f_o}\right)^2}}{\left(\dfrac{f}{f_o}\right)^2 + \left(\dfrac{f^2}{2f_o^2} - 1\right)^2}$$

The phase delay in the stage is

$$\phi = +\tan^{-1}\tfrac{1}{4}\left(\frac{f^3}{f_o^3} + 2\frac{f}{f_o}\right)$$

and the time delay

$$\triangle t = \frac{\phi}{2\pi f} = +\frac{1}{2\pi f}\tan^{-1}\tfrac{1}{4}\left(\frac{f^3}{f_o^3} + 2\frac{f}{f_o}\right)$$

APPENDIX II.

Gain, phase and time delay in an uncompensated stage of a video amplifier.

Let r_p be very large in comparison to Z_L, so that the gain may be written as $g_m\,Z_L$.

$$Z_L = \frac{\dfrac{R}{S\omega C}}{R + \dfrac{1}{S\omega C}} = \frac{R\,(1 - SRC\omega)}{R^2C^2\omega^2 + 1} = \frac{R}{\sqrt{R^2C^2\omega^2 + 1}}$$

Let $\frac{\omega_o}{2\pi}$ be the frequency at which $R = \frac{1}{2\pi f_o C}$, then

$$Z_L = \frac{R}{\sqrt{1 + f^2/f_o^2}} \text{ and the gain} = \frac{g_m R}{\sqrt{1 + \frac{f^2}{f_o^2}}}.$$

With $r_p >> Z_L$ constant current flows through Z_L, and the phase shift in voltage due to the presence of C is equal to the phase angle of the complex impedance $Z_L = R_L - jX_L$.

Phase delay $\phi = \tan^{-1}\left[\frac{X_L}{R_L}\right] = + \text{ten}^{-1} RC\omega$ or, substituting

$$R = \frac{1}{2\pi f_o C}.$$

The time delay at any frequency f is $\triangle t = \frac{\phi}{2\pi f}$ which here equals

$$+\frac{1}{2\pi f}\tan^{-1}\frac{f}{f_o}.$$

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.

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[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.

Reprinted from *Proc. I.R.E.*, August, 1937.

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

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[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.

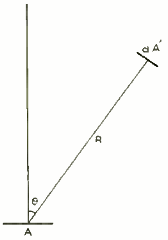

Fig. 1

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

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

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[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:

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

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

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

$$\frac{I_2}{I_0} = \frac{1}{M^2} \left[1 - (1 - M^2 \sin^2 \beta) \epsilon^{-(E_2 e/kT)(M^2 \sin^2 \beta / 1 - M^2 \sin^2 \beta)}\right]. \tag{20}$$

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 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.

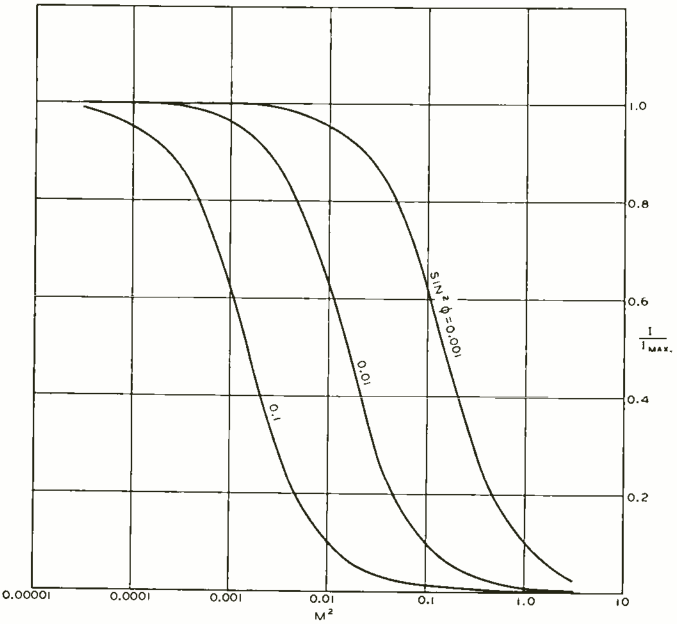

Fig. 2—Current density at image as function of magnification (M) and half angle subtended by beam (ϕ) when $E_2e/kT=10{,}000$. $I_{\max}=I_0((E_2e/kT)+1)\sin^2\phi$.

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 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.

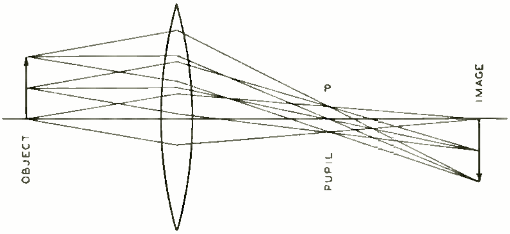

Fig. 3

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

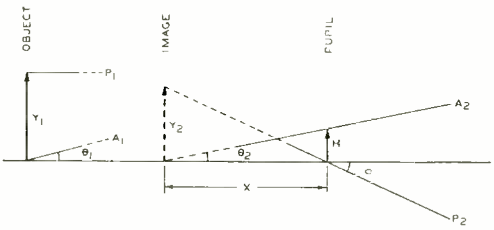

Fig. 4

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[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

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

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[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).

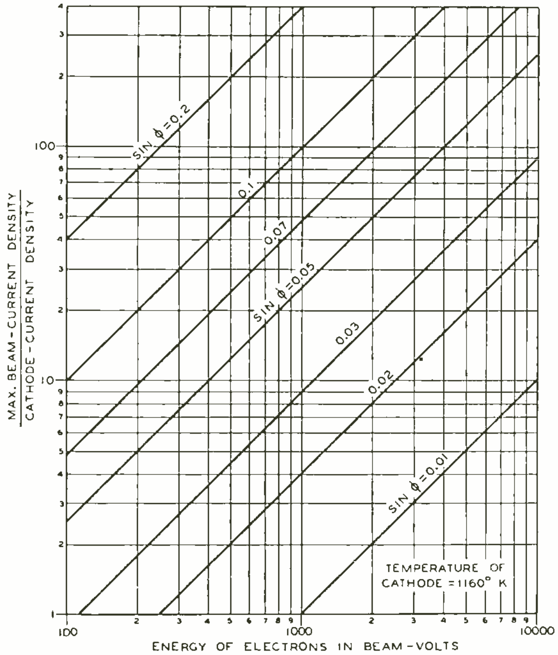

Fig. 5—Curves showing maximum current density obtainable in a focused spot of electrons as function of final voltage and half angle of beam.

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/cm^2

E_2 volts	Sin ϕ		
	0.01	0.032	0.10
100	0.1 amp/cm^2	1 amp/cm^2	10 amp/cm^2
1000	1	10	100
10,000	10	100	1000

V. CONCLUSIONS

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

$$I_0 \left(\frac{E_2 e}{kT} + 1 \right) \sin^2 \phi.$$

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)

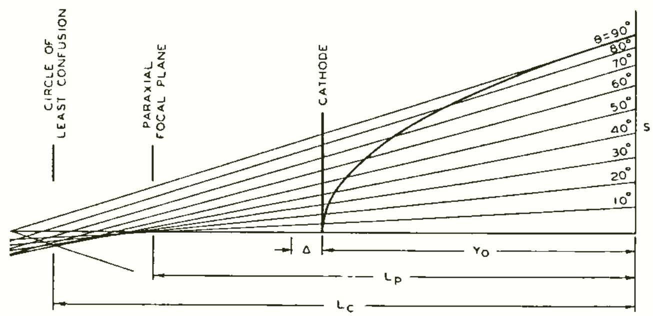

Fig. 6—Spherical aberration in a bundle of trajectories formed by the electrons accelerated in a uniform electric field. Electrons are all emitted with the same speed from the point where the axis intersects the cathode. Tangents to parabolic orbits are drawn at plane S. Heavy curve is trajectory for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

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

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[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 $\theta =$ 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.

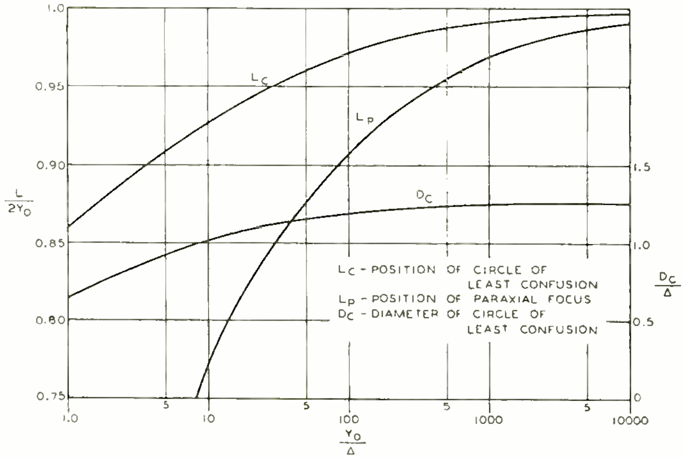

Fig. 7—Image forming properties of uniform field as function of y_0/Δ equals the distance which the electron can travel against the field by virtue of its initial energy.

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.

THE BRIGHTNESS OF OUTDOOR SCENES AND ITS RELATION TO TELEVISION TRANSMISSION

By

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RCA Manufacturing Company, Inc., RCA Radiotron Division, Harrison, New Jersey

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-

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[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).

Reprinted from *Proc. I.R.E.*, August, 1937.

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

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[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.

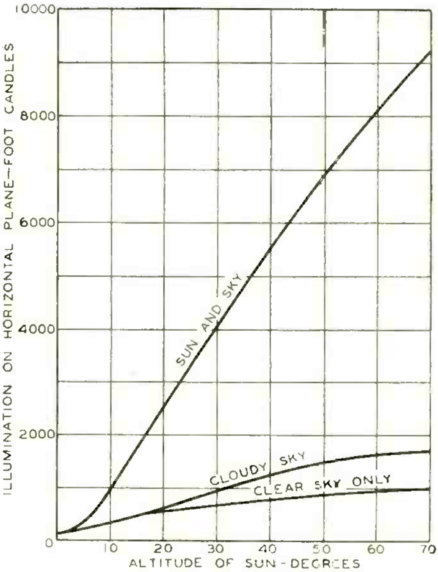
[4] W. N. Goodwin, Jr., "The Photronic photographic exposure meter," *Jour. S.M.P.E.*, vol. 20, pp. 95–118; February, (1933).

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

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 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 93½° 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



COURTESY OF I.E.S

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

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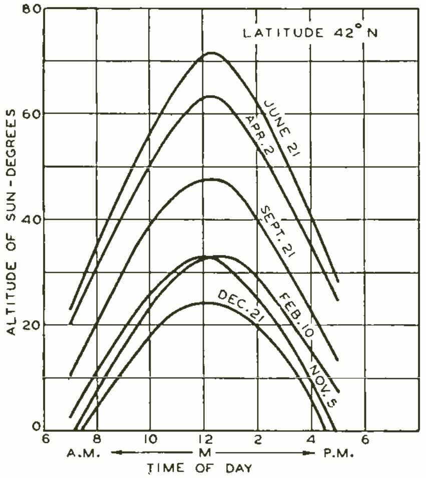
[5] W. Kunerth and R. D. Miller, "Variations of intensities of the visible and of the ultraviolet in sunlight and in skylight," *Trans. Ill. Eng. Soc.*, vol. 27, pp. 82–94; January, (1932); and vol. 28, pp. 347–353; April, (1933).

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 expected 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.



COURTESY OF I.E.S.

Fig. 2—Altitude of the sun for different times of the day and year at 42° N latitude and 93½° W longitude.

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 $(0.25\times 200)/\pi = 16$ 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 $(0.32\times 9100)/\pi = 930$ candles per square foot.

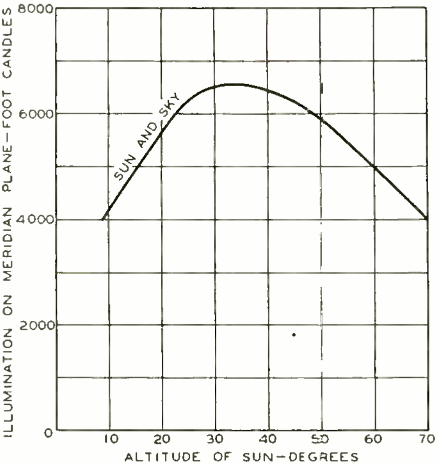


Fig. 3—Illumination from the sun and sky on a meridian plane for different altitudes of the sun.

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

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[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 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.

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	6½
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

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

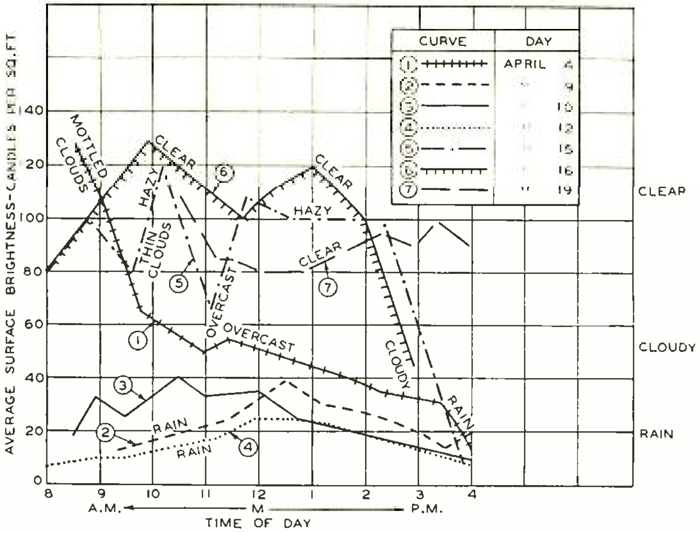


Fig. 4—Average surface brightness of a scene at Harrison, N. J., under various weather conditions during different times of the day.

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

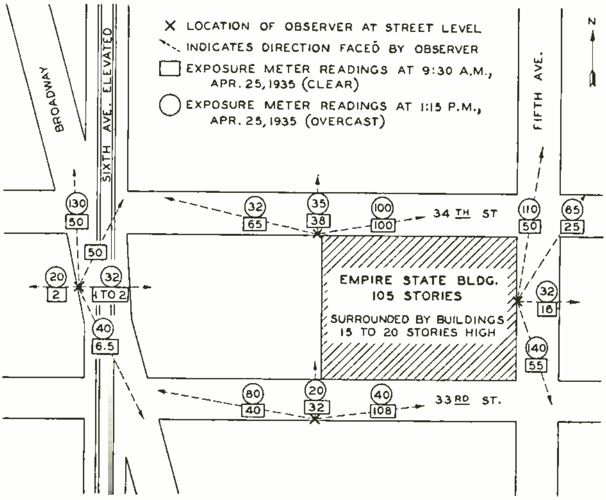
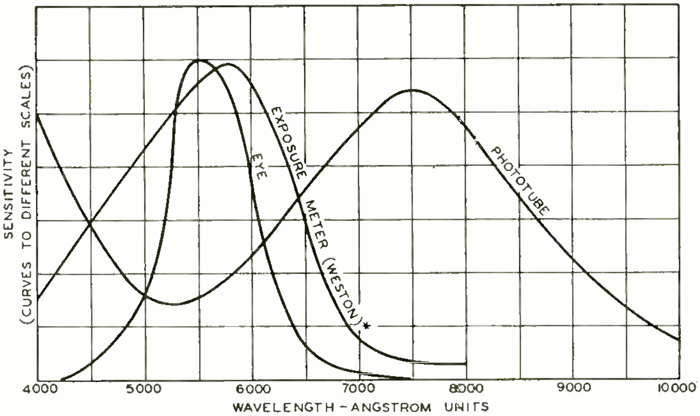


Fig. 5—Surface brightness at points around the Empire State building in clear and in cloudy weather.

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



*COURTESY OF WESTON E.I. CO.

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

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

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[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 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.

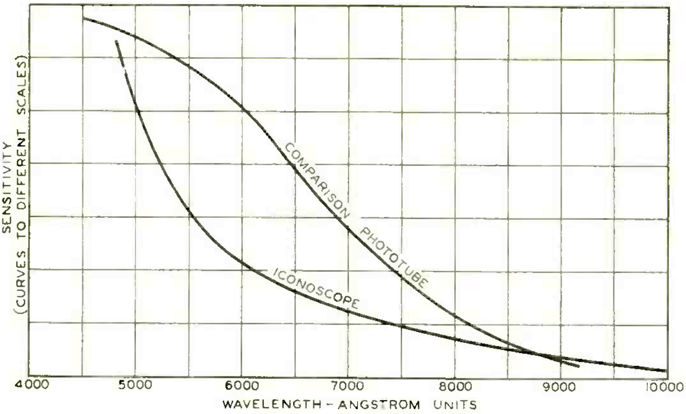

Fig. 7—Relative spectral sensitivities of the present Iconoscope and a comparison phototube.

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

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[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.

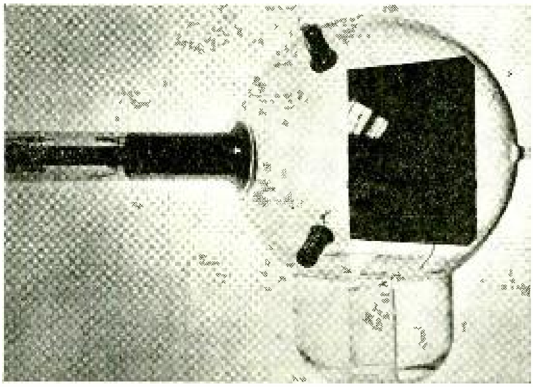

Fig. 8—Iconoscope with silver evaporation sensitization.

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 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.

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

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

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[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.

ICONOSCOPES* AND KINESCOPES** IN TELEVISION

BY

V. K. ZWORYKIN

RCA Manufacturing Company, Inc., Camden, N. J.

TWO extremely important elements in any television system are the pickup device which converts the light image into electrical signals, and the viewing arrangement transforming the electrical signals back into visible images. In fact, the success or failure of a televison system depends perhaps more on these two links than on any other part of the chain. In its present project RCA Manufacturing Company is using the Iconoscope and Kinescope for dissecting and resynthesizing images, and it is the purpose of this discussion to explain the operation of these instruments and point out the reasons for selecting them over other devices designed to serve as pickup and viewing equipment.

Historically, the development of any form of television had to await a means of converting a light signal into a corresponding electrical impulse. This step became possible through the discovery of the photoconductive properties of selenium in 1873. Within two years after this discovery, Carey proposed to make use of the properties of selenium in the solution of the problem of televison. His suggestion was to construct a mosaic consisting of a great number of selenium cells, in a sense imitating the retina of the human eye. These cells were to be connected to shutters or lamps in corresponding positions on a viewing board. Although the suggestion was made in 1875, the device was not put into operation until 1906 when Rignoux and Fournier used this arrangement to transmit simple patterns and letters. Their mosaic consisted of a checker-board of sixty-four selenium cells. Each cell was connected to a shutter on a viewing screen which was also made up of sixty-four elements in positions correspond-

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* From the Greek word "Icon" meaning an image, and "scope" signifying observation. Trade Mark Registered U. S. Patent Office.

** From Greek word "Kineo" meaning movement. Trade Mark Registered U. S. Patent Office.

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ing to those in the pick-up screen. When a picture was projected on the selenium cells the resistance of those illuminated decreased allowing an electric current to flow which opened corresponding shutters on the viewing screen. A light behind these shutters made the reproduced picture visible.

The idea of dividing the picture into elements, converting the illumination on each element into electric current and sending the signal from each over individual wires is practical for a small number of divisions or picture elements and for transmission over short distances, but is useless as a means of producing pictures of the standard required of television today.

The next step was proposed by Nipkow in 1884. Instead of using individual wires connecting each picture element, he suggested sending the information from one element at a time over a single communication channel and then reassembling this information again at the viewing screen. This process was to be carried out at such a rate that the picture appeared continuous due to persistence of vision. The means proposed to accomplish this point-by-point transmission was the scanning disc. At the time of its invention the necessary technique of handling and amplifying small currents had not yet been developed so that it was a number of years before this scanning principle could be put to practical use. However, the principle was sound and the scanning principle has been the basis of all televison systems since then.

While this development represents a great step forward, it was only attained at considerable expense of available picture signal. The loss is due to the fact that each element only contributes to the picture a small fraction of the total time, whereas with the first system suggested each element operated continuously. To make this clear, consider again the simple sixty-four element mosaic used by Rignoux and Fournier. Each photoelectric element was connected to the viewing screen by a separate conductor and the picture to be transmitted projected continuously on all the elements, so that a signal current passed through every light sensitive element all the time. To reduce the scanning system to a comparable case, assume that we have the same mosaic of sixty-four photosensitive elements, but that they are all connected to a common communication channel. The elements are covered with shutters (i.e., the scanning disc) which allow only the light from one element of the picture at a time to reach its corresponding photocell. These shutters are opened one at a time in rotation covering the entire picture twenty or thirty times a second. Thus each light sensitive element is only operating for a fraction of the total time equal to one over the number of picture elements, in this case one-sixty-fourth of the time.

In order to regain this lost signal and yet retain the principle of scanning, the development of the Iconoscope was undertaken. To illustrate the method of attack, consider again the sixty-four element array of photocells. Instead of scanning the elements with shutters, assume that each element is connected to the contact points of a switch which connects them in rotation to the main communication channel. Thus the scanning is accomplished by means of a commutator switch.

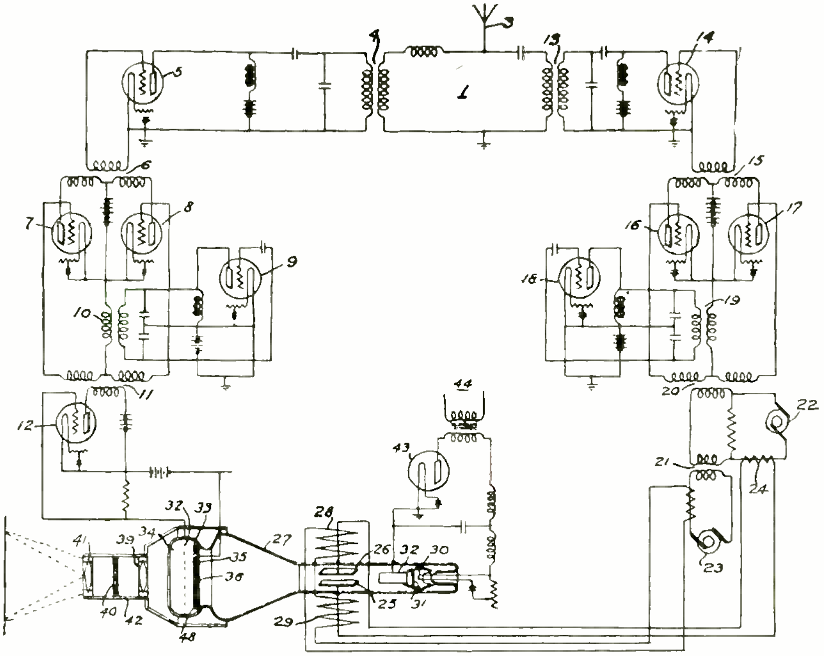

Figure 1

So far, we have gained nothing over the previous method of scanning, but now if a condenser is placed across each of the photocells in such a way that it accumulates the entire charge released by the action of the light during the time the element is not connected to the communication channel, this charge can be used when the commutator switch again makes contact with this element. Therefore, photoelectric current is being released by every element continuously and this charge stored in the condenser belonging to that element until it is needed at the end of a scanning cycle.

The reduction of this principle to some practical form is obviously a difficult problem. The number of individual photocells and condensers required for a 360-line picture with a 4 to 3 aspect ratio will be of the order of 173,000 units, and it is quite apparent that a screen composed of that many conventional photocells and condensers is out of the question.

A solution devised by the author some years ago was to build up a mosaic screen which contained the equivalent of a vast number of photosensitive elements and condensers. This mosaic was mounted in a cathode-ray tube in such a way that an electron beam could be used to commutate the elements. Fig. 1 shows one of these tubes together with its associated circuits taken from one of the author's early patents.[1] Aside from the advantage gained through the application of the principle of storing the charge on each element for the entire picture time, this tube had the additional advantage that it involved no mechanical moving parts such as a scanning disc, mirror screw or drum, the scanning being done electrically.

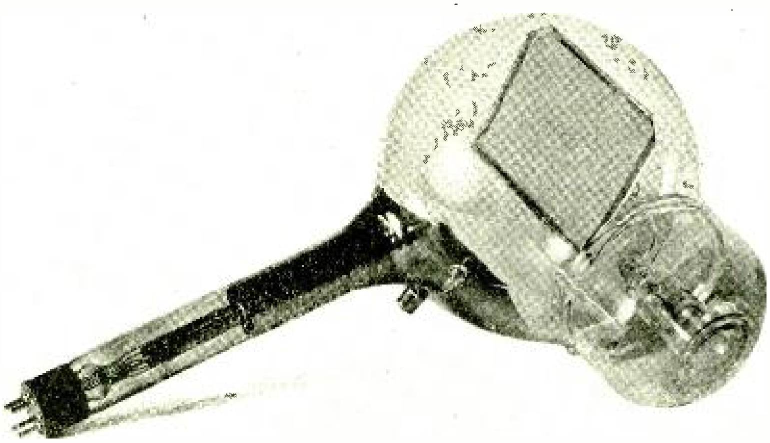

Figure 2

Although the first of this type of tube was built as far back as 1923, many years of research and development had to be undertaken before it was perfected sufficiently to meet the re-

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[1] V. K. Zworykin, Patent No. 1,691,324 "Television System."

quirements of a satisfactory television system. The history of this development is interesting, but is somewhat outside the scope of this paper, which will be limited to a discussion of the tube as it is today.

The Iconoscope, as this type of tube has been named, is shown photographed in Fig. 2. It consists of an electron gun and photosensitive mosaic enclosed in a highly evacuated glass envelope. The arrangement of these elements is shown diagrammatically in Fig. 3.

The electron gun produces a narrow pencil of cathode rays which serves, as will be shown later, as a commutator to the tiny photocells on the mosaic. The gun is in reality a form of electron projector which concentrates the electrons from the cathode onto the mosaic in a very small spot. The electron optical system consists of two electron lenses which are formed by the cylindrically symmetrical electrostatic fields between the elements of the gun. Fig. 4 shows diagrammatically the arrangement of this gun, together with the equipotentials of the electrostatic fields making up the electron lenses. Below this diagram is the approximate optical analogue. Details of the gun construction are as follows: The cathode is indirectly heated with its emitting area at the tip of the cathode cylinder. It is mounted so that the emitting area is a few thousandths of an inch in front of an aperture in the control grid. A long cylinder with three defining apertures whose axis coincides with that of the cathode cylinder

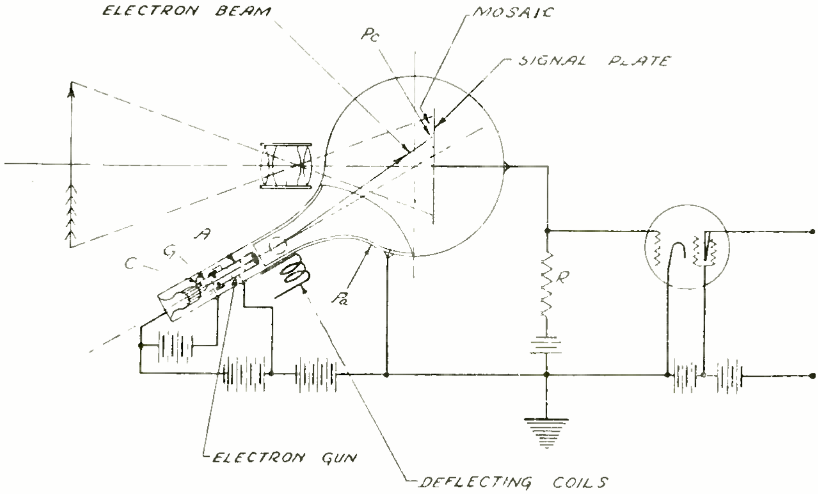

Figure 3

and control grid serves to give the electrons their initial acceleration and is known as the first anode. A second cylinder coaxial with the first anode and of somewhat greater diameter serves as second anode and gives the electrons their final velocity. The second anode is in general formed by metalizing the neck of the Iconoscope bulb, as shown in Fig. 3. The gun used in the Iconoscope is designed so that it will concentrate a beam current of from one-half to one microampere into a spot about five mils in diameter. Under ordinary operating conditions, a potential of about a thousand volts is applied between the cathode and second anode and the voltage of the first anode adjusted until minimum spot size is obtained. The exact value of the beam current to be used will, of course, depend upon the type of picture to be transmitted and the exact conditions of operation.

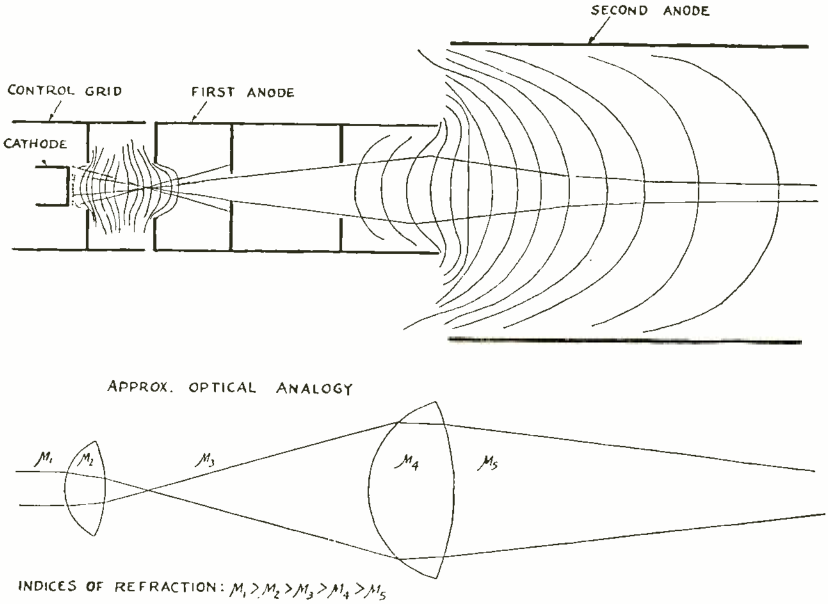

Figure 4

The beam from the gun is made to scan the mosaic in a series of parallel horizontal lines repeated at thirty cycles per second. This is accomplished by two sets of magnetic deflecting coils arranged in a suitable yoke and slipped over the neck of the Iconoscope. These sets of coils are driven by two special vacuum tube generators supplying a saw-toothed current wave, one operating at picture frequency supplying the vertical deflecting coils, the other at horizontal line frequency driving the second set of coils.

The element which characterizes the Iconoscope is the mosaic. It consists of a vast number of photosensitive globules mounted on a thin mica sheet in such a way that they are insulated from one another. The back of this sheet is coated with a conducting metallic film which serves as a signal plate and is connected to the input of the picture amplifier. The appearance of the mosaic is shown in Fig. 5. Such a mosaic may be formed in a variety of ways. For the standard type of mosaic the silver globules are formed by reducing particles of silver oxide dusted over the mica. Under proper heat treatment the silver globules reduced from the oxide will not coalesce but will form individual droplets.

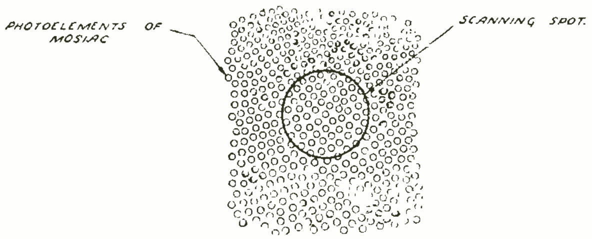

Figure 5

These droplets are sensitized after the mosaic has been mounted in the tube and the tube evacuated. The sensitization is similar to that used in the ordinary cesium photocell, that is, the silver is oxidized, exposed to cesium vapor, and then heat treated. The result is that the photoelectric response of these globules is about the same as that of a high vacuum cesium photocell, both in sensitivity and spectral response. The spectral characteristic is shown in Fig. 6. The cut-off in the violet part of the spectrum is due to absorption of the glass walls. It is evident that the Iconoscope with a quartz window is sensitive from well into the infra-red, through the visible, and into the ultra-violet. Actual tests have produced images using radiation from 2000 Å down to more than 9000 Å.

The mica on which the silver droplets are mounted serves to insulate them from one another and further is made thin enough so that the capacity between each globule and the metallic signal plate will be reasonably large. The uniformity of cleavage sheets of mica, together with their excellent insulating properties, low dielectric hysteresis and low loss make them very suitable for this purpose. Other insulating materials, however, can be used;

for example, a thin film of vitreous enamel on a metal signal plate has proven very satisfactory.

The mosaic is mounted in the tube with the silver beads facing the beam. In order that the optical image may be focused on its front surface, it is placed in the tube in such a way that a normal to its face makes an angle of 30° to the axis of the electron gun.

In essence, the Iconoscope may be thought of as a plain mosaic made up of a great number of individual photocells, all connected by capacity to the common signal plate and commutated by the scanning beam. The fundamental cycle of operation is as follows:

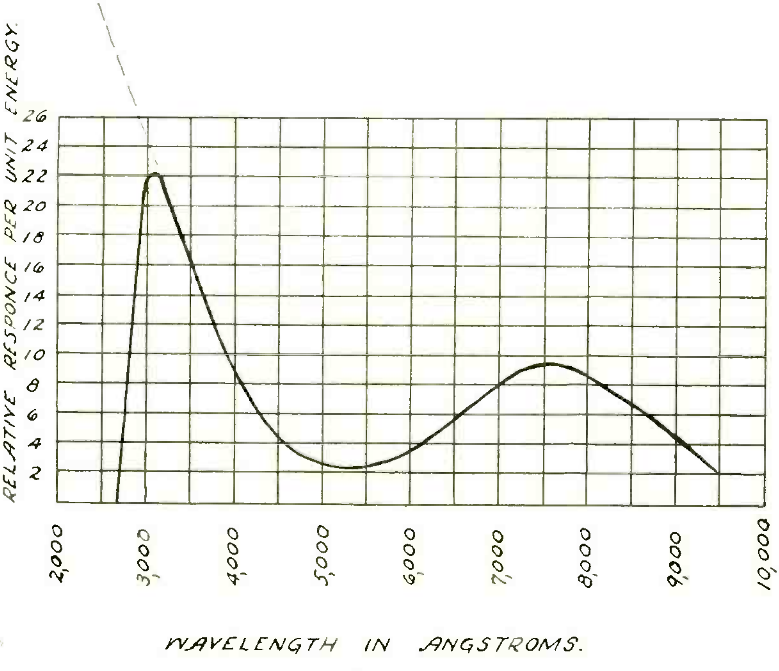

Figure 6

Every silver globule making up the mosaic is photosensitized so that when a light image is projected on the latter the light causes electrons of a number proportional to the light brilliance to be emitted from each illuminated minute size photosensitive area. The resulting loss of electrons leaves each photosensitive area at a positive potential without respect to its initial condition which potential is then proportional to the number of electrons which have been released and conducted away so that the mosaic tends to go positive at a rate proportional to the light falling on it. As the electron beam scans the mosaic, it passes over each element in turn, releasing the charge it has acquired and driving it to equilibrium. Due to the fact that each element is coupled by capacity to the signal plate, the sudden change of charge of the elements will induce a change in charge on the signal plate and result in a current pulse in the signal lead connected to the amplifier. The magnitude of these pulses will be proportional to the intensity of the light falling on the scanned element. Thus the signal output from the Iconoscope will consist of a chain of current pulses corresponding to the light distribution over the mosaic. This chain can be resynthesized at the receiver into a reproduction of the original image, as will be described later.

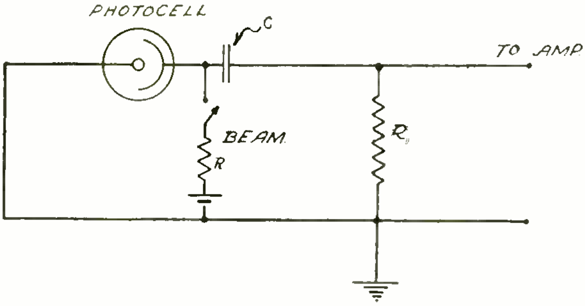

Figure 7

To clarify this cycle the equivalent circuit representation of a single element is shown in Fig 7. The beam is represented by the switch and series resistance R. This switch may be considered as being open except at such times as the beam is actually on the element. When the scanning beam moves off the element, the photo-emission from it starts to charge the condenser C, the rate of accumulating charge being proportional to the illumination on the element. In the next scanning cycle, the beam again sweeps over the element, closing the switch and discharging the element. During this discharging cycle the entire charge accumulated during the time the beam was not on the element must now flow through the input resistor R_L generating an e.m.f. which is applied to the input of the picture amplifier.

In designing the mosaic, it is evident that the time constant of the circuit discharging the condenser C must be small enough to allow it to fully discharge during the time the beam is on the element. This condition requires that $C \times (R_1 + R)$ be less than the time the beam is on the element. In practice, this condition is not difficult to fulfill.

At this point it is interesting to compare the e.m.f. supplied to the amplifier by this storage system with the equivalent voltage from a non-storage system. The equivalent circuit for the non-storage case is shown in Fig. 8. The current through the input resistor R_2 will be:

$$I_s = \frac{F.s}{n}$$

where F is the light flux in the picture, s the sensitivity of photosensitive elements, and n the number of picture elements. The voltage to the input of the amplifier is:

$$V_2 = \frac{Fs\,R_2}{n}$$

In the storage case the charge accumulated by the element is:

$$Q = \frac{F.s}{n}\,t_p$$

where t_p is the picture time or $1/N$ for N pictures per second. When the beam strikes the element this charge leaves the condenser resulting in an average current of

$$i = \frac{Q}{t_e}$$

where t_e is the time the beam is on the element or $1/Nn$. This current is therefore:

$$i = \frac{F.s\,Nn}{n\;N}$$

and the voltage to the amplifier will be:

$$V_1 = FsR_1$$

Comparing the signal voltages generated in the two cases, we see that the ratio is:

$$\frac{V_1}{V_2} = \frac{FsR_1}{\dfrac{FsR_2}{n}} = n \qquad \text{where } R_1 = R_2$$

Where the number of picture elements is large as is the case in pictures with good definition, this gain in signal is extremely important. For example, the ratio in the case of a 360-line picture is 173,000 times the signal that could be obtained from the non-storage case.

In order to give a pictorial idea of the conditions on the surface of the mosaic, Fig. 9 is included. It represents the appearance of the charged image on the mosaic if it were visible to the eye. The region just behind the scanning beam is an equilibrium potential and therefore shows no visible image. As we examine the mosaic further away from the line just scanned, we find that the charged image gets more and more intense since the elements have been charging for a greater length of time. Just ahead of the scanning beam the image reaches its maximum intensity.

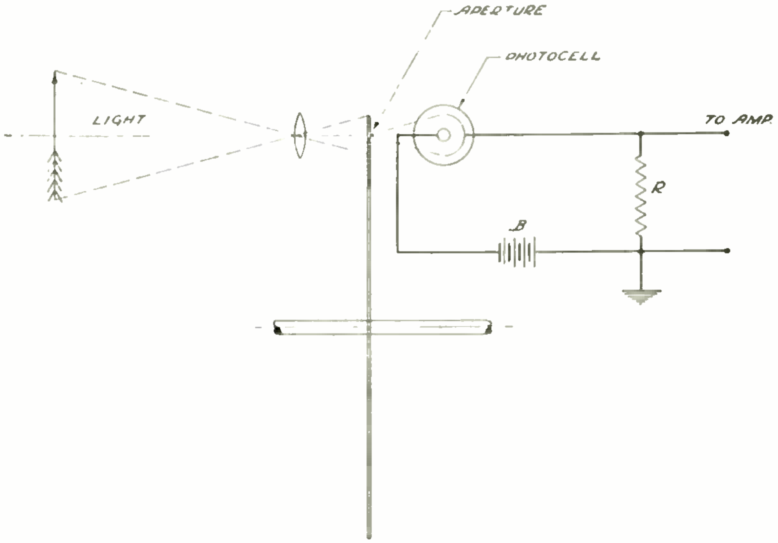

Figure 8

The picture just drawn of the operation of the Iconoscope is very much simplified. A number of factors complicate this seemingly straightforward cycle. Among the most important of these complicating factors are the potential distribution over the mosaic and the redistribution of secondary electrons emitted from the elements under bombardment. If the average potential of the mosaic is measured in darkness while it is being scanned, it will be found to be between 0 and 1 volt negative with respect to the electrode which collects the electrons leaving the mosaic, that is, with respect to the second anode. However, the potential is not uniform over the surface of the mosaic. Elements directly under the beam are found to be in the neighborhood of 3 volts positive with respect to the second anode. As we investigate elements which have previously been bombarded, we find them less positive, until at a point one-quarter to one-third of the vertical distance along the mosaic from the point being bombarded, the potential has reached $-1\frac{1}{2}$ volts negative with respect to the collector. The rest of the mosaic is found to be at $-1\frac{1}{2}$ volts.

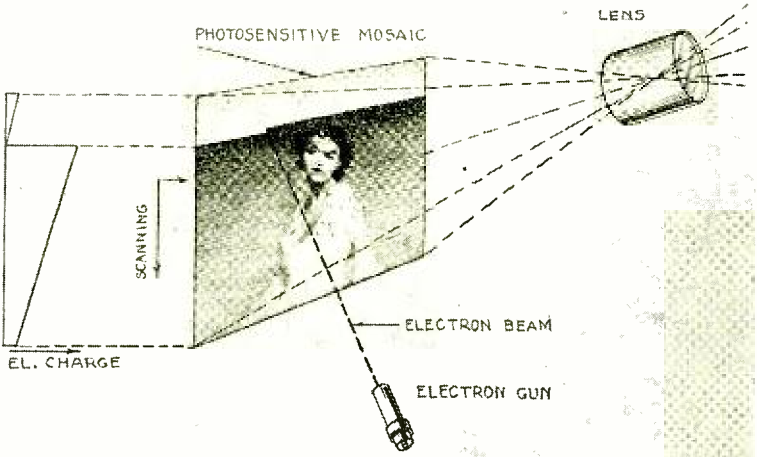

Figure 9

Cathode-ray oscillograph measurements of the potential distribution over the mosaic shows that it can be mapped somewhat as shown in Fig. 10.

In order to account for the potential distribution over the surface of the mosaic, it is necessary to consider what takes place among the secondary electrons emitted from the cesiated silver elements under bombardment. It is well known that when a cesiated silver surface is bombarded by an electron beam of the order of 1000 volts velocity, a secondary emission of 7 or more times the primary bombarding current can be collected. However, since the mosaic elements are insulated they must assume, when in equilibrium, a potential such that the secondary emission current equals the bombarding current. This potential is found to be about 3 volts positive with respect to the second anode. In the case of the mosaic in darkness it is obvious that the average secondary emission current leaving the mosaic must also be equal to the beam current since the mosaic is an insulator. Thus it must come to an equilibrium potential such that the average current escaping to the second anode equals the bombarding current.

Perhaps we should digress at this point and discuss more fully the mechanism by which an element acquires this positive equilibrium potential. Measurements of the velocity distribution of the secondary electrons from a bombarded surface show that they can be represented by a distribution curve such as shown in Fig. 11. In this figure the abscissa gives the velocity in electron volts of the emitted electrons, while the ordinates give the current per volt range in velocity composed of electrons having a given velocity. If the target is surrounded with an electrode to collect secondary electrons, the current it can collect will depend upon its potential relative to the target. When this collector is at zero potential the current reaching it will equal the total secondary emission as represented by the total area under the curve in Fig. 11. As the collector is made more negative, the current

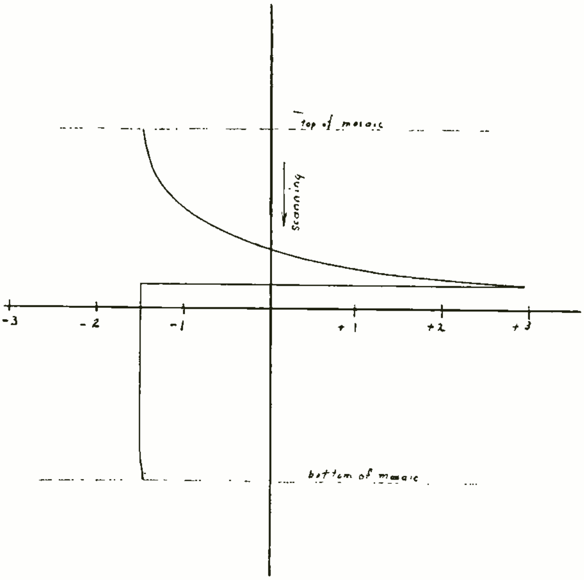

Figure 10

decreases since some of the electrons leaving will not have sufficient velocity to reach the electrode and will be driven back to the target. The current reaching the collector at some negative potential V_1 will be given by the area under the distribution curve from V_1 to the highest velocity; in other words

$$i_c = \int_{V_1}^{\infty} f(V)\ dV$$

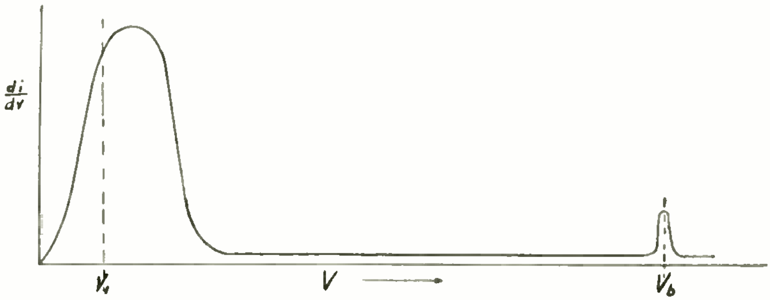

Figure 11

As the potential of the collector is decreased further eventually it will reach a point where the current collected just equals the current in the primary beam. At this point no current flows in the external lead to the target under bombardment. Experiment shows that for a cesiated surface such as is used to make up the globules on the Iconoscope mosaic, this potential is in the neighborhood of 3 volts. Hence, if an insulated target such as a mosaic element is bombarded more electrons will leave than arrive until the element reaches 3 volts positive, at which potential the element will be in equilibrium and the current arriving and leaving will be equal.

When the mosaic elements are scanned the secondary emission from them may be divided into three parts, one going to the second anode, another returning to the element itself, and a third being redistributed over the entire mosaic. This latter group which returns to the mosaic comes back as a more or less uniform rain of electrons having a maximum velocity of about 1½ volts.

This can be verified by removing a portion of the mosaic and substituting a metal sheet electrode in its place. If the mosaic, except for the substituted portion, is scanned and the current to the metal electrode measured, it will be found to decrease as the potential of the probe is decreased. At −1½ volts negative the current will be dropped to zero.

Let us now consider the operation of the Iconoscope in the light of the phenomena just discussed. In the first place, due to the potential of the mosaic, there is very little electrostatic field aiding the escape of photo-electrons from the illuminated elements. This means that the charging of the globules is dependent in a large measure upon the initial velocities of the electrons. Therefore, the photo-electric emission is not very efficient and becomes less so as the illumination is increased. It should be remembered, however, that the photo-emission occurs during the entire picture time, the charge being accumulated on the condensers formed by the silver beads and the signal plate. In other systems, since photo-emission occurs only during the time a picture element is being scanned, there is a gain of the order of 10^5 to be had by using the storage system so that even if the above-mentioned photoelectric inefficiency were insurmountable there is still a very great advantage in favor of the Iconoscope system.

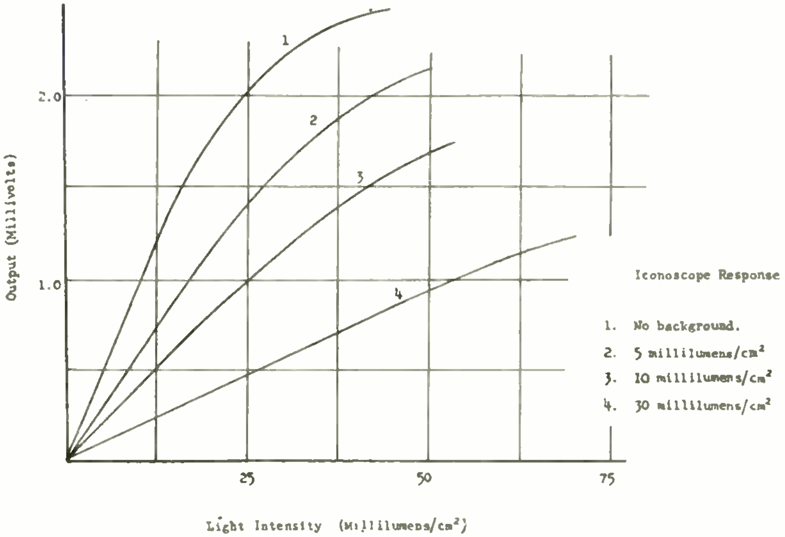

Figure 12

As was pointed out in the discussion of the potential distribution, there is a line across the mosaic directly behind the scanning beam which is 3 volts positive with respect to the second anode, while just ahead of the beam the potential is in the neighborhood of 1½ volts negative. There is, therefore, just ahead of the scanning beam, a row of elements which have a strong field aiding the leaving photo-electrons. This field very much increases the photo-sensitivity along this line and gives rise to a phenomenon known as line sensitivity. This phenomenon can be demonstrated very strikingly in the following way:

The image from a continuously run moving picture film (i.e., by removing the intermittent and shutter from a moving picture projector) 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 of the Iconoscope and in a direction such that the image moves opposite to the vertical direction of scanning.

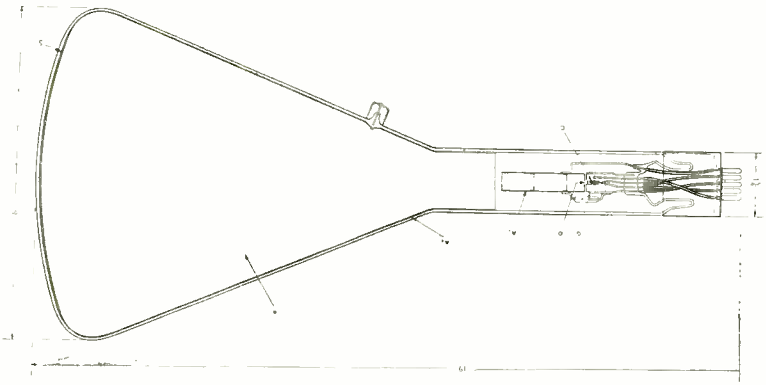

Figure 13

Under these conditions we find that the Iconoscope transmits 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.

Thus we have two sources of signal, one the stored charge over the entire mosaic surface; the second from the sensitive line at the scanning beam. At low or normal light intensities by far the greater part of the signal comes from surface sensitivity, but under high illumination as much as 50% of the signal may come from line sensitivity.

As was pointed out above, due to the fact that the secondary emission is not saturated, some electrons from the point where the beam strikes the mosaic have not sufficient velocity to leave the mosaic entirely, but return to its surface as a shower of low-velocity electrons. The redistributed electrons act to some extent as a high resistance, short-circuiting the elements, since an element which is more positive than its neighbors tends to receive a greater share of these electrons. This resistance is, in effect, identical with that of the dynamic resistance of a triode tube and under normal operating conditions is high enough so that it does not produce a very serious loss in efficiency, but under high illumination where considerable difference in charge between nearby elements may be developed, this shunting resistance may become quite low with the result that there is a fairly large loss of signal.

This redistribution of electrons is furthermore responsible for the generation of a spurious signal. It appears as an irregular shading over the picture even when the mosaic is not illuminated. The cause of this signal is the variation in instantaneous secondary emission current escaping from the mosaic to the second anode. As has been pointed out, the average secondary emission from the mosaic must be unity, but when we consider that a certain fraction of the secondary electrons from the point under bombardment returns to other parts of the mosaic, it is quite apparent that the instantaneous current leaving the mosaic may vary from point to point. This variation is produced by the lack of uniformity of potential and space charge over the mosaic.

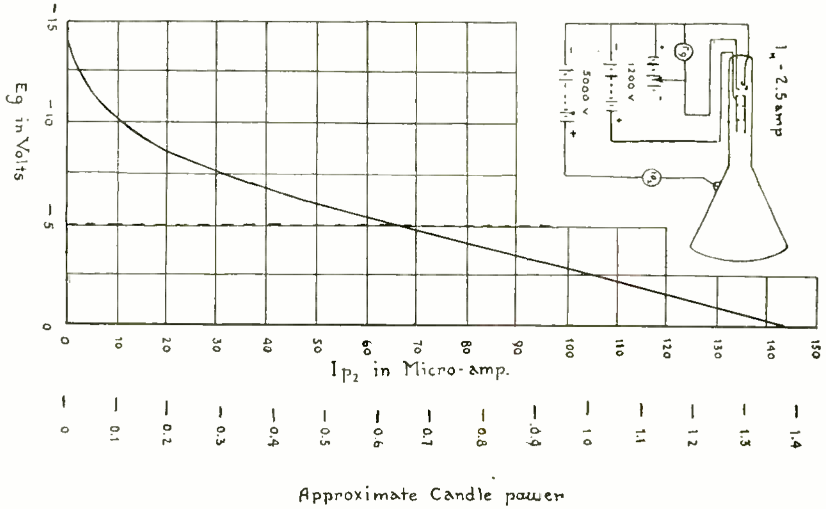

Figure 14

It is interesting to note that if a clean sheet of metal is substituted for the mosaic, the spurious signal appears when it is scanned, provided the secondary emission is not saturated. The signal disappears, however, if the metal plate is made sufficiently positive or negative with respect to the second anode. Under these conditions, the secondary emission is either saturated or suppressed. In practice the effect of this signal can be eliminated by the introduction of a compensating signal. The spurious signal varies rapidly with beam current and under conditions of low beam intensity and moderately high illumination it is negligible compared with the picture signal.

So far, the scanning beam has been considered as some sort of commutating switch which sweeps over the mosaic. Actually, the beam does behave in just this way. The beam when falling on an element connects it through a resistance (dynamic, of course) to the second anode. This is obvious when we consider the action of the beam. As has been pointed out, the ratio of secondary electrons to primary electrons from a cesiated silver surface is about 7 when saturated. However, if the bombarded surface is made positive this ratio decreases, reaching unity at +3 volts and one-half at about 10 volts. From curves giving the secondary emission ratio of an element for various collector potentials, together with a knowledge of the beam current, the effective resistance connecting the bombarded element with the second anode can easily be estimated. This resistance turns out to be of the order of 10^6 ohms. If the beam current is too weak, it will not fully restore the illuminated element to equilibrium. Considering a stationary picture, and neglecting the effect of the redistribution of scattered electrons, this would not reduce the signal obtained from a given amount of light. However, it would cause a lag and consequent blurring of the image of a moving object. In the actual Iconoscope because of the rôle the beam plays in establishing the potential of the mosaic and because of the shunting effect of redistributed electrons, there is an opti-

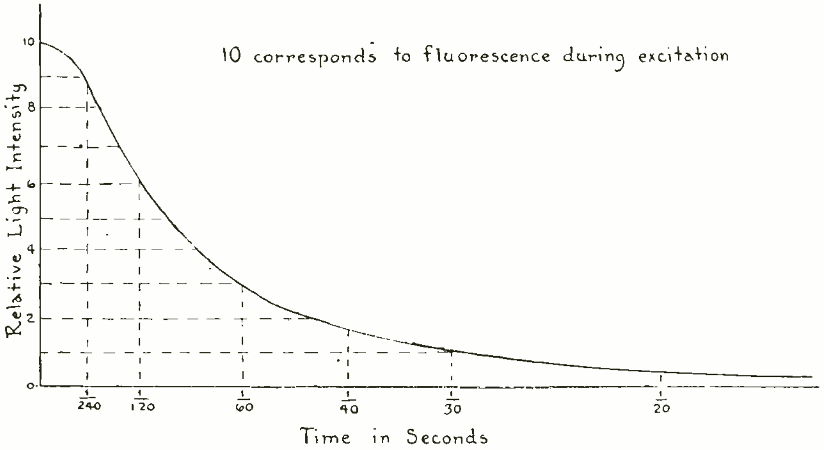

Figure 15

mum beam current at which the signal is a maximum for a given condition of light.

Taking into account the various factors tending to reduce the output of the Iconoscope, it is found that the net efficiency of conversion is in the neighborhood of 5 to 10%. In other words, the signal output is about 1/20 that which would be expected on the basis of the light flux reaching the mosaic, the saturated photo-emission of photo-electric elements, and the assumption that the entire photo-current is stored by the mosaic. The efficiency of conversion is not constant, but as explained above depends on the amount of light used. The efficiency is a maximum at low light and decreases as the light is increased. This point will be considered again under a discussion of the actual performance of the Iconoscope.

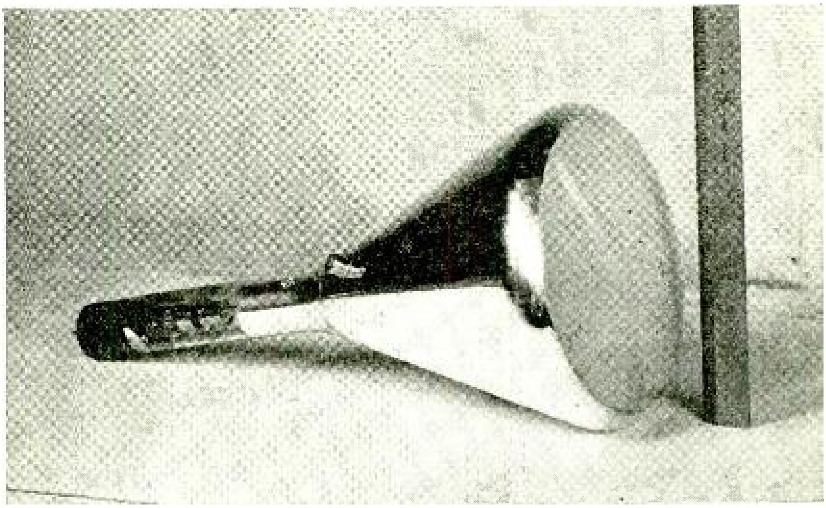

Figure 16

Up to this point we have based our consideration of the relative merits of the storage and non-storage types of systems on a comparison of signal output alone. The recent development of the secondary emission multiplier makes it necessary to introduce other considerations into this comparison. The electron multiplier provides a means of amplifying a photoelectric current to almost any desired extent without introducing any additional "noise" into the signal. It might seem, therefore, that we could amplify the minute photo-current obtained by the conventional scanning system to such an extent that the sensitivity of the two systems were equal. This, however, cannot be done because even with a perfect amplifying system the statistical fluctuations in the original photo-current are amplified just as much as the signal is amplified. Because of this there is a definite limit to the sensitivity of this type of system imposed by the original shot noise in the photo-current. In the case of the Iconoscope there is a similar limit, but because the charge representing each picture element is so much greater than in the non-storage case the ideal sensitivity is very much greater. Actually, in the type of Iconoscope described in this paper, the limit of the sensitivity is not set by the statistical fluctuations of the stored charge, but by the thermal noise in the coupling resistor to the amplifier. A quantitative comparison of the limiting sensitivity of the Iconoscope used at present, taking into account its inefficiency and imperfections, shows that it is able to operate at one-tenth the light required by a *perfect* non-storage system. This, of course, includes the use of an electron multiplier and applies to electrically scanned as well as mechanically scanned non-storage systems.

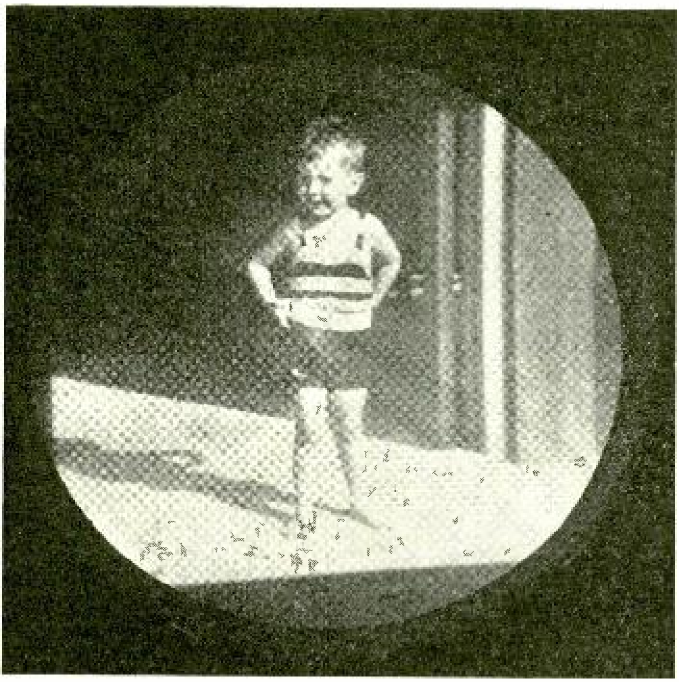

Figure 17

The resolution of an Iconoscope may be limited either by the size of the photoelectric elements or by the size of the scanning beam. The size of the silver globules in the Iconoscope described is many times smaller than a picture element so that many hundreds of them act together under the scanning spot. The resolution is limited, therefore, by the spot size. At present, the resolution adopted is about 360 lines, but when necessary the beam size can be reduced and the resolution made much higher.

Figure 18

The actual response of an Iconoscope under various conditions of illumination is shown in Fig. 12. The output is measured in millivolts across a 10,000-ohm coupling resistance and the light input measured 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 is in darkness. The other curves of the family show the response from the same area when the mosaic is illuminated with a uniform background of light. The response is not linear but falls off as the illumination is increased until it reaches a saturation value. The saturated voltage output is nearly constant

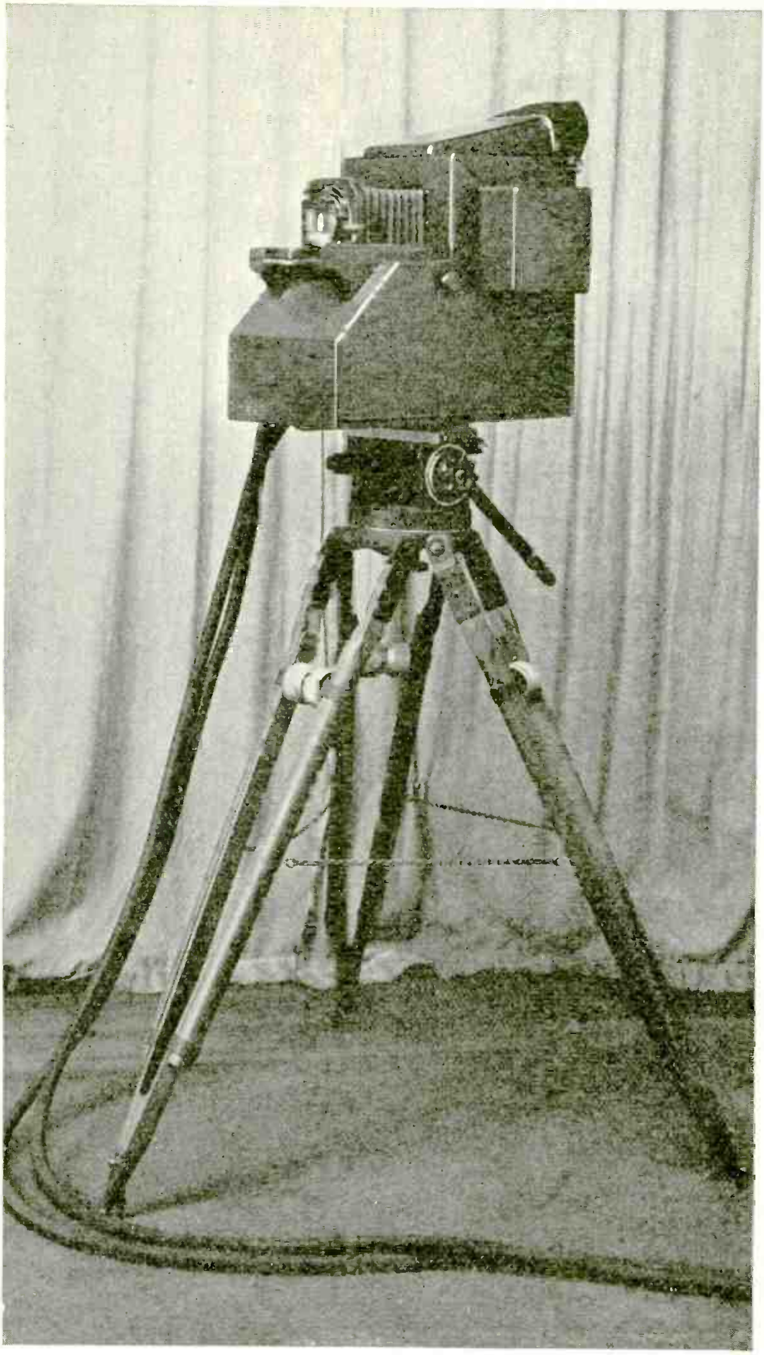

Figure 19

for tubes of a given design, but the slope of the response curve may vary from tube to tube depending upon treatment and is a measure of the sensitivity.

The decrease in sensitivity with illumination is not wholly disadvantageous in that it permits the transmission of a wider range of contrast over a given electrical system than would otherwise be possible. In a sense, this is similar to the compressor-expander systems used in sound recording.

In spite of the complicated manner of its operation and the factors mentioned reducing its efficiency, the Iconoscope is an extremely sensitive and stable device for obtaining television transmission. Excellent and consistent results are obtained under widely varying conditions of operation. The practical lower limit to light which can be used to transmit a picture is set by the "noise" in the picture amplifier. Measurements have been made to determine the illumination necessary for satisfactory operation. With an F/2.7 lens to focus the image on the mosaic, an average surface brilliancy of from 30 to 50 candles/sq. ft. on the object viewed gives completely satisfactory transmission. A recognizable image can be obtained from a good Iconoscope with 8 candles/sq. ft. using an F/16 lens, that is, with 1/150 the illumination mentioned above.

For comparison, the illumination of some scenes commonly met with is given in the following table:

Scene	*Location*	*Date*	*Time*	*Weather*	*Brightness*
Beach	Atlantic City	August	2:00 P.M.	Hazy	500
Boardwalk	Atlantic City	August	2:00 P.M.	Hazy	275
Street	Philadelphia	August	2:30 P.M.	Clear	200
Times Square	New York City	November	1:30 P.M.	Rain	40
Street Parade	East Orange	November	10:30 A.M.	Rain	40 to 60

It is evident that perfectly satisfactory outdoor pickup may be obtained under almost all average conditions of light.

The device used to reproduce the television picture is also electron operated. This tube, which has been named the "Kinescope," is similar to a cathode-ray oscilloscope in many respects. It consists of an electron gun for defining and controlling a cathode-ray beam and a fluorescent screen which becomes luminous under bombardment from the electron gun. A diagram of a typical Kinescope is shown in Fig. 13.

The cathode-ray beam is made to sweep across the fluorescent screen in synchronism with the scanning beam in the Iconoscope which is transmitting the picture. Furthermore, the current in the Kinescope cathode-ray beam is controlled by the signal im-

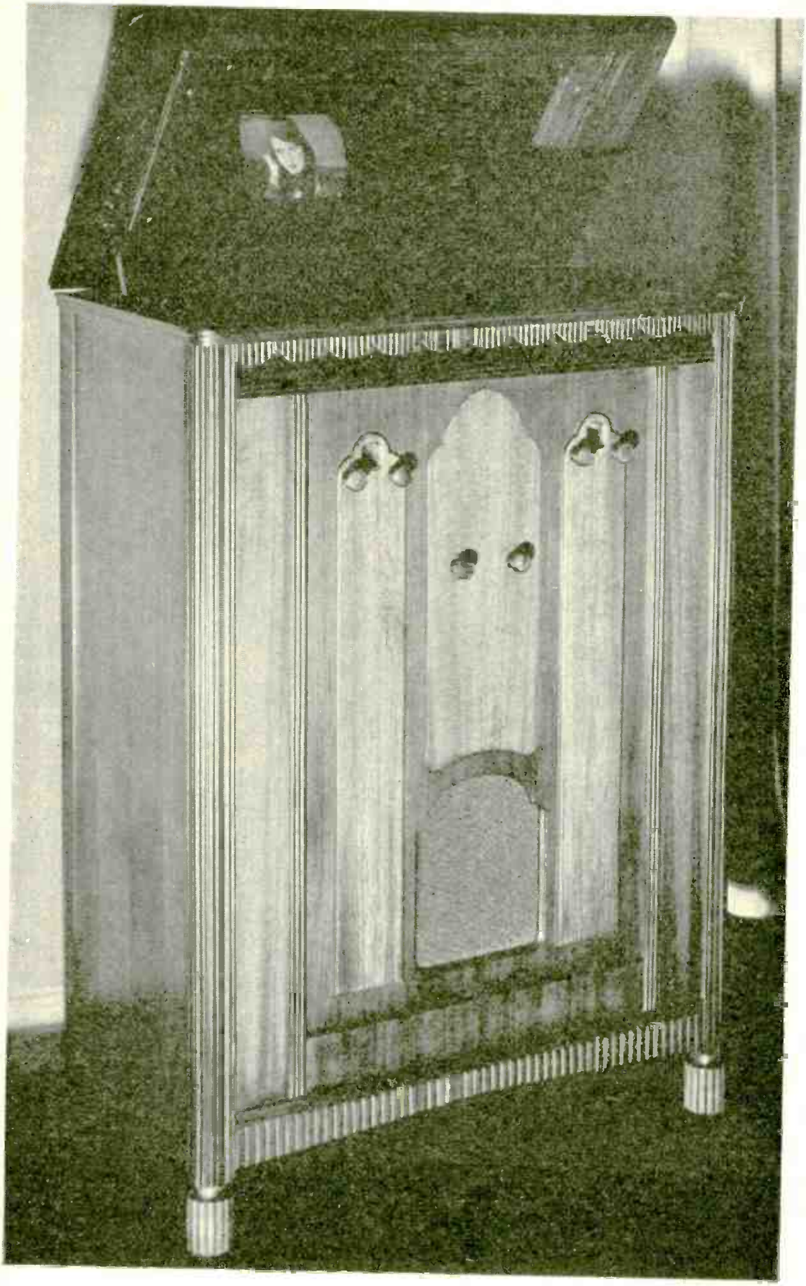

Figure 20

pulses generated at the Iconoscope. This control acts in such a way that the impulse corresponding to a bright area on the Iconoscope causes an increase in current, while a dark region causes a decrease. There will, therefore, be an exact correspondence both in position and intensity between the fluorescent illumination on the Kinescope screen and the light on the mosaic in the Iconoscope. A picture projected on the Iconoscope will therefore be reproduced by the Kinescope.

The electron gun in the receiving tube is similar in principle to that in the Iconoscope, but is made to handle larger currents and to operate at higher voltages. Furthermore, since the picture is reproduced by modulating the beam current, the control grid is a much more critical item. The control grid characteristic is determined by a number of factors such as the grid aperture, the spacing and geometry of the cathode, the first anode, etc. Fig. 14 shows a typical control characteristic for a Kinescope gun.

The fluorescent screen is made by coating the flat portion of the glass bulb with a synthetic zinc orthosilicate, very similar to natural Willemite. The synthetic material has high luminous efficiency, the light output at a given voltage being proportional to the current striking it. At 6000 volts the material gives nearly 3 candles per watt. The efficiency of light production varies somewhat with voltage used, but at higher beam velocities is nearly constant. This can be seen from the general relation between candlepower P, current intensity I, and applied voltage V, which is given by the equation:

$$P = AI\ (V - V_o)$$

A is a constant depending upon the phosphor and V_o the extrapolated minimum exciting voltage, which proves to be in the neighborhood of 1000 volts.

In addition to its high luminous efficiency, this material does not burn or disintegrate under bombardment with electrons. The phosphorescent properties of a fluorescent material are an important consideration. An ideal substance for television work should emit a constant amount of light for one entire picture frame and drop to zero at the end of this period. If the phosphorescent time is too long, the moving portions of a picture will leave a "trail." For example, the path of a moving ball will be marked with a comet-like tail. On the other hand, if the decay time is too short, flicker becomes noticeable. The phosphorescent decay curve for zinc ortho-silicate is shown in Fig. 15.

Fig. 16 shows a photograph of a "Kinescope" with a 9-inch viewing screen. This is only one of a number of sizes, both larger and smaller, and designs possible for the "Kinescope."

Between the transmitting Iconoscope and the reproducing Kinescope there is a chain of electrical equipment involving the picture amplifier, transmitter, radio receiver and synchronizing system. This field is much too large to cover in this paper and has been treated in detail elsewhere.[1]

In closing, it might be well to illustrate the performance of the systems with some photographs of televised pictures as they appear on the screen of the Kinescope. These are shown in Figs. 17 and 18. The appearance of a typical studio pickup camera using the Iconoscope is shown in Fig. 19, while that of a console type television receiver can be seen in Fig. 20.

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[1] Description of an Experimental Television Receiver, *Proc. I.R.E.*, Vol. 21, No. 12, December, 1933.

An Experimental Television System, Part II—Transmitter, *Proc. I.R.E.*, Vol. 22, No. 11, November, 1934.

An Experimental Television System, Part III—Receivers, *Proc. I.R.E.*, Vol. 22, No. 11, November, 1934.

An Experimental Television System, Part IV—Radio Relay Link for Television Signals, *Proc. I.R.E.*, Vol. 22, No. 11, November, 1934.

DEVELOPMENT OF THE PROJECTION KINESCOPE[1]

By

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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 7½×10 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

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[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).

Reprinted from *Proc. I.R.E.*, August, 1937.

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.

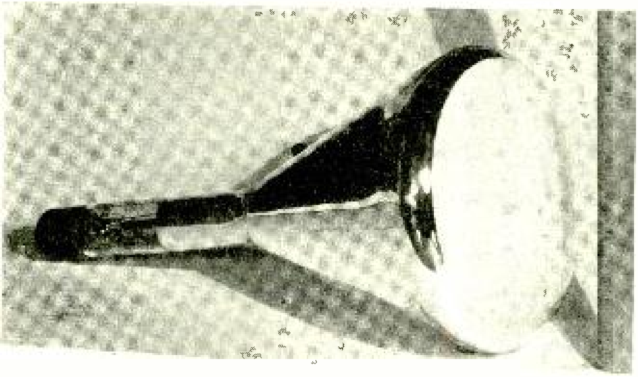

Fig. 1—Conventional 9 inch-diameter Kinescope. The television image is viewed directly on the large end of the tube.

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 material has a luminous output of about two candles per watt. The brightness of the screen, therefore, will be

$$\frac{1.5\times 2}{75\times\frac{1}{144}}=5.8 \text{ candles}$$

per square foot, or 18.2 foot-lamberts.

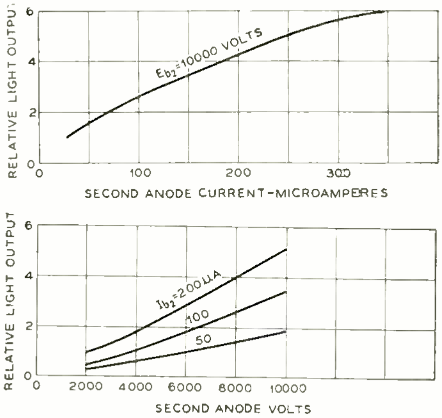

Fig. 2—Top curve shows variation of light output of fluorescent material with beam current. Bottom curve shows light output vs. second anode potential. Both curves are for RCA phosphor No. 1.

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

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[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 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 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.

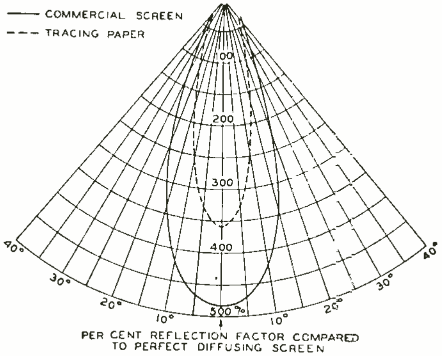

Fig. 3—Brilliance distribution of two types of transmission screens.

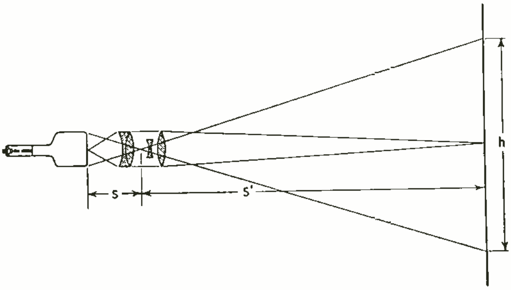

Fig. 4—Schematic diagram of optical system for projection Kinescope.

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 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.

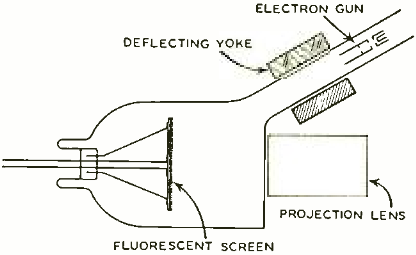

Fig. 5—"Front surface" type of projection Kinescope. Use is made of the greater amount of light emanating from the side of the screen which is scanned.

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

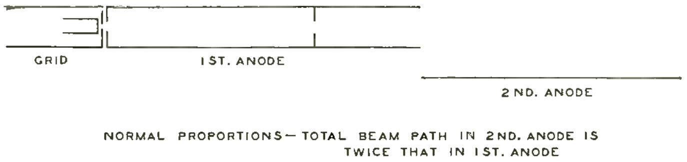

Fig. 7—Sectional diagram of the electron gun used in a projection Kinescope. The second anode is formed by a conductive coating on the bulb wall.

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.

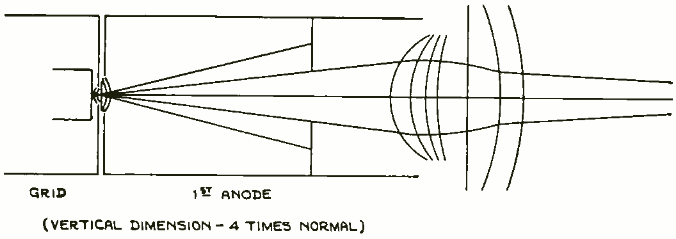

Fig. 8—Diagram of electron trajectories through the electron gun of Fig. 7. The electron lenses are represented by the lines of equal potential.

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.

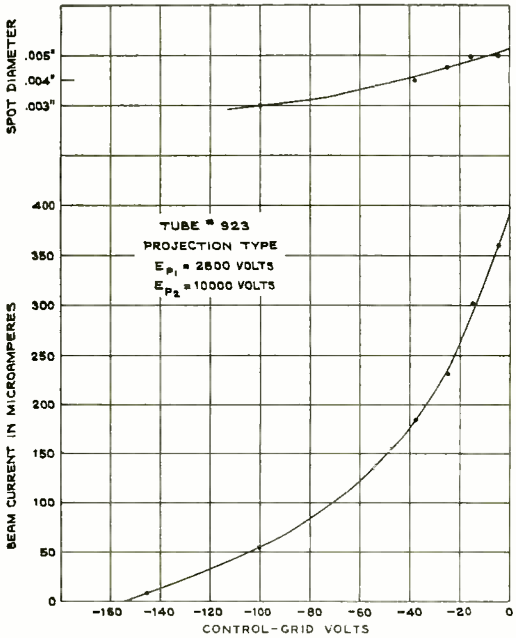

Fig. 9—Control characteristic of a projection Kinescope. The upper curve represents the variation of focused spot size with control grid bias.

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

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[5] D. W. Epstein, "Electron optical ssytem 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.

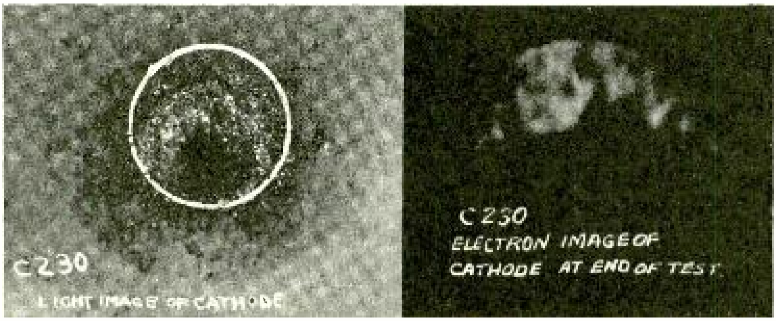

Fig. 10—Effect of positive ion bombardment on oxide-coated cathode. The dark central area is a hole through the cap. The pebbled area is bare nickel. The uniformly gray part is oxide coating. The useful area of the cathode is contained within the inner circle. The photograph to the right is the electron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

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[6] R. R. Law, "High current electron gun for projection Kinescopes," *Proc. I.R.E.*, August, 1937.

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.

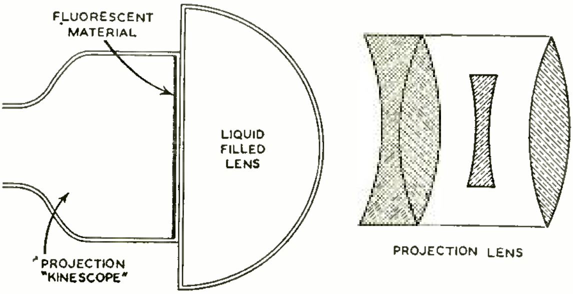

Fig. 11—A hollow shell filled with liquid and sealed to the face of a projection Kinescope will increase the amount of light entering the projection lens. Aberration is a serious defect in this system.

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.

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

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[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).

Reprinted from *Proc. I.R.E.*, August, 1937.

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

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[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 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.

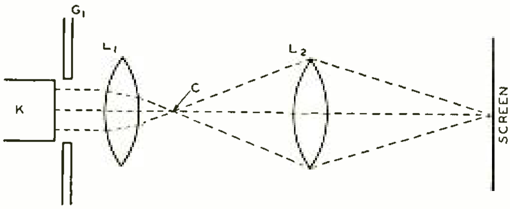

Fig. 1—Schematic optical analogy of an electron gun.

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

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[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

$$f_1 f_2 = UV.$$

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[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, 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.

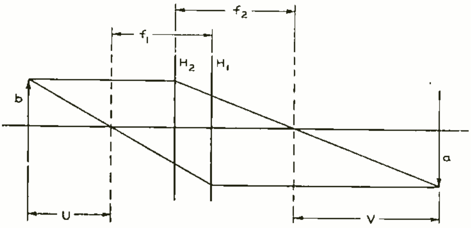

Fig. 2—Optical constants of a thick lens.

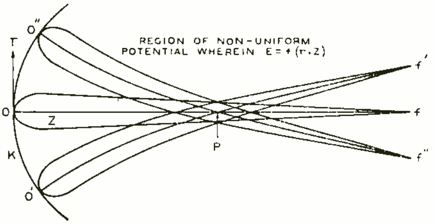

Fig. 3—Generalized representation of a first crossover forming system.

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

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[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

$$r = \sqrt{\frac{E_{r_0}}{E}}\, f(Z). \tag{3}$$

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

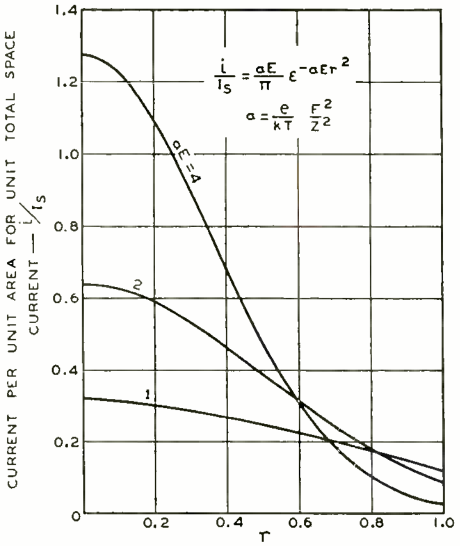

Fig. 4—Computed variation of current density in a crossover.

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

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 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.

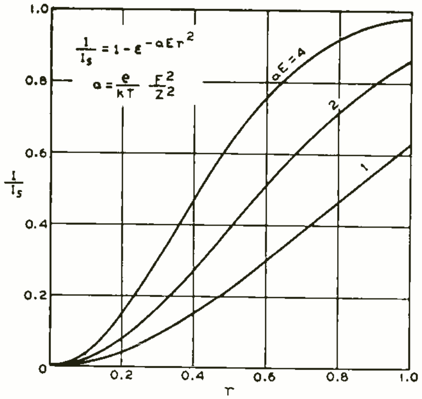

Fig. 5—Computed variation of current through a crossover defining aperture.

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 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.

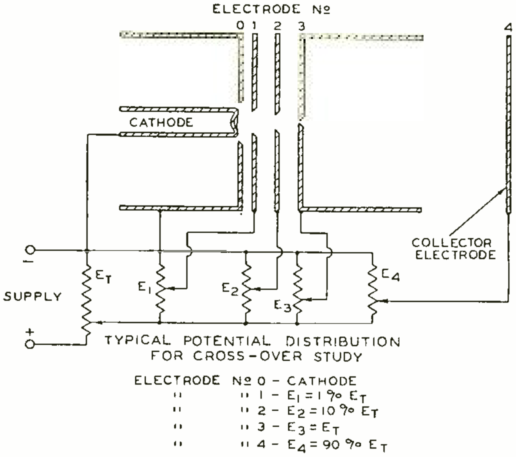

Fig. 6—Beam forming structure and circuit for studying crossover characteristics.

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

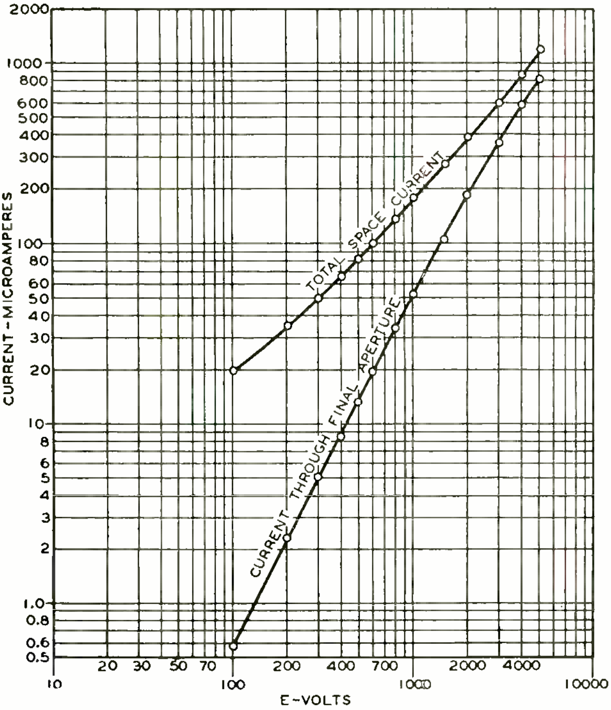

Fig. 7—Typical curves of space current and current through final aperture as a function of voltage applied to first crossover forming system.

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 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.

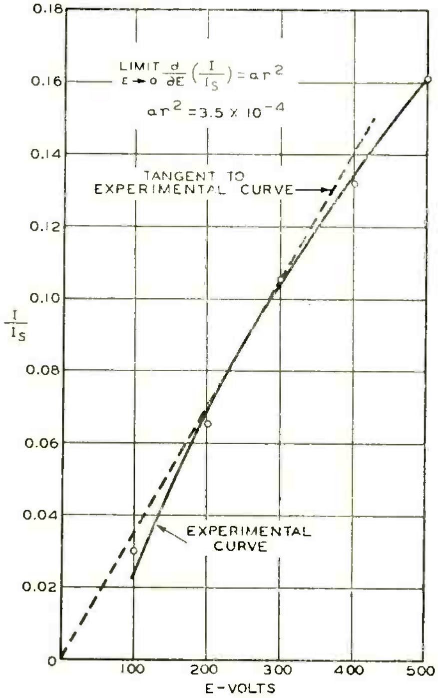

Fig. 8—Evaluation of ar^2 from experimental data.

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

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

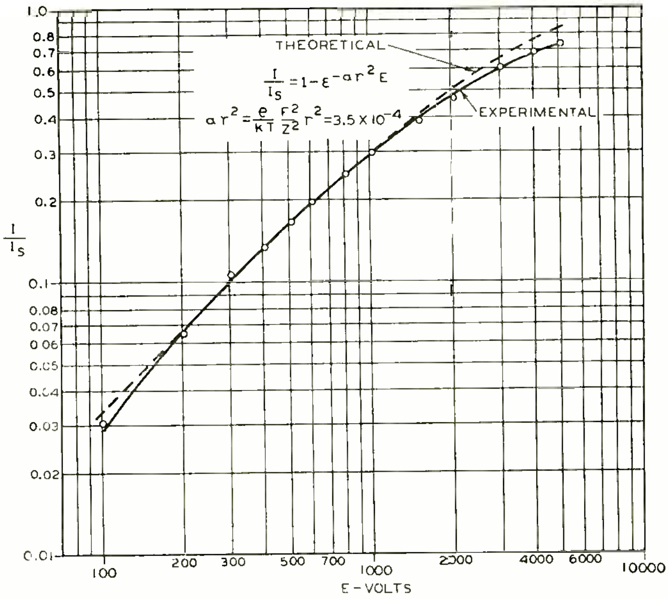

Fig. 9—Ratio of current through final aperture to total space current as a function of voltage applied to first crossover forming system.

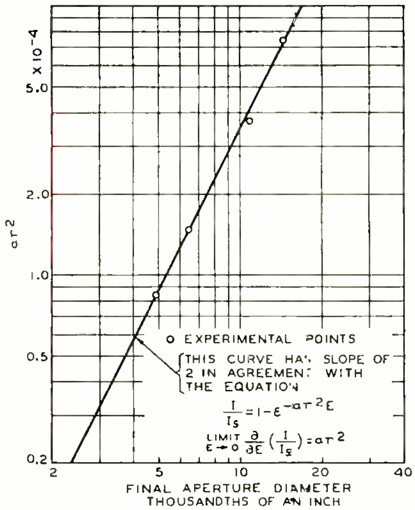

Fig. 10—Variation of ar^2 with final aperture diameter.

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

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[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, $r^2E = (2.22)^2\ (2) = (1)^2\ (10) =$ 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 Kinescope utilizing such an electron gun. Fig. 12 gives an enlarged view of the first crossover forming system.

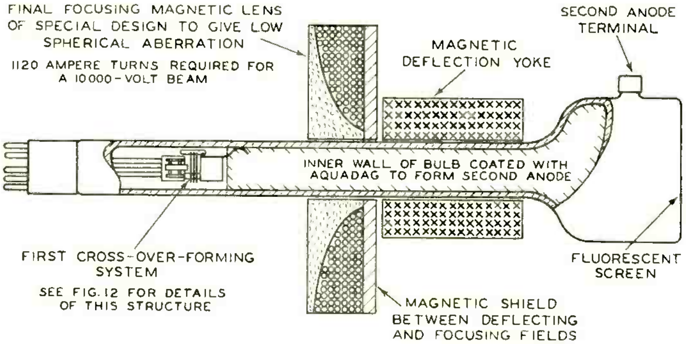
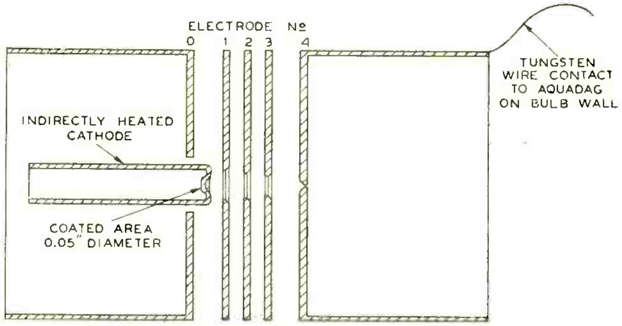


Fig. 11—General assembly of a developmental projection Kinescope.



ELECTRODE №	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.

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

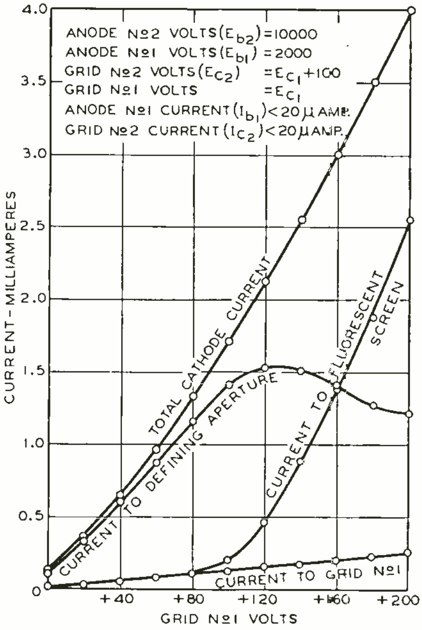


Fig. 13—Characteristics of the electron gun.

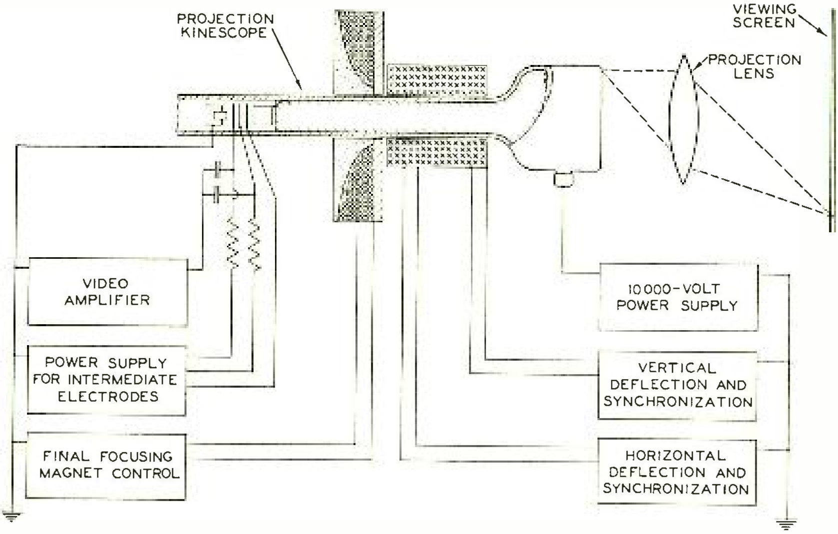


Fig. 14—Block diagram of a projection Kinescope and its associated equipment.

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 system 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.

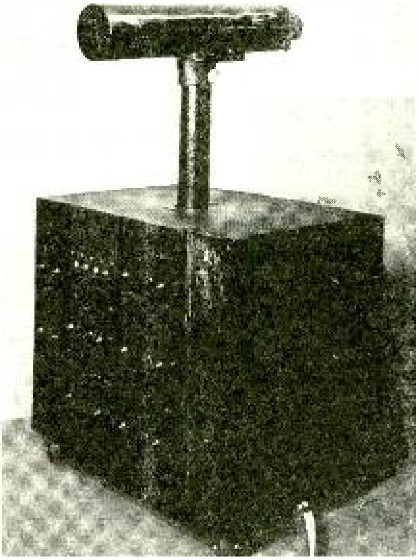


Fig. 15—Laboratory set for demonstrating projection Kinescopes.

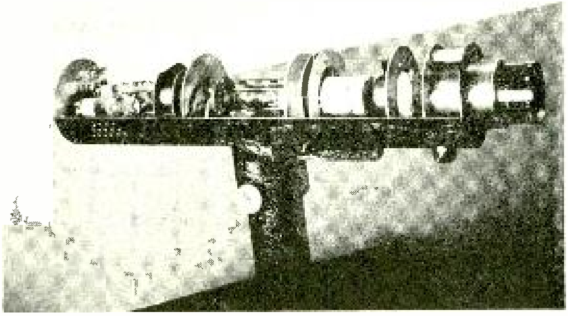


Fig. 16—Projection Kinescope housing opened to show details of the tube mounting and the optical system.

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.

TELEVISION PICKUP TUBES WITH CATHODE-RAY BEAM SCANNING

By

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RCA Manufacturing Company, Inc., Harrison, New Jersey

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

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[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).

Reprinted from *Proc. I.R.E.*, August, 1937.

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.

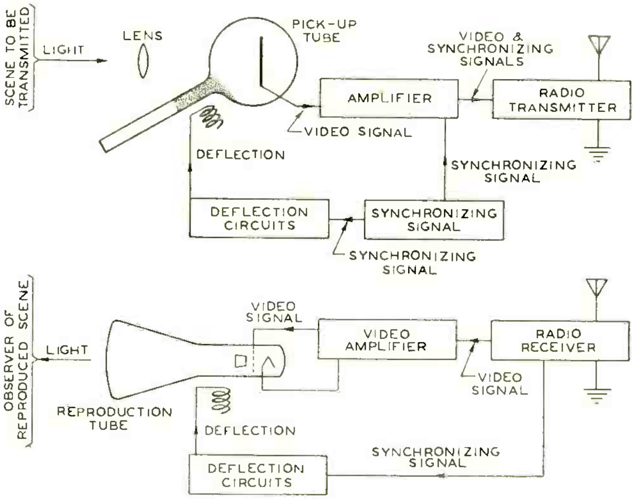


Fig. 1—Schematic diagram showing relation of pickup tube to television system.

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

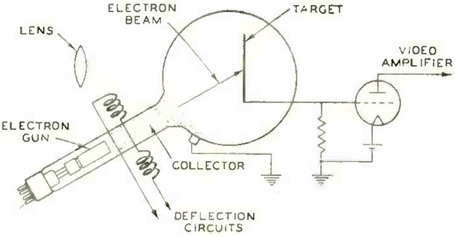


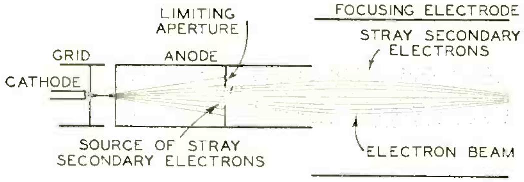
Fig. 2—Typical television pickup tube.

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.

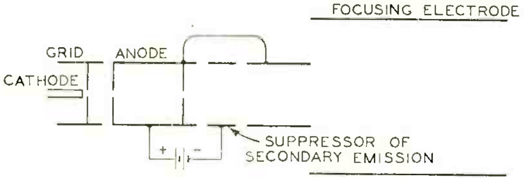
A pickup tube with a cathode-ray scanning beam may take many different shapes, depending upon whether the beam is formed as a result of photoemission, secondary emission, or thermionic emission. Since the latter is usually most convenient, it will be taken for purposes of illustration. A tube as shown 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

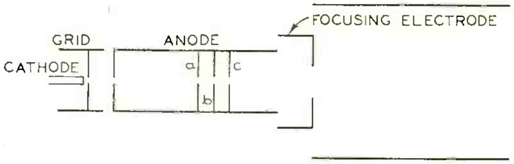
Electron guns suitable for use in cathode-ray tubes have been described by Zworykin and others.[3,4] We have, however, found it advisable to modify some of the simpler designs to insure the supression of secondary emission from the anode. Fig. 3(a), which illustrates a conventional type of electron gun, 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



(a) USUAL ELECTRON GUN



(b) GUN WITH SUPPRESSOR ELECTRODE



(c) GUN WITH IMPROVED FOCUSING AND NEGLIGIBLE SECONDARY EMISSION

Fig. 3—Electron gun designs.

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[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

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

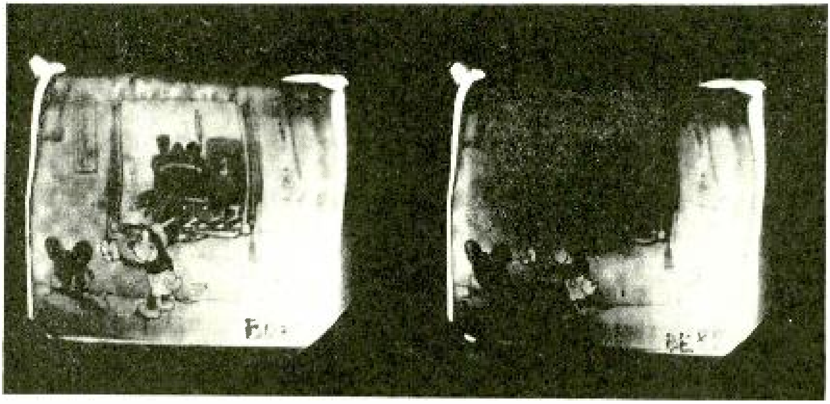

Fig. 4—Television pictures illustrating effects of secondary electrons from electron gun.

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 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.

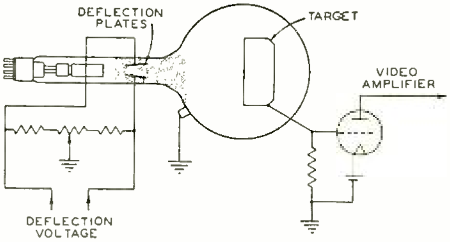

Fig. 5—Circuit for minimizing pickup from electrostatic deflection plates.

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 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.)

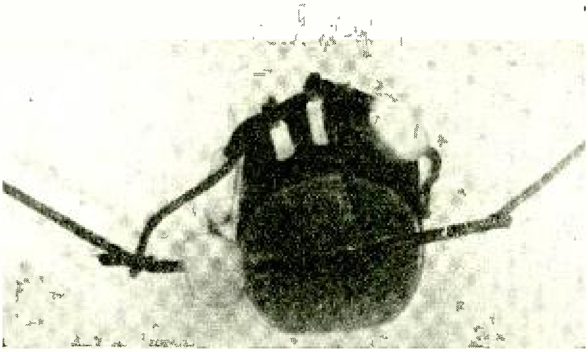

Fig. 6—Television picture of electrode scanned by electron beam.

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

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[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 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 $\Delta E/\Delta I$ = about 7 megohms.

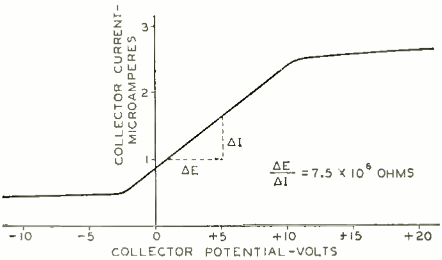
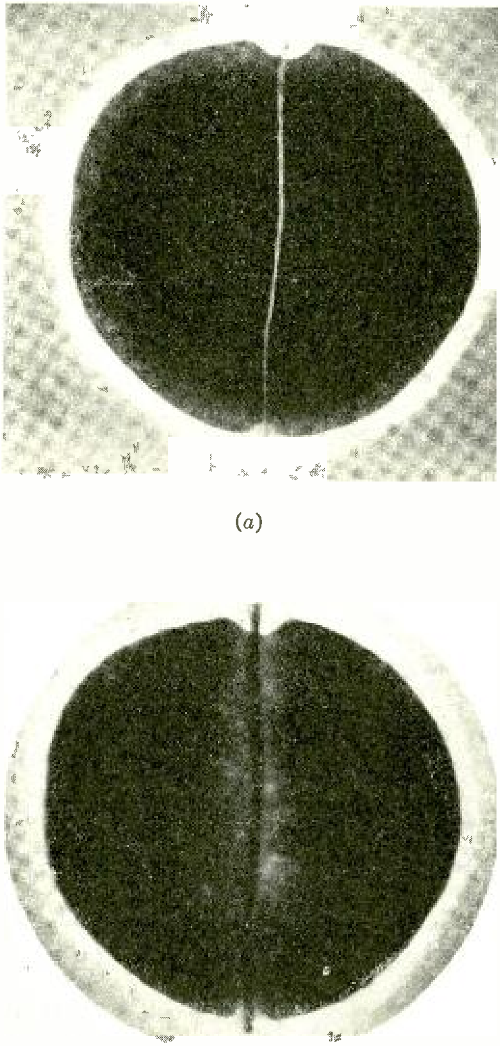


Fig. 7—Curve showing relation between collector voltage and collector current.

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.

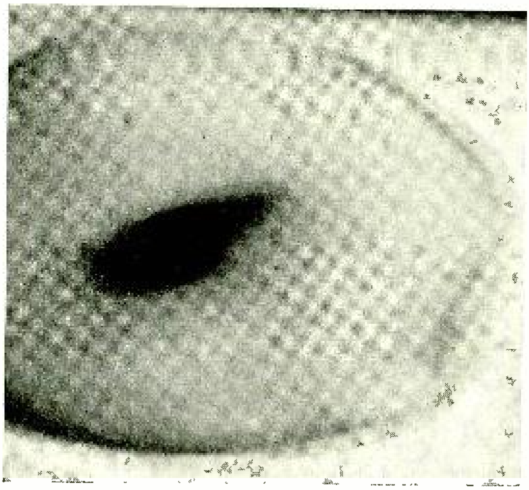


Fig. 9—Television picture showing pattern caused by magnetic field near target.

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-

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[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]

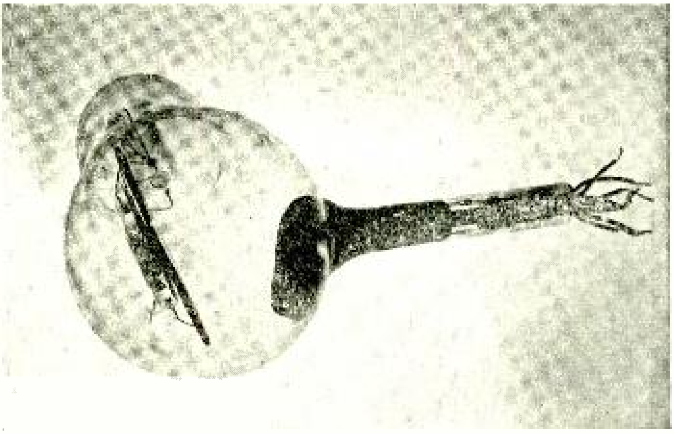

Fig. 10—Pickup tube having silver target sensitized with caesium.

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[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

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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 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 tub-

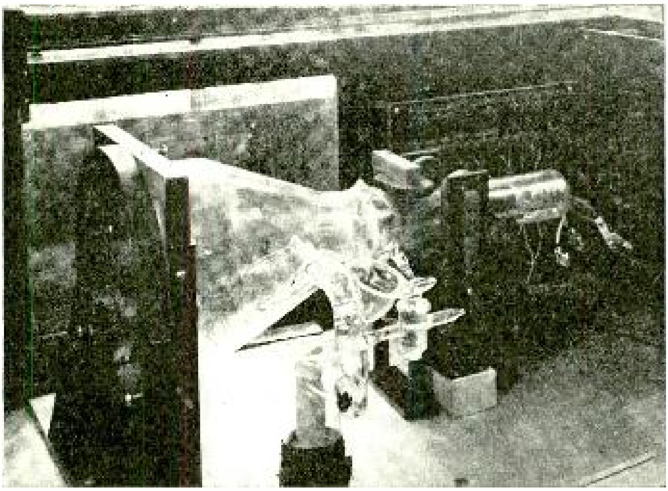

Fig. 11—Demountable cathode-ray tube.

ing 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 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

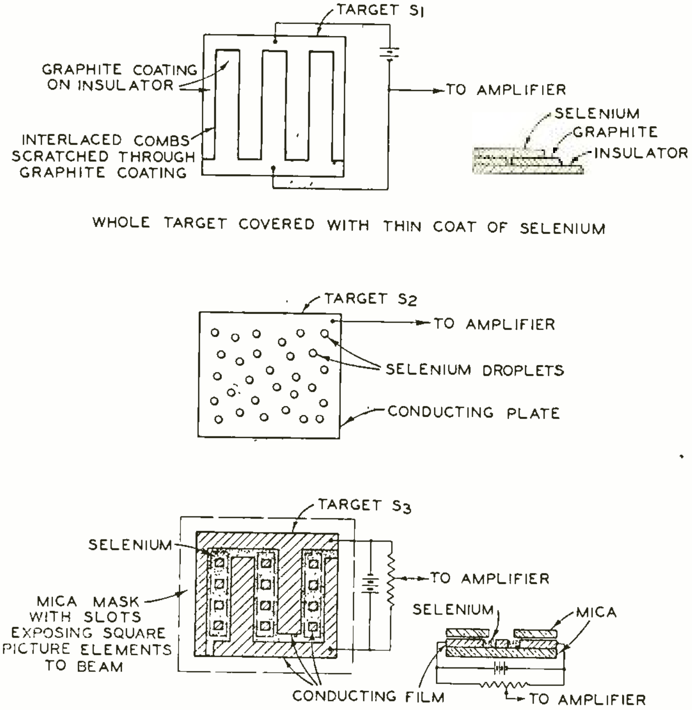

Fig. 12—Various kinds of selenium sensitized targets.

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.

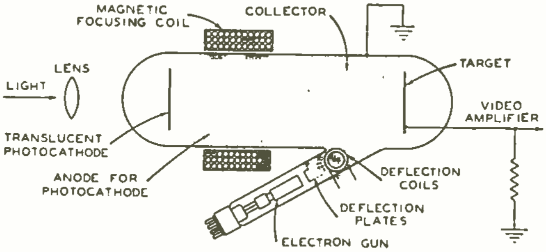

Fig. 13—Pickup tube with electron picture focused upon scanned target.

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

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[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.

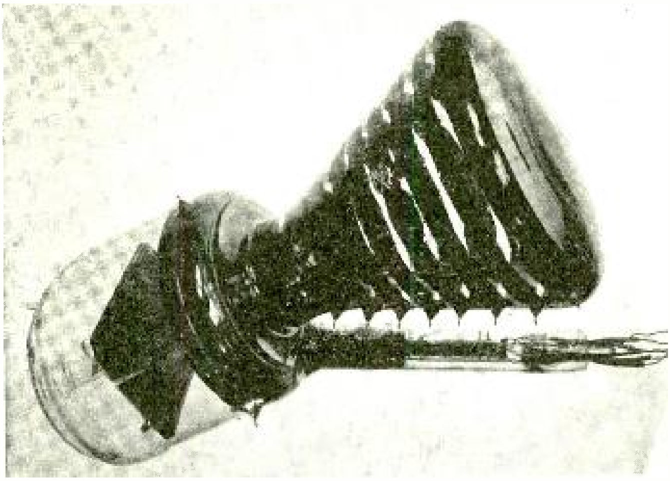

Fig. 14—Pickup tube using electrostatically focused electron picture.

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 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.

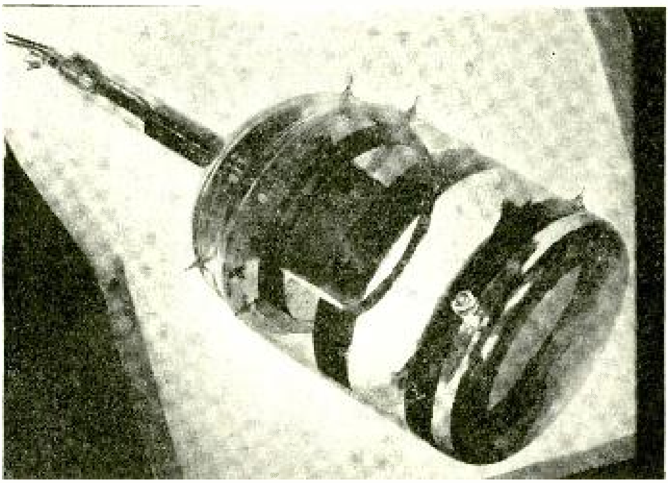

Fig. 16—Pickup tube utilizing magnetically focused electron picture.

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.

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

THEORY AND PERFORMANCE OF THE ICONOSCOPE[1]

BY

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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

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[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).

[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).

Reprinted from *Proc. I.R.E.*, August, 1937.

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 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.

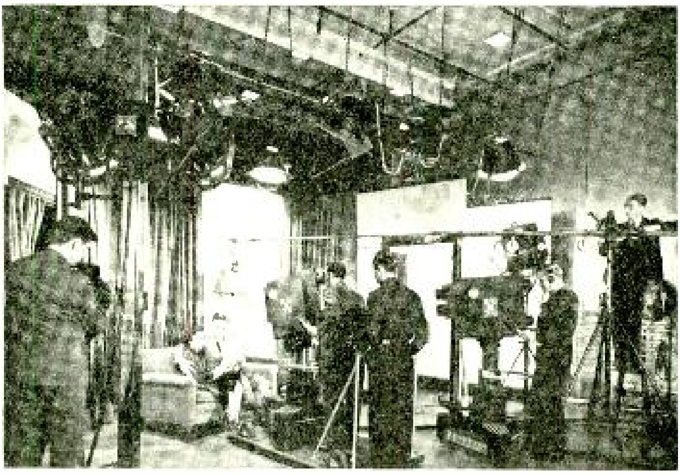

Fig. 1—Scene in N.B.C. television studio.

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 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.

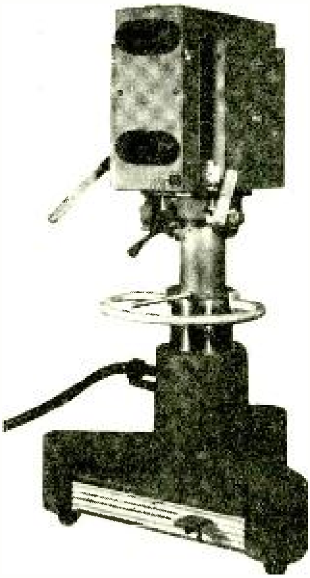

Fig. 2—N.B.C. studio Iconoscope camera.

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 micro-microfarads 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 uniform 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 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.

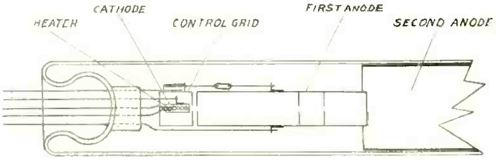

Fig. 3—Diagram of electron gun.

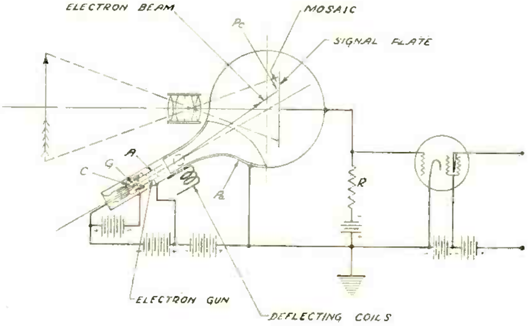

Fig. 4—Diagram of Iconoscope.

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 with in the case of the Iconoscope. Experimental measurements show this beam impedance, Z, to be given by the relation

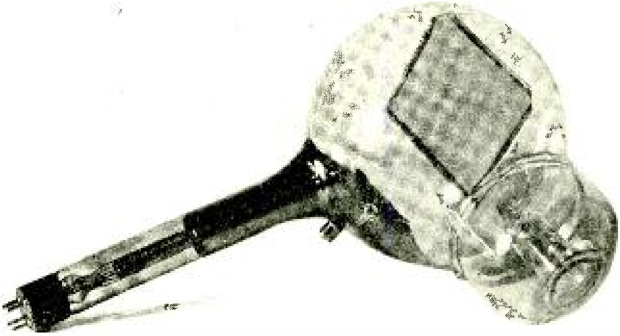

Fig. 5—Iconoscope—Spherical bulb type.

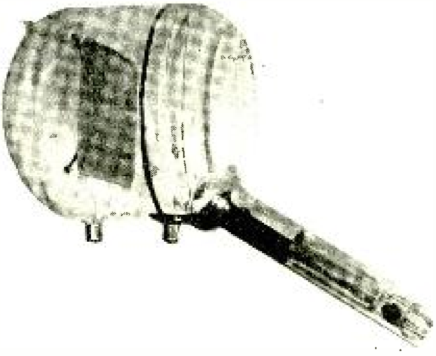

Fig. 6—Iconoscope—Optical flat window type.

$$Z = \frac{Z_0}{i_b}$$

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 one-half volts to its equilibrium of approximately plus three volts. The capacitance of this area will be

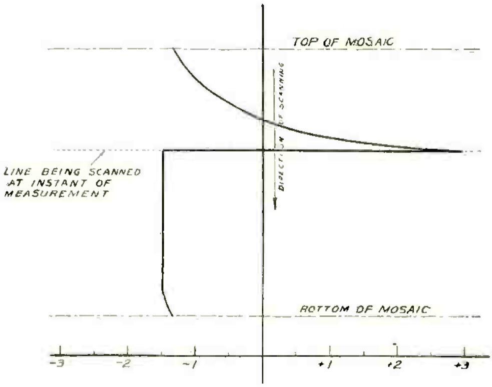

Fig. 7—Instantaneous potential of the mosaic.

$$C = C_0 ds$$

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

$$\begin{aligned} V &= (V_2(xy) - V_1(xy))(1 - e^{(-t/Z_0C_0ds)/\rho ds}) \\ &= (V_2(xy) - V_1(xy))(1 - e^{-t\rho/C_0Z_0}). \qquad (1) \end{aligned}$$

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

$$\frac{Z_0 C_0}{\rho} < t = T$$

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

$$\frac{Z_0 C_0}{\rho} = 1.2 \times 10^{-7} \text{ seconds.}$$

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

$$di_e = -\left(C_0 \frac{dV}{dt}\right) ds. \tag{2}$$

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

$$di_s = f(xyV)\left(\rho + C_0 \frac{dV}{dt}\right) ds. \tag{3}$$

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

$$i_e = \frac{hv\rho}{Z_0}(V_2 - V_1)\int_0^T e^{-t\rho/C_0Z_0}dt$$

$$\cong hvC_0(V_2 - V_1)$$

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.

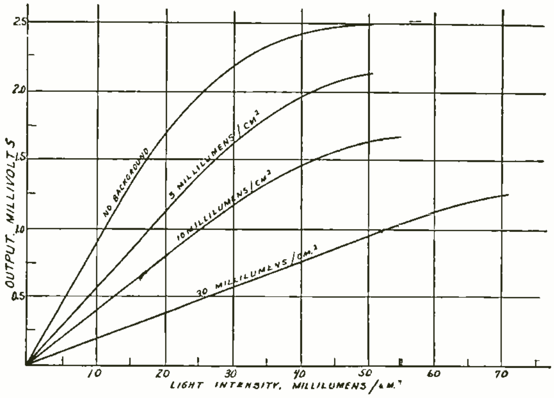

Fig. 8—Variation of output with light for different background illumination.

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 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.

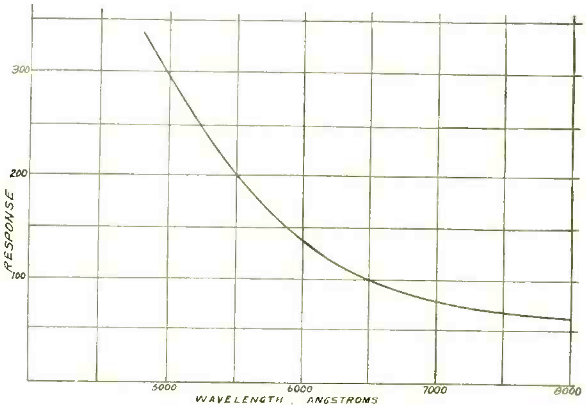

Fig. 9—Color response of standard Iconoscope No. 454.

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

$$V_N{}^2 = K_1FR$$
$$= 9.6 \times 10^{-10}$$

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

$$R = \frac{I_s}{I_n} = \frac{kA}{\sqrt{K_2 F}} \sqrt{\frac{B-1}{2B}}\, L/\sqrt{i_b}. \qquad (7)$$

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/cm²; 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

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[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.

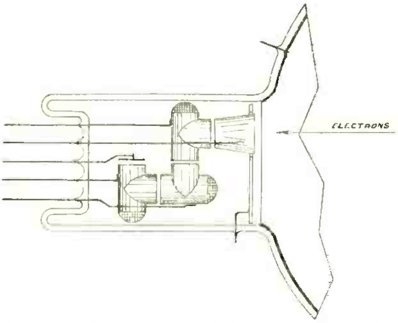

Fig. 10—Diagram of T type multiplier.

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

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[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 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.

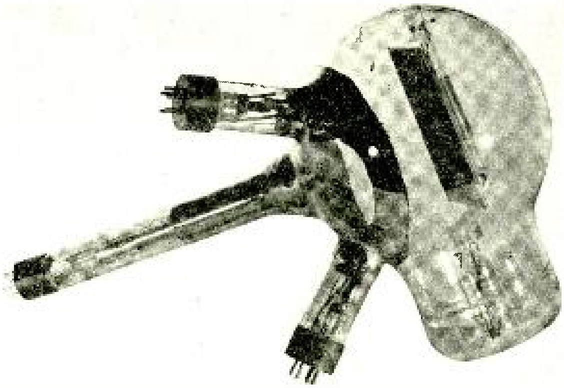

Fig. 11—Signal multiplier Iconoscope.

The second method of approach is by the use of secondary emission 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

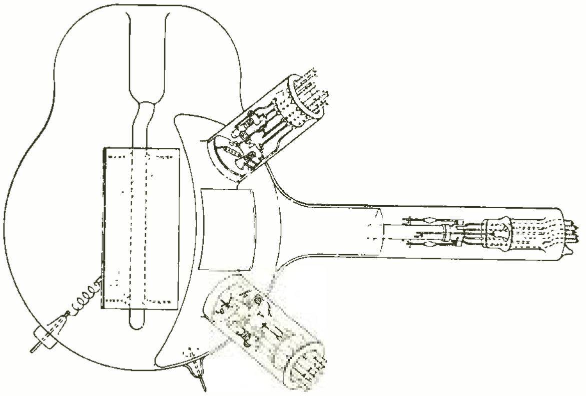

Fig. 12—Diagram of signal multiplier Iconoscope.

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

$$L = \frac{2eF(1 + k'')R^2}{Ap}$$

$$= 7 \times 10^{-7}\ \text{lumens/cm}^2. \tag{9}$$

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

$$L = \frac{2eFR^2}{Ap}. \tag{10}$$

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 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.

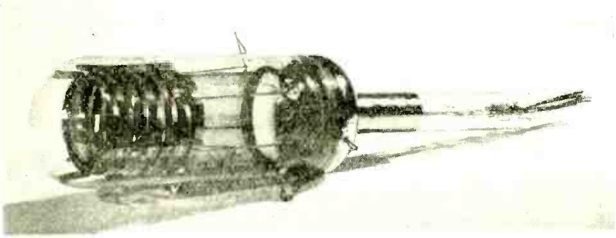

Fig. 13—Image multiplier Iconoscope.

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,

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[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.

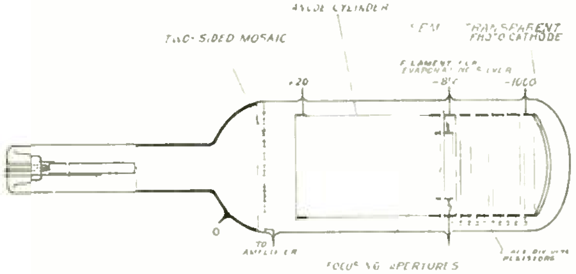

Fig. 14—Diagram of image multiplier Iconoscope.

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.

PROBLEMS CONCERNING THE PRODUCTION OF CATHODE-RAY TUBE SCREENS

By

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I. Introduction

THE scope of the present article is the description of some problems incidental to applying cathodoluminescent materials in cathode-ray (CR) tubes and Kinescopes (i.e., CR tubes with modulation as used in television) as these problems have been treated in the Electronic Research Laboratories at the Victor Division of the RCA Manufacturing Company, Inc.

Although much of that which follows is generalized, specific differences in theory and practice arise from the use of different cathodoluminescent materials (i.e., oxides or sulphides) and the use of different ways of viewing, projecting, or photographing the luminescent image (i.e., whether on the obverse or reverse side to that which is struck by the scanning electron beam).

Most of the described experimental procedures have been developed for producing oxide-type luminescent screens in CR tubes such as shown in Figure 1. In this usual type of tube the image is viewed, or projected, from the side of the screen which is opposite the scanning beam. A major portion of this article will be devoted to the screening problems of this type of tube.

CR tubes in which the screen is viewed from the same side as it is scanned, such as sketched in Figure 2, are the least complicated and most efficient types as far as image contrast and screen efficiency are concerned. However, such "direct-viewing" tubes have over-compensating disadvantages of geometry and the unfavorable psychological impression of looking at the image through a window.

Before proceeding with tube and screen types, we shall calculate the penetration distances of cathode rays into several luminescent materials.

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II. CALCULATION OF CATHODE-RAY PENETRATION INTO SEVERAL IMPORTANT LUMINESCENT MATERIALS

H. Bethe[1] has developed a general formula for the penetration (p) of a corpuscular beam into matter:

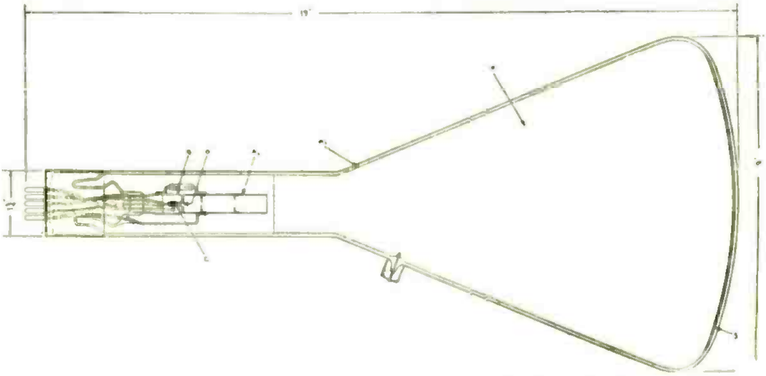

Fig. 1—Longitudinal section through a typical cathode-ray tube or Kinescope.

$$\frac{v_0^4 - v^4}{p} = \frac{16\pi e^4 z^2 N}{m M_1} \sum f_{nl} \ln \frac{4\overline{W}}{A_{nl}}, \qquad (1)$$

v_0 = initial velocity of particle,
v = velocity of particle after traversing the thickness p,
e = the electronic charge (4.774×10^{-10} E.S.U.),
z = number of charges carried per unit particle,
N = number of atoms per unit volume,
m = mass of electron,
M_1 = mass of impinging particle,

$\Sigma f_{nl} \ln \dfrac{4\overline{W}}{A_{n1}} = B =$ deceleration factor. Experimentally determined for several elements and listed on page 374 of Bethe's article.

Using summed values of B determined at constant (room) temperature, we employ the following simplified form of Eq. (1):

$$\frac{v_0^4 - v^4}{p} = \frac{16\pi e^4 z^2 NB}{m^2}, \qquad (2)$$

$m = M_1$ for electron beam,
$z = 1$ for electron beam.

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[1] Ann. d. Physik 5, 325-401 (1930).

Since: $$v_0^2 = eV/150m \tag{3}$$

where V = voltage accelerating the electron, then by substituting Eq. (3) in Eq. (2), setting $V = 0$ for total absorption and solving for p, we obtain:

$$p = V^2/(16 \times 2.25 \times 10^4 \pi e^2 NB). \tag{4}$$

Or: $$p = (3.9 \times 10^{12} V^2)/NB. \tag{5}$$

Substituting the equality:

$$N = (\sigma N_a)/A \tag{6}$$

σ = density in g/cm^3,
N_a = Avogadros number = 6.06×10^{23} mole^{-1},
A = atomic weight in grams,

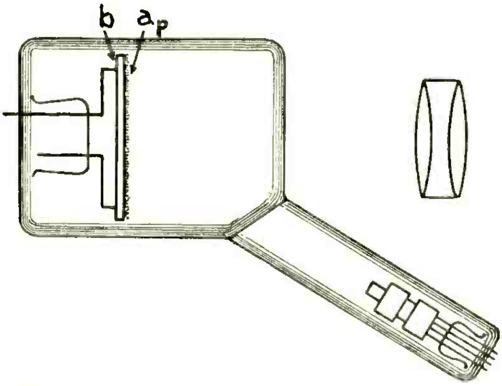

Fig. 2—Longitudinal section through a "direct viewing" or "front surface" type cathode-ray tube (Kinescope).

in Eq. (5) we obtain:

$$p = (6.48 \times 10^{-12} V^2 A)/B\sigma, \tag{7}$$

or, for a compound:

$$p = (6.48 \times 10^{-12} V^2 (\text{M.W.}))/(B_c \sigma N_f), \tag{8}$$

where (M.W.) = molecular weight of the compound, N_f = number of atoms/molecule and B_c is a weighted average of the B's for the atoms comprising the molecule.

Eqs. (5)–(8) are accurate within the range of 1000 to 30,000 volts, but above 100,000 volts the relativity correction $(1 - (v/c)^2)^{-1}$ must be applied to the primary electron's mass.

The elemental values of B may be obtained directly or by interpolation from the experimental data given by Bethe[1] on page 374 of his article. See Table I, which contains elemental N and

B values for the elements comprising the luminescent materials being considered.

The molecular values of B_c are calculated as a weighted average from the B's of the component atoms and their numerical ratios.

Similarly, the molecular N may be totalled for each substance, *viz.*, for Zn_2SiO_4:

$$\begin{aligned} N_{\mathrm{Zn}} &= 2.28 \times 10^{22} \\ N_{\mathrm{Si}} &= 1.14 \times 10^{22} \\ N_{\mathrm{O}} &= 4.55 \times 10^{22} \\ \hline \sum N_{\mathrm{Zn_2SiO_4}} &= 7.97 \times 10^{22} \text{ atoms/cm}^3. \end{aligned} \tag{9}$$

Substituting the ΣN and B_c values given in Table II in Eq. (5) we obtain:

TABLE I.

ATOMIC NUMBER	ELEMENT	B(EXPER.)	B(INTERP.)	$N \times 10^{22}$(CALC.)
4	Be		~ 7.8	3.35 ($2BeO \cdot SiO_2$)
8	$1/2O_2$	13.3		6.56 ($2BeO \cdot SiO_2$) 4.55 ($2ZnO \cdot SiO_2$) 5.06 ($CaO \cdot WO_3$)
14	Si		~ 19.8	1.64 ($2BeO \cdot SiO_2$) 1.14 ($2ZnO \cdot SiO_2$)
16	S		~ 21.9	2.53 (ZnS) 2.01 (CdS)
30	Zn		~ 32.5	2.28 ($2ZnO \cdot SiO_2$) 2.53 (ZnS)
48	Cd		~ 38	2.01 (CdS)
74	W		~ 47	1.26 ($CaO \cdot WO_3$)

TABLE II.

LUMINESCENT MATERIAL	σ	B_c(AVERAGE)	ΣN
$2BeO \cdot SiO_2$	2.98	12.66	11.55×10^{22}
$2ZnO \cdot SiO_2$	4.218	19.70	7.97×10^{22}
ZnS	4.09	27.20	5.06×10^{22}
CdS	4.82	29.95	4.02×10^{22}
$CaO \cdot WO_3$	6.06	20.87	7.595×10^{22}

$$p_{Be_2SiO_4}=\frac{3.9\times10^{12}V^2}{12.66\times11.55\times10^{22}}$$

$$=2.68\times10^{-12}V^2\ \text{cm},\qquad(10)$$

$$p_{Zn_2SiO_4}=\frac{3.9\times10^{12}V^2}{19.7\times7.97\times10^{22}}$$

$$=2.5\times10^{-12}V^2\ \text{cm},\qquad(11)$$

$$p_{ZnS}=\frac{3.9\times10^{12}V^2}{27.2\times5.06\times10^{22}}$$

$$=2.83\times10^{-12}V^2\ \text{cm},\qquad(12)$$

$$p_{CdS}=\frac{3.9\times10^{12}V^2}{29.95\times4.02\times10^{22}}$$

$$=3.24\times10^{-12}V^2\ \text{cm},\qquad(13)$$

$$p_{CaWO_4}=\frac{3.9\times10^{12}V^2}{20.87\times7.595\times10^{22}}$$

$$=2.46\times10^{-12}V^2\ \text{cm}.\qquad(14)$$

Using Eqs. (10)–(14) we have calculated the penetration distances into these listed luminescent materials, for various voltages, and tabulated the data in Table III.

TABLE III. Penetration (p) in μ ($1\mu=10^{-4}\ cm=0.001\ \text{mm}=10^4\ A$)

VOLTAGE V	$2BeO\cdot SiO_2$ $p(\mu)$	Zn_2SiO_4 $p(\mu)$	ZnS $p(\mu)$	CdS $p(\mu)$	$CaWO_4$ $p(\mu)$
100	0.00027	0.00025 (2.5A)	0.000283	0.000324	0.000246
1000	0.027	0.025 (250A)	0.0283	0.0324	0.0246
2000	0.107	0.10 (1000A)	0.113	0.13	0.0984
3000	0.241	0.225	0.254	0.292	0.222
4000	0.429	0.40	0.45	0.52	0.394
5000	0.67	0.655	0.71	0.81	0.615
6000	0.965	0.90	1.02	1.17	0.885
7000	1.31	1.225	1.39	1.59	1.215
8000	1.72	1.60	1.81	2.08	1.58
9000	2.17	2.02	2.30	2.62	2.00
10,000	2.68	2.50 (25,000A)	2.83	3.24	2.46
15,000	6.16	5.65	6.37	7.30	5.54
20.000	10.72	10.0	11.32	12.96	9.84
30.000	24.1	22.5	25.4	29.2	22.2
50,000	67.0	65.5	71.0	81.0	61.5
100.000	268.0	250.0	283.0	324.0	246.0

One would predict from the data of Table III that sulphide screens should be made 13–30 percent thicker than screens made of the listed oxide phosphors luminescent materials). This prediction finds experimental verification in practice.

III. DIRECT VIEWING CR SCREENS

Screen production for CR tubes viewed on the scanned side of the luminescent screen is relatively simple in that screen thickness is not critical as long as the screen thickness is made considerably greater than the penetration distance given in Table III for a particular voltage and material. The luminescent spot size is a minimum for this type of screen and, as a result, image definition and contrast is at its best.

In the absence of single-crystal sheets of luminescent materials, the question of optimum particle size will be considered specifically for the following case of indirect viewing screens.

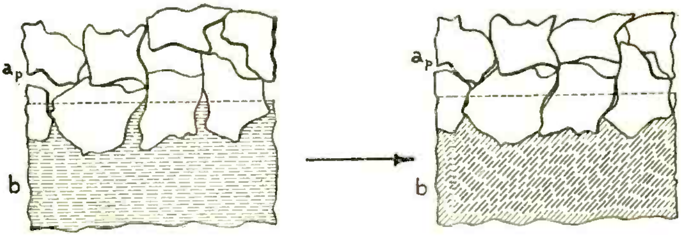

Fig. 3—Section illustrating the preparation of a luminescent screen by partially embedding phosphor particles in a vitreous medium.

The luminescent particles (a_p) may be made to firmly adhere to the metal or glass base member (*b*, Fig. 2) by using suitable binders (Na_2SiO_3, K_2SiO_3) or by partially embedding some of the luminescent particles in a molten vitreous medium such as B_2O_3 and allowing the vitreous base to cool, whereupon it contracts and interlocks adjoining particles as shown in Figure 3.

IV. INDIRECT VIEWING CR SCREENS

With the present, normal type of CR tube the image is viewed, or projected, from the side of the cathodoluminescent screen which is opposite to the side being scanned by the electron beam. A cross-sectional view of this type of screen arrangement is shown in Figure 4 where the screen is shown in the ideal form of a transparent section from a large single crystal of luminescent material.

The electron beam of average intensity $(V \cdot I)/\pi a^2$ ($V =$ voltage accelerating electrons to the screen, $I =$ total current carried by the electron beam, and a = radius of the beam) impinges upon the luminescent material, whereupon the electrons are scattered and decelerated by collisions with crystal units and interaction with lattice forces. Upon deceleration, the primary electrons' energy losses are transformed into secondary electrons, high frequency electromagnetic radiation, photoelectrons, and heat energy in the crystal. The secondary electrons, soft x-rays, ultraviolet radiation, and photoelectrons scatter in all directions and may be the principal exciting agents for the desired visible (or actinic) radiant energy. The electron beam cross section (πa^2) is, therefore, always smaller than the luminescent spot (πr^2). The radius "r" represents an outer limit of visible intensity corresponding to a certain value of the quantity $(V \cdot I)/\pi a^2$. The distance $r - a$ increases in size as the current (I) is increased since the scattered primary and secondary energy per unit volume increases in the annular region ($r - a$) around the projected primary beam within the crystal, thus increasing the intensity of emitted visible light and making a formerly invisible outer region of the luminescent spot brilliant enough to be observable.

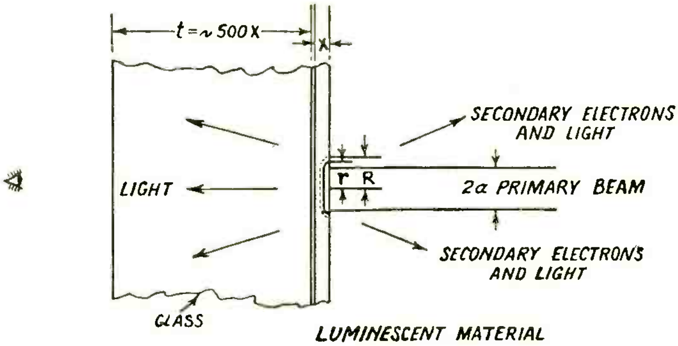

Fig. 4—Section through an "ideal" luminescent screen.

Conversely, the distance $r - a$ decreases as a is increased (keeping V and I constant). The quantity $r - a$ would be expected to decrease with increasing V only if the screen thickness x were less than the penetration distance of the electrons (p) and if the primary electrons contribute the bulk of luminescence excitation energy, since the scattering of primary electrons decreases with increasing velocity. One should, therefore, expect an increase of $r - a$ with : 1. Increase of either I or V, or 2. A decrease of a while holding the remaining two variables constant. This relationship between visible spot and beam diameter holds true until the energy density $(V \cdot I)/\pi a^2$ is sufficient to cause saturation or destruction of luminescence power (commonly known as "burning") of the particular luminescent material of which the screen is composed.

Spurious rings, which are attributed by J. V. Hughes[2] to multiple reflections in the transparent supporting member, are not considered in the above discussion, but may be minimized by keeping the glass thickness small and avoiding the use of binders in screen production.[3]

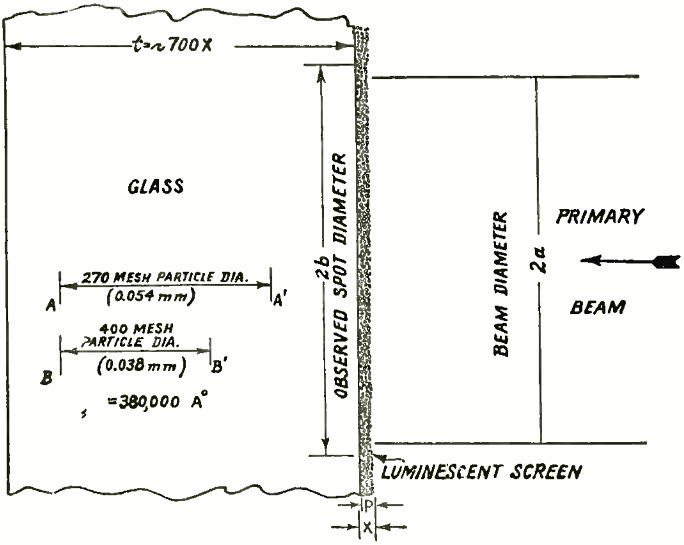

Fig. 5—Section through an actual luminescent screen. The thickness *t* would be 1.42 meters at this magnification. Scale: 1 mm = 0.00238 mm.

If we had large transparent single crystals of our luminescent materials, the screen thickness "x" would be immaterial, except as affecting the spurious rings. In such an ideal case the light output and contrast would then depend only upon the characteristic efficiency of the phosphor, the beam diameter and reflection losses at the boundary surfaces of the glass and screen. It is a moot question whether the increased efficiency which could be obtained by using transparent sheets of luminescent materials would be more than offset by a loss in heat-radiating surface.

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[2] *Proc. Phys. Soc.*, pp. 434-441, May 1 (1933).

[3] See also, M. von Ardenne, Hochfreq. u. Elektroakustik 46, 1, 1-4, July (1935).

Small particles have the definite advantage of a relatively large surface from which to radiate secondary heat energy which represents 95 percent or more of the primary beam energy.

In any event, it is with small crystals that we are at present making luminescent screens and the considerations affecting attainment of optimum luminescence efficiency are presented in the following.

An actual, indirectly viewed screen cross section is shown drawn to scale in Figure 5. The primary electron beam carries $100 \mu A$ at $10{,}000\ V$ with an observed luminescent spot diameter of 0.1 mm ($= 2b$). In 9″ Kinescopes used for television, operating at 6000 volts with $75 \mu A$ beam current, the spot size for a 343-line image averages about 0.7 mm diameter, or seven times as large as shown in Figure 5.

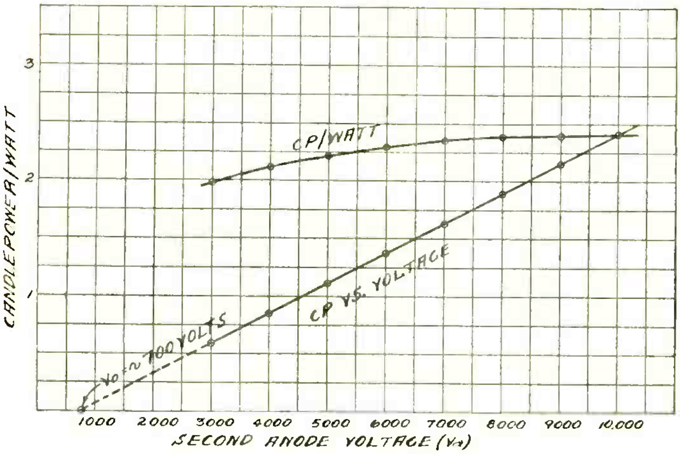

Fig. 6—Candlepower voltage relationship for an indirectly viewed $2ZnO{\cdot}SiO_2$: Mn screen. Scanned area, $6 \times 8\ cm^2$. Beam current $= 100 \mu A$.

From Table III we find that the penetration distance (p) of 10,000-volt electrons into certain phosphors is: 2.5–3.2μ ($= 0.0025$–0.0032 mm) depending upon the phosphor. The effective beam penetration (p) is a function of beam current density just as the visible spot size is also a function of current density ($I/\pi a^2$), since the electrons are exponentially attenuated in energy, as they pass through the luminescent material, and a phosphor region at the electron penetration limit may be brought from formerly unobservable intensity to detectable brilliancy by increasing the energy density in this region as a consequence of increasing the primary beam current density.

Having determined the approximate penetration of our primary electrons for a particular screen we next proceed to the problems of optimum particle size and optimum screen thickness. We shall use synthetic willemite, $2ZnO \cdot SiO_2 : Mn$, as an illustrative example.

A candlepower *vs.* applied voltage curve for a $2ZnO \cdot SiO_2 : Mn$ screen, as measured with a Macbeth illuminometer using a suitable calibrated Wratten filter and keeping the beam current constant, is shown in Figure 6. The graphical relationship follows a modified Lenard's[4] equation:

$$
\begin{aligned}
L &= K_1 \varphi(I, a)\ (V_A - V_0) - K_2 f(V), \\
L &= \text{luminous intensity (candlepower)}, \\
K_1 \text{ and } K_2 &= \text{constants characteristic of the phosphor}, \\
I &= \text{beam current}, \qquad\qquad (15) \\
a &= \text{beam radius}, \\
V_A &= \text{applied voltage}, \\
V_0 &= \text{"dead" voltage (see Figure 5)}, \\
-K_2 f(V) &= \text{secondary emission function (to be discussed later)}.
\end{aligned}
$$

The quantity V_0 has been termed "dead" voltage and was first interpreted by Lenard and Saeland[5] as caused by inactive surface layers of the luminescent particles. These layers do not luminesce efficiently, but nevertheless absorb energy and necessitate a certain minimum voltage V_0 for penetration through to the active interiors of the luminescent particles.

In the present case of $2ZnO \cdot SiO_2 : Mn$ it is seen that V_0 equals ~700 volts, $p_0 = 0.000012$ mm (0.012μ) (from Eq. (12)). As is shown in Figure 6, V_0 is an extrapolated quantity and does not represent the lowest voltage at which $2ZnO \cdot SiO_2 : Mn$ particles will luminesce if subjected to extremely high current density. Experiments conducted by H. C. Thompson at the Radiotron division of the RCA Manufacturing Co., Inc. showed luminescence of $2ZnO \cdot SiO_2 : Mn$ as low as 12 volts when subjected to enormous current densities.[6]

The question of optimum particle size (y) is made complex by the random orientations and multireflections encountered in the screen. If the observer were to review the screen from the same side as it is scanned, the particle size (y) would be made large (up to ~1/10 the beam diameter—larger particles would

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[4] Ann. d. Physik 12, 462 (1903).

[5] Ann. d. Physik 28, 485 ff (1909).

[6] Communicated by Dr. L. B. Headrick.

give the image a definite "grain") and the screen thickness (x) would be made equal to several times the penetration (p) of the electrons. Thus, the number of internal reflections of the emitted light would be reduced, the number of "dead" voltage layers per unit volume would be decreased and the ample excess screen thickness would assure complete utilization of all the primary and derived secondary energy. However, since the emitted light must suffer many reflections before emerging through to the glass, the distance (x) must be reduced to an optimum depending upon both (p) and (y).

The problem of transmission of light through a suspension of randomly orientated particles has been worked out by B. Mukhopadhyay.[7] The expression shows, in agreement with experiment, a much smaller transmission for a suspension of doubly refracting particles than for those of an isotropic body.[8]

For crystalline powders:

$$L = L_0 \exp -\frac{4\pi^2}{\lambda}\left[(\mu_0-\mu)^2\left(\frac{\pi}{8}-\frac{\pi^2}{36}\right) + (\mu_e-\mu_0)^2\left(\frac{\pi}{30}-\frac{\pi^2}{324}\right) + (\mu_e-\mu_0)(\mu_0-\mu)\left(\frac{\pi}{12}-\frac{\pi^2}{54}\right)\right]\cdot x\cdot y \quad (16)$$

L = intensity of light encountering the nth layer,
L_0 = initial intensity,
y = diameter of the particles,
x = total thickness (n.y),
n = total number of layers,
λ = wave-length of the light,
μ = refractive index of fluid (vacuum),
μ_0 = " " " ordinary vibration,
μ_e = " " " extraordinary vibration.

$$\mu_e > \mu_0 > \mu.$$

The relative scattering powers of small particles are numerically given in Table IV.[9]

From the above Eq. (16) we perceive that to increase L, we should:

(1) Decrease (x), (y), (μ_e) and (μ_0).
(2) Increase (μ) and (λ).

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[7] Indian J. Phys. 7, 307-315 (1932).

[8] The materials listed in Table III are all weakly birefringent.

[9] W. M. Hampton, *J. Soc. Glass Tech.* 16, 401 (1932).

The only variables which we can appreciably affect are (x), (y) and (λ).

Variation of (λ) requires shifting the luminescence spectrum, such as by polymorphic transition[10] or by the substitution of Cd for Zn in ZnS : Cu, ZnS : Ag or $2ZnO \cdot SiO_2$: Mn, and is not to be discussed in the present article.

TABLE IV.

PARTICLE DIAMETER	REL. SCATTERING POWERS CONSTANT VOLUME OF PARTICLES	CONSTANT NUMBER OF PARTICLES
0.2×10^{-3} mm	125	1
0.5	690	87
1.0	1730	1730
2.0	3470	35000

Of the two remaining variables, (x) and (y), we have a definite lower limit for (y). This lower limit is the smallest producible crystal of luminescent material which is still capable of appreciable luminescence. It is obvious that, for $2ZnO \cdot SiO_2$: Mn, we should not decrease (y) below $\sim 2(0.000012)$ mm = approximately 0.000024 mm because the entire crystal would then be "dead" as far as luminescence is concerned (since the "dead voltage" penetration (p_0) is approximately 0.000012 mm). It is also obvious that the particle size should be such that the ratio of luminescent volume to nonluminescent volume is efficiently large (10 times or more). Numerically expressed, this volume ratio, for either spheres or cubes, fits the general equation:

$$10[y^3 - (y - 2p_0)^3] \geqq (y - 2p_0)^3 \tag{17}$$

$$y_{\text{min.}} \geqq 64p_0. \tag{18}$$

or:

$64p_0$ for $2ZnO \cdot SiO_2$: Mn is approximately 0.00077 mm or about 3/4 the average particle size as shown in Figure 5. The "dead voltage" value of 700 volts, from which p_0 was calculated, is probably too large since the curve slope (Figure 6) is affected by the secondary emission factor $-K_2 f(V)$ and, furthermore, the cumulative effect of the beam traversing 2–3 particles, each with "dead voltage" layers, should actually reduce the true p_0 per particle to approximately 200 volts, whereupon $p_0 = \sim 0.000001$ mm and $64p_0 = 0.000064$ mm or 1/15 of the particle diameter shown in Figure 5. The inactive thickness p_0 should

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[10] Schleede and Gruhl, Zeits. f. Elektrochem. u. angew. Physik. Chem. 29, 17/18, 411-412 (1923).

increase as y decreases because the relative surface distortion energy of the particles will increase upon volume diminishment. It will be appreciated that means of comminution play an important part in affecting p_0, especially with the less rugged sulphide luminescent materials.

Having established at least the lower practical optimum magnitude for y, we now investigate the optimum screen thickness x. Experimental determinations, Figure 7, established an optimum screen thickness, under the conditions described in connection with Figure 5, of $x = 0.7$ mg $2ZnO \cdot SiO_2 : Mn/cm^2$. The average compact, effective thickness x_e of such a screen is:

$$x_e = (0.0007 \times 10^4)/4.2 = 1.66\mu. \qquad (19)$$

Since the actual material thickness is only 1.66μ and, from Table III, the penetration of a 10,000-volt electron beam is 2.5μ, we have a discrepancy of:

$$2.5\mu - 1.66\mu = 0.84\mu. \qquad (20)$$

Therefore, it would appear that, for an applied potential of 10,000 volts, the electrons are passing entirely through the luminescent screen and bombarding the glass tube wall. However, discounting any error in the data of Table III, it is more likely that the effective accelerating potential (V) on the screen is only 8200–9000 volts ($p = 1.66$–2μ). The higher values are indicated by the finding of Lange and Brasch[11] that CR rays lose most of their energy in approximately 1/3 of the distance to which they can penetrate matter. This viewpoint finds experimental verification in investigating secondary emission processes. The voltage at which secondary emission equilibrium (i.e., when the number of primary electrons equals the number of secondary electrons) takes place on a dielectric powder, placed as shown in Figure 5, is normally lower than the applied voltage and measurements have indicated a difference $-K_2f(V)$ as large as 1500 volts for $V_A = 10{,}000$ volts (Schnabel[12] finds a difference of 2000 volts for $V_A = 8000V$). The value of $-K_2f(V)$ is dependent upon the phosphor and upon V_A; since the secondary emission ratio above about 300 volts decreases as the primary electron penetrations increase. Accurate quantitative measurements of the effective voltage, $V = (V_A - K_2f(V))$, accelerating the electrons to the screen have not been made, but

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[11] Strahlentherapie 51, 119 (1934).

[12] Archiv. f. Elektrotechnik 28, 794 (1934).

the optimum screen thickness x gives us an approximate indirect determination of this quantity since:

$$x \cong p_{(V_A - K_2 f(V))} \tag{21}$$

for a certain beam current density and scanning frequency.

Having determined that optimum screen thickness is dependent upon both beam current density ($I/\pi a^2$) and actual accelerating voltage (V), we next consider the problem of obtaining luminescent materials with very small particle size (y).

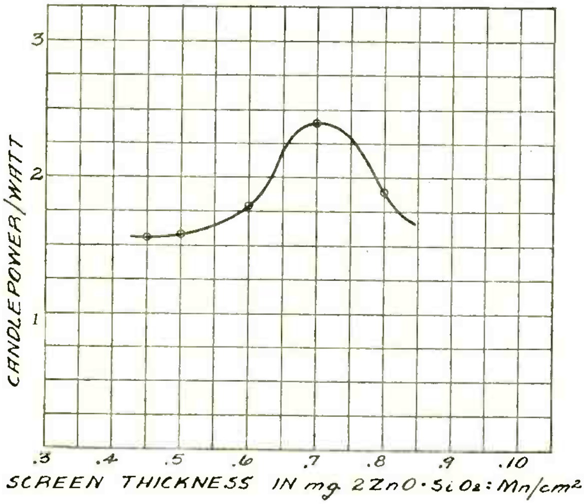

Fig. 7—Experimental determination of optimum screen thickness for a given applied voltage (V_A), beam current (I), and pattern area (S)
$V_A = 10{,}000$ volts. $I = 100 \mu\text{A}$. $S = 6 \times 8\ \text{cm}^2$.

V. COMMINUTION OF LUMINESCENT MATERIALS

Solid, inorganic luminescent materials are very sensitive, complicated latticeworks. Drastic localized actions such as mechanical stress or chemical attack seriously disturb their delicate atomistic mechanisms, reducing their efficiencies as converters of high energy excitation (cathode rays, x-rays, ultraviolate light) into lower energy radiant emission (e.g., visible light). It is usually necessary to reduce the particle size of freshly-synthesized phosphors to about 1/100 of their original diameter (~0.1 mm) in order to obtain particles small enough to adhere to the glass without resorting to a binder. The task of grinding a luminescent material should be accomplished with as little mechanical force as is necessary to split the large crystals into smaller fragments without appreciable reduction of luminescence efficiency or increase of the inactive layers (p_0) per unit volume.

Sulphide phosphors are not only much less chemically stable, but are also less physically stable than oxide phosphors. Schleede and Gantzckow[13] have determined a distinct structural inversion from wurtzite to sphalerite upon grinding zinc sulphide. Sulphide phosphors must, therefore, be used "as synthesized" in order to retain their original good efficiencies and to avoid changing their spectral distributions. Reheating of comminuted sulphides is usually less practicable than making the original particles as small as possible by skillful crystallization, especially with certain beneficial fluxes such as halides of the elements in vertical groups I or II of the periodic system.

Grinding of oxide luminescent materials, such as $2ZnO \cdot SiO_2 : Mn$, $2BeO \cdot SiO_2$, and $CaO \cdot WO_3$ is conveniently possible because of the great stability of oxide compounds.

It has been our practice to comminute synthetic $2ZnO \cdot SiO_2 : Mn$ in a transparent fused quartz ball mill, Figure 8, using small quartz balls. The Moh hardness of $2ZnO \cdot SiO_2 : Mn$ is 5.5 and it was found that Pyrex glass ball mills and balls were rapidly ground away, whereas fused silica (hardness on Moh scale = 7), suffered no apparent scorification. Ball milling has the advantage of tending to produce a uniform particle size in that the smallest particles are washed away from beneath a falling, or preferably sliding, ball leaving the larger particles to be broken.

Suitable fluids for use in the ball mill include many relatively inert organic liquids such as ethers, alcohols, acetates and ketones, as well as distilled water with or without certain easily volatilized electrolytes such as carbon dioxide, ammonium carbonate and ammonium hydroxide.

The ball mill is rotated at such a speed that the balls slide instead of tumbling and the milling is continued until the rate of fall of the particles in the fluid decreases to a value which may be approximately calculated from Stokes' law:

$v_m = (2r^2zg)/9s$,
v_m = rate of fall (cm/sec),
r = radius of falling sphere (assumed) = $\frac{1}{2}y$,
z = density of the sphere (4.218 for $2ZnO \cdot SiO_2 : Mn$), (22)
g = gravitation constant = 981 cm/sec.^{2},
s = coefficient of viscosity of the fluid = 0.002 for ether,

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[13] Zeits. f. Physik 15, 184-189 (1923).

100 to 200-hour grinding in ether yields suspensions such that $v_m = 0.020$ cm/sec. (3 mm in 15 seconds). Substituting $v_m = 0.02$ in Stokes' equation, rearranged to solve for y:

$$y = 6[(sv_m)/(2zg)]^{\frac{1}{2}} \qquad (23)$$

we obtain a value of $y = 0.004$ mm, which is in fair agreement with the microscopically measured average value of $y = 0.001$ mm, even though aggregation, electrostatic charging, nonuniformity and deviation from sphericity have not been taken into consideration. The luminescent material so comminuted may be dried and stored, or made up directly into a suitable spraying or settling suspension.

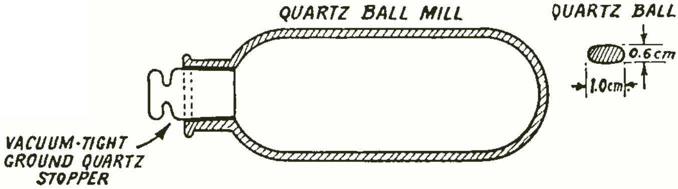

Fig. 8—Section through quartz ball mill used for comminuting luminescent materials.

VI. Screening

Spraying suspensions may be made with many highly volatile organic fluids, with or without easily removable temporary binding ingredients such as nitrocelluloses or acetates. Sprayed screens are entirely practical and economical to prepare, but lack the tenacity and uniformity of the settled screens to be described later. Satisfactory screens may be prepared also by simple "dusting" or settling of the finely divided phosphor powder in the air upon a clean glass or metal surface. Atmospheric conditions and electrostatic charging greatly affect the dusting process and the resultant screens are subject to the same criticisms as sprayed screens.

Screens may be accurately settled in a liquid medium, such as water, which is subsequently poured off the settled screen by means of a machine shown in Figure 9. This screening method has been in use for over six years and allows consistent, controllable production of uniform cathode-ray tube screens which, notwithstanding the complete absence of any binder, may be subjected to the full force of water from a faucet without dislodging the settled particles. The following considerations apply to the settling suspension and method.

(A) Liquid settling suspensions

The ideal settling suspension should contain the luminescent material in separate, nonaggregate particles which may be shaken into homogeneous distribution throughout the liquid and which will then descend under the influence of gravitational force along (except as influenced by Brownian movement) without any local or spatial charges accumulating in the fluid suspension. Furthermore, the settling solution should not strongly react with the phosphor or with the glass or second anode coating in the CR tube.

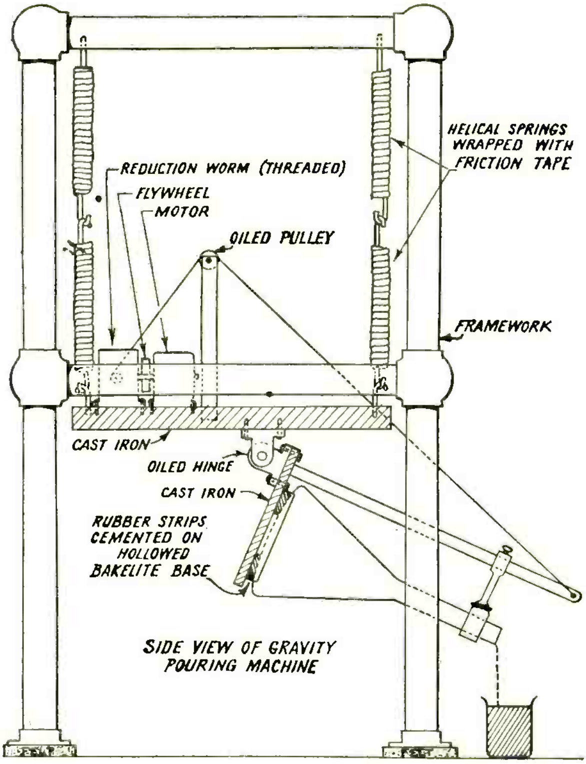

Fig. 9—Section through gravity-pouring machine used for decanting suspension liquid.

It is advisable to use setting liquids of low viscosity (w) and high surface tension (q).[14] Low viscosity decreases the frictional force upon the settled screen during pouring and insures high ionic mobilities for the added electrolytes (explained in the following). High surface tension (q) is desirable in order to have the surface of the liquid as pure as possible and thus decrease "wetting" and other adsorption phenomena during settling and pouring. The relationship between surface tension and surface purity is expressed by Gibb's (1877) equation:

$$a = -\frac{c}{RT} \cdot \frac{d(q)}{d(c)}, \tag{24}$$

$a =$ excess of deficiency of number of moles (of solute) in the unit surface, as compared with,
$c =$ average concentration of the entire solution,
$R =$ the universal gas constant,
$T =$ the absolute temperature.

Therefore, capillary active substances (alcohols, fatty acids and their esters) which lower (q) with increasing concentration ($[d(q)/d(c)] < 0$) are adsorbed in the surface layer[15] ($a > 0$); whereas, capillary inactive substances (most electrolytes and albuminoids) which increase (q) with increasing concentration ($[d(q)/d(c)] > 0$) are negatively adsorbed (thrown out) by the surface layer ($a < 0$).

Gibb's law also shows that high concentration, c, of capillary inactive electrolyte (solute) and low temperature, T, of solution are favorable to the desired purity of the surface liquid.

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[14] Silverman and Roseveare, J. Am. Chem. Soc. 54, 4460 (1932), give an equation relating viscosity and surface tension:

(a) $W = E'/(V_s - V_L) =$ viscosity,
(b) $q = E(D - d)^4 =$ surface tension,
E' and $E =$ constants for a given liquid,
$V_s =$ specific volume,
$V_L =$ limiting volume (or approximately van der Waal's "b"),
$D =$ density of the liquid,
$d =$ density of the vapor.

Neglecting d and equating V_s to $1/p$, we obtain:

(c) $$q^{-1/4} = E_1(1/W) + E_2, \text{ or: } W = \frac{E_1}{\dfrac{1}{4\sqrt{q}} - E_2},$$

where E_1 and E_2 are constants characteristic of the liquid.

The equation holds true for 25 liquids (water included), but deviates as the fluidities of the liquids decrease.

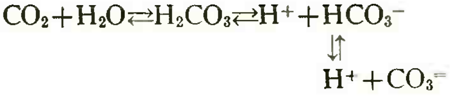
[15] Comptes rendus 194, 1076-1077 (1932).

We have previously mentioned that our present average particle size (y) of the ground $2ZnO \cdot SiO_2 : Mn$ is about 0.001 mm. This small size of particle brings us close to the realm of ordinary pseudocolloids. We must, therefore, observe the physical principles of colloidal phenomena in our settling suspensions. One important empirical law (Coehn, 1898) of colloid physics is:

If a colloidal dispersion consists of two dielectrics, the substance having the greater dielectric constant (ε) charges itself positively (i.e., loses electrons) with respect to the substance of lower dielectric constant.

Note: Water (ϵ) $= 80$; $2ZnO \cdot SiO_2 : Mn (\varepsilon) = \sim 15$.

We had been using very pure, distilled water, $(W) = 0.01005$ (20°C), $(q) = 72.75$ (20°C), for our settling liquid and experienced no serious difficulty in *settling* screens until we decreased our particle size from approximately 270 mesh (0.05 mm) to far less than 400 mesh (0.001 mm), in order to reduce pouring failures. Immediately after the decrease in particle size, we encountered a period of trouble during which the settled screens looked like the force lines traced by a myriad of tiny iron filings in an inhomogeneous magnetic field. Vigorous shaking failed to eliminate streamer-like volumes, approximately 1/16″–1/4″ wide, which were visibly distinguished by having very few suspended particles. The problem of eliminating the charges which were evidently accumulating throughout the solution was first solved by saturating water with carbonic acid evolved from solid carbon dioxide ("dry ice"). Complete saturation yielded excellent results as long as the temperature was low and the dry ice particularly pure and oil-free. The reaction:



$$\begin{array}{l} CO_2 + H_2O \rightleftarrows H_2CO_3 \rightleftarrows H^+ + HCO_3^- \\ \qquad\qquad\qquad\qquad\qquad\qquad\quad \downarrow\uparrow \\ \qquad\qquad\qquad\qquad\qquad\qquad\quad H^+ + CO_3^{=} \end{array}$$

yielded enough high mobility hydrogen ions to discharge the negatively charged phosphor particles as fast as they formed on falling through the solution. Pure water is unable to do this, since the dissociation constant of pure water is only 10^{-14}, whereas the dissociation constant for the first H^+ of carbonic acid is 3×10^{-7}, and for the second H^+ is 6×10^{-11}.

We have discontinued the use of carbonic acid because pure, oil-free, solid carbon dioxide is not commercially obtainable and it is difficult to prevent explosions of saturated carbonic acid solutions in glass-stoppered bottles. In its place we are using ammonium carbonate, (carbamate) $\mathrm{NH_4HCO_3NH_4NH_2CO_3}$, which is even more satisfactory by virtue of its high solubility (thus increasing (q) in Eq. (24)), and high dissociation without the disadvantage of explosive qualities. The aqueous ionic reactions for ammonium carbonate (carbamate) are given below:

$$
\begin{array}{rl}
\mathrm{2NH_4HCO_3NH_4NH_2CO_2+2HOH} \rightleftarrows & \\
& \mathrm{3(NH_4)_2CO_3+H_2CO_3} \\
& \quad \downarrow\uparrow \qquad\qquad \downarrow\uparrow \\
& \mathrm{6(NH_4)^{+}+3CO_3^{=}H^{+}+HCO_3^{-}} \\
& \qquad\qquad\qquad\qquad \downarrow\uparrow \\
& \qquad\qquad\qquad \mathrm{H^{+}+CO_3^{=}}.
\end{array}
$$

Other easily volatilized electrolytes, such as ammonium halides, ammonium acetate, ammonium hydroxide, and weak acids such as acetic acid, have been employed with varying success, but ammonium carbonate has given the best results to date.

Further advantages of the ammonium carbonate solutions are:

1. Many phosphors may be comminuted in a concentrated aqueous solution of ammonium carbonate, and thereupon diluted directly to form the desired concentration of settling suspension. Aggregates formed when ground phosphors are dried from an organic liquid, and which must be dispersed by remilling with very small balls or pure, round (*viz.*, Ottawa) quartz sand, are thereby obviated.

2. The slightly alkaline solution of ammonium carbonate serves a twofold purpose:

(*a*) A very slight surface decomposition of the phosphor particles may be made to occur whereupon the inactive layers (p_0) may be diminished or allowed to recrystallize with lessened localized stresses. This action seems to proceed best in mildly alkaline solutions, but the decomposition may be accomplished also by weak acids.

(*b*) The slight surface chemical action (decomposition and/or hydrolysis) produces an active surface, particularly upon silicate phosphor particles. Such an active surface readily interacts with the siliceous[16] surface of glass and, upon drying and heating, forms an additional bond which may sometimes exceed the normal adhesive forces, which latter are presumably of the van der Waals or field valency type of attraction.

In practice, we make suspensions having phosphor concentrations ranging from 0.002–0.020 gram/ml of water, triple distilled in Pyrex. The ammonium carbonate (carbamate) concentration is made constant with respect to the phosphor concentration and has been found to be most effective in the ratio of 12.5 grams of ammonium carbonate (carbamate) to each gram

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[16] Keram. i. Steklo 7, No. 11-12, 36-41 (1931).

of comminuted phosphor having an average particle size of 0.001 mm.

The suspensions are kept in Pyrex, glass-stoppered bottles, stored in a refrigerator at 2–4°C, and should be agitated at least once a week if not in constant use.

(B) Pouring the settled screen

The pouring process may be conveniently accomplished with a comparatively vibration-free machine such as the one sketched in Figure 9. A small beaker of mercury placed upon the heavy iron pouring platform should show no surface ripples during the pouring operation. The room in which the pouring machine is located should be kept at a reasonably constant cool temperature (10–15°C) in order to assure purity of the surface liquid, minimize Brownian movement and prevent "loading" of the screen in the center or at the edges. The "loading" effect is caused by large changes or differences of temperature between the original suspension and the air outside of the tube. Such large differences cause convection currents at the inner glass surface and seriously interfere with normal settling. A small, controlled room temperature decrease during the settling operation may be calibrated to compensate for a variation in suspension height from the center to the outer edge of the screen. The same uniform settling result may be more easily obtained by accurately controlling the initial room- and suspension-temperatures, such that the former is lower than the latter by an amount depending upon the CR blank size and geometry.

An accurately measured volume of well-shaken suspension may be pipetted from the cold "stock" previously described (*A*), diluted and well mixed with distilled water which is kept at a controlled temperature, and poured into the *clean* CR tube blank. The blank is placed in an upright position on the pouring machine (Figure 9) and the suspended particles allowed to settle upon the broad end of the blank. After three to eight hours, depending upon the particle size and suspension height, there should be no Tyndall effect noticeable when a narrow beam of light horizontally traverses the suspension liquid. If the Tyndall effect test is satisfactory, the pouring machine may be turned on and allowed to slowly decant the liquid in 30 to 40 minutes. When the liquid has been poured, the tube may be immediately removed and the screen dried with a current of warm, filtered air.

The resultant screens have the following advantages:

1. There is no waste of luminescent material such as occurs in spraying.
2. The screens are uniform and have a *known* thickness which may be accurately controlled to give optimum luminescence efficiencies for particular beam voltages and beam current densities.
3. No binder is used in applying the phosphor particles, yet the screens are surprisingly adherent.
4. The slightly acid or alkaline settling suspension may be used to reduce "dead voltage (V_0)" by decreasing the thickness (p_0) of the "dead" outer layers of the phosphor particles.

In conclusion, the writer acknowledges excellent experimental assistance afforded by Mr. H. W. Rhoades and the generous advice and encouragement given by Dr. V. K. Zworykin, Director of Electronic Research.

ELECTRON OPTICS OF AN IMAGE TUBE

By

G. A. Morton and E. G. Ramberg

RCA Manufacturing Company, Inc., Camden, N. J.

(I). Introduction: Description of fixed-focus and variable-focus electrostatic image tube; scope of paper. (II). Focusing properties: Measurement of the variation of image distances and magnification with object distance and ratio of applied voltages for both types of tubes; calculation of potential distributions and electron paths; comparison of experimental and theoretical results. (III). Aberrations: Classification of aberrations; measurement of tangential and sagittal image surfaces for fixed-focus tube; calculation of axial (chromatic and spherical) aberrations; calculation of field aberrations; comparison between measurements and calculation; reduction of field aberrations by curving the cathode.

I. Introduction

In a recent paper, Drs. Zworykin and Morton[1] have described several electron optical systems for producing, on a fluorescent screen, slightly magnified or unmagnified images of extended objects, such as photosensitive surfaces on which light images are projected. The combination of such a photocathode, a suitable electron lens system and a fluorescent screen for observing the electron image, we shall call an "image tube." In the image tubes considered in the paper referred to above, the focusing of the electrons was accomplished by purely electrostatic means. The simplest ("fixed-focus") type of tube (Figure 1, a) consisted of two narrowly separated cylinders of equal diameter at cathode and screen potential, respectively, the juncture of the two being described as the "lens." By replacing the cathode cylinder by a system of rings at uniformly increasing or decreasing potential (Figure 1, b) simulating a resistive cylinder between whose ends a voltage is applied, it was found possible to obtain exact focusing for a given object and image distance by varying the ratio of the voltages applied across the system of rings (V_2) and that between the anode and cathode (V_1). Finally, it was found that, in either case, giving the cath-

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[1] V. K. Zworykin and G. A. Morton, J. Opt. Soc. Am. 26, 181 (1936).

Reprinted from *Physics*, December, 1936.

ode a curvature such that its center of curvature falls into the lens (Figure 1, c), greatly improves the quality of the image, especially in the peripheral portions.

In the present paper, a more detailed experimental and theoretical study of the focusing properties and image defects of the above image, tubes will be presented. It is hoped that such a study may help to outline the scope of these image tubes by pointing out the natural limits imposed by the focusing characteristics and aberrations, and suggesting in what directions future improvements must be sought.

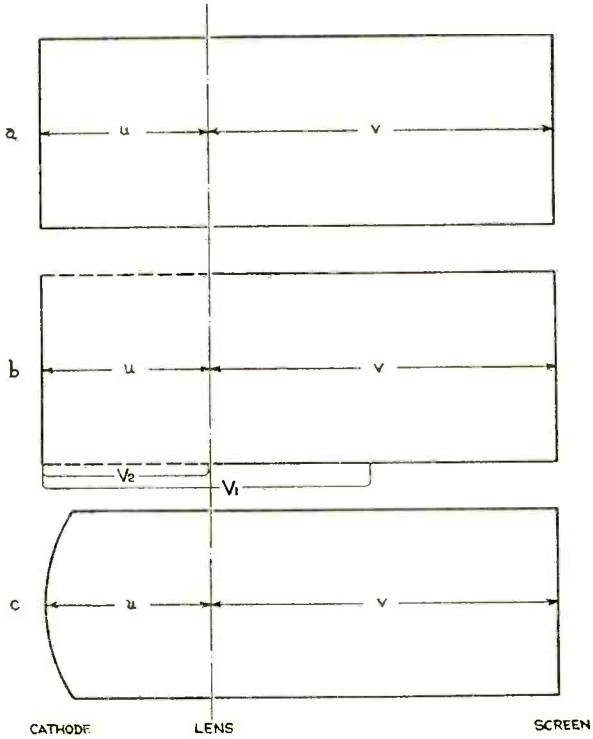

Fig. 1—Schematic diagram of image tubes.

II. Focusing Properties

In order to measure the variation of image distance v with object distance u, both measured from the "lens," in the fixed-focus type of tube, the tube shown in Figure 2 was constructed. The cathode and screen are movable and can be shifted by tilting the tube. Catches are provided which hold the cathode in place when the tube is tilted in one position, and the screen in place when it is rotated above its axis through 180°. This allows the two elements to be moved independently. The lens-to-image distance v, for which the center of the image appeared sharp, as well as the corresponding magnification m, were measured for a set of cathode-to-lens distances u.

Figure 3 shows a corresponding modification of the focusing ring type tube shown in Figure 1, b. Here, the screen is made movable, and the cathode fixed at a distance of 1.8 lens radii from the lens, the image distance and magnification being measured for different values of V_2/V_1, the ratio of the voltage applied between the cathode and outermost ring, and that applied between the cathode and anode.

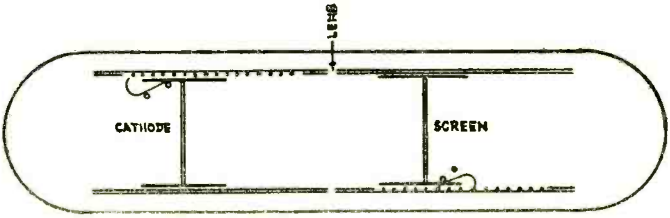

Fig. 2—Experimental tube with movable cathode and screen.

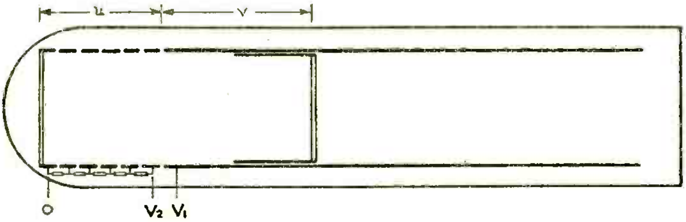

Fig. 3—Variable focus tube with movable screen.

To obtain similar information by calculation, it is necessary first to find the variation of the refractive index n, of the medium, which is conveniently given by the square root of the potential, if we choose the latter to be zero at points where the velocity of the electrons vanishes (e.g., at the cathode if we neglect the initial velocities).[2] Then, with the aid of Fermat's law,

$$\delta \int n ds — 0, \qquad (1)$$

ds being an element of path of the ray considered, and the variation applying to paths with fixed endpoints, the paths actually

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[2] See e.g., E. Brüche and O. Scherzer, *Geometrische Elektronenoptik* (Springer, 1934), p. 3.

taken by electrons emitted from the cathode and, hence, the position and magnification of the image can be determined.

The variation of potential within the tube is governed by Laplace's equation and conditions imposed at the boundaries, i.e., the potentials applied to the cylinders and the cathode. We shall, for convenience, imagine the anode cylinder to be extended to infinity. This introduces no appreciable error, as electrons which have entered the anode cylinder, owing to their high velocities, are but slightly affected by any "end-effects," including among these the presence of the fluorescent screen.

Cylindrical coordinates, with their origin at the center of the cathode, are most convenient. z will denote the distance from this point along the axis of symmetry, and r the separation of any point from this same axis. The radius of the focusing cylinders ("lens radius") will be taken as unit of length. The substitution

$$\chi(r, z) = F(z) \cdot G(r) \tag{2}$$

in Laplace's equation

$$\nabla^2 \chi = 0 \tag{3}$$

reduces its solution to that of the two ordinary differential equations.

$$(1/F)\,(d^2F/dz^2) = -k^2, \tag{4a}$$

$$(1/rG)\,(d/dr)\,(r dG/dr) = k^2, \tag{4b}$$

k^2 being a separation parameter, with the general solutions

$$F = ae^{ikz} + be^{-ikz}, \tag{5a}$$

$$G = cJ_0(ikr) + dN_0(ikr). \tag{5b}$$

The solution for the potential must have the form of a linear combination of products of such functions with the same value of k, which may be any value in the complex plane. The requirement that the potential remain finite as $z \rightarrow \infty$, eliminates terms with complex k. Furthermore, the condition that it be finite on the axis, eliminates those containing the Neumann function N_0. Finally the fact that the potential vanishes (in the case of the flat cathode) all over the cathode plane, limits the trigonometric functions to be considered to sines. The solution for the potential thus becomes

$$\varphi(r, z) = \int_0^\infty b_k J_0(ikr) \sin kz dk. \qquad (6)$$

The coefficient b_k can be evaluated by substituting the values of $\varphi(r, z)$ for $r=1$ by the usual methods used for evaluating Fourier coefficients. For the fixed-focus tube, assuming the gap between the cathode and anode cylinders to be negligible, the potential along the axis becomes

$$\Phi(z) = \varphi(0, z) = \frac{2}{\pi}\int_0^\infty V_1 \frac{\cos ku}{k} \frac{\sin kz}{J_0(ik)} dk, \qquad (7)$$

the first two derivatives being given correspondingly by

$$\Phi'(z) = \frac{2}{\pi}\int_0^\infty V_1 \cos ku \frac{\cos kz}{J_0(ik)} dk, \qquad (7')$$

$$\Phi''(z) = \frac{-2}{\pi}\int_0^\infty V_1 k \cos ku \frac{\sin kz}{J_0(ik)} dk. \qquad (7'')$$

Figure 4 shows the axial potential distribution of the fixed-focus type of tube with $u=1.8$, together with its first four derivatives.

Similarly, for the focusing ring type tube, replacing the set of rings by a cylinder of uniformly increasing or decreasing potential, the result for the potential along the axis is

$$\Phi(z) = \frac{2}{\pi}\int_0^\infty \left(\frac{V_2}{u} \frac{\sin ku}{k^2} + (V_1 - V_2) \frac{\cos ku}{k} \right) \frac{\sin kz}{J_0(ik)} dk. \qquad (8)$$

For any given object distance u, it is thus possible, by numerical or graphical quadrature of the above integrals, to find the potential along the axis for different values of z. Furthermore, the potential off the axis is given in terms of the axial potential and its derivatives by the relation[3]

$$\varphi(r,z)=\Phi(z)-\frac{r^2}{4}\Phi''(z)+\frac{r^4}{64}\Phi^{\mathrm{IV}}(z)-\cdots. \quad (9)$$

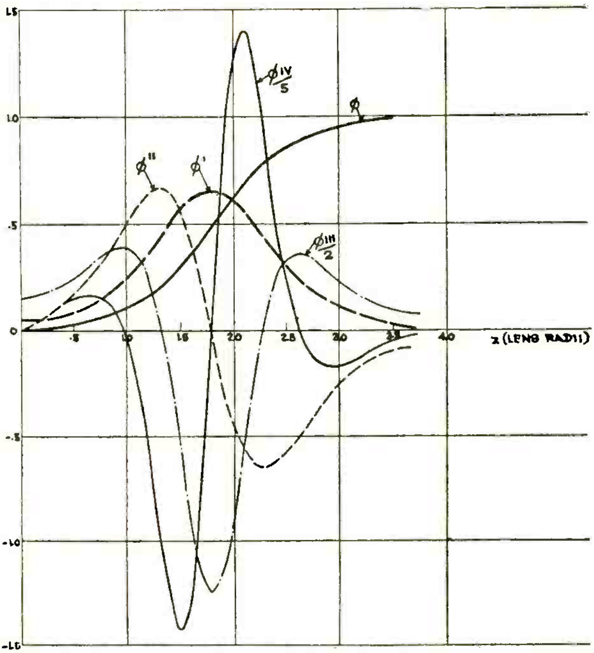

Fig. 4—Axial potential for fixed-focus tube and its first four derivatives.

Replacing, temporarily, the cylindrical coordinates r, ϑ by Cartesian coordinates x, y $(r^2=x^2+y^2)$, Fermat's law can be written

$$\delta\int F(x,y,x',y',z)dz=\delta\int\{\varphi(x,y,z)$$
$$\times[x'^2+y'^2+1]\}^{\frac{1}{2}}dz=0, \quad (10)$$

where a prime denotes differentiation with respect to z. The corresponding Euler equations for the electron paths,

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[3] Reference 2, p. 66, Eq. (16).

$$(d/dz)F_{x'}-F_x=0, \tag{11a}$$

$$(d/dz)F_{y'}-F_y=0, \tag{11b}$$

thus become

$$x''=\frac{x'y'y''}{1+y'^2}-\frac{1}{2\varphi}x'\left(1+\frac{x'^2}{1+y'^2}\right) \tag{12a}$$
$$\times\left(\frac{\partial\varphi}{\partial r}\left[\frac{x'x+y'y}{r}\right]+\frac{\partial\varphi}{\partial z}\right)+\frac{(1+x'^2+y'^2)^2}{1+y'^2}\frac{x}{r}\frac{1}{2\varphi}\frac{\partial\varphi}{\partial r},$$

$$y''=\frac{x'y'x''}{1+x'^2}-\frac{1}{2\varphi}y'\left(1+\frac{y'^2}{1+x'^2}\right) \tag{12b}$$
$$\times\left(\frac{\partial\varphi}{\partial r}\left[\frac{x'x+y'y}{r}\right]+\frac{\partial\varphi}{\partial z}\right)+\left(\frac{1+x'^2+y'^2}{1+x'^2}\right)^2\frac{y}{r}\frac{1}{2\varphi}\frac{\partial\varphi}{\partial r}$$

When the rays considered are in meridian planes only, attention may be confined to the first of these equations, and x may be replaced throughout by r, y being set equal to zero. If, finally, the expression (9) is substituted for φ we may drop, for "paraxial rays," i.e., such that deviate infinitesimally from the axis of the system, all terms involving higher powers than the first of r and r' yielding:

$$r''=-(\Phi'/2\Phi)r'-(\Phi''/4\Phi)r. \tag{13}$$

If the radial distance from the center of the cathode to the starting point of an electron ray, $r(0)$, and its initial slope, $r'(0)$, are given, this equation, by a process of numerical integration, enables us to find the distance of the ray from the axis, $r(z)$, for any value of z.

To locate the image position, we shall consider the path of an electron leaving the center of the cathode with an infinitesimal initial radial velocity. The determination of the path is simplified by introducing, as dependent variable.

$$b=1/2z-1/r(dr/dz). \tag{14}$$

which reduces Eq. (13) to a first-order equation. The term $-(dr/dz)/r$ is the convergence of the ray at the point z, i.e., the reciprocal of the segment of the axis measured from the abscissa of the point considered to the intersection with the tangent to the ray; $-1/2z$, on the other hand, is the initial convergence of the ray, which describes a parabola of the form $r^2 = pz$ ($p = a$ constant) in the uniform field immediately in front of the cathode. The convergence variable, b, is thus chosen so as to vanish for $z = 0$, where the convergence itself becomes negatively infinite.

Substituting (14) in (13), the equation governing b becomes

$$\frac{db}{dz} = b^2 - b\left(\frac{1}{z} + \frac{\Phi'}{2\Phi}\right) + \frac{\Phi''}{4\Phi} + \frac{1}{2z}\left(\frac{\Phi'}{2\Phi} - \frac{1}{2z}\right). \quad (15)$$

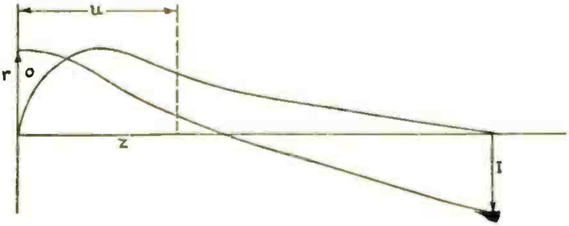

Fig. 5—Electron paths.

This equation, again, cannot be integrated analytically but must be evaluated numerically. The value of b is determined, by a step-by-step process of integration, for some particular value of z, far enough to the right of the lens so that the ray path is essentially a straight line. From the convergence of the ray at this point the image position is located.

To determine the magnification, as illustrated in Figure 5, the point of intersection of the image plane, as determined above, and the path of an electron leaving the cathode, with zero initial velocity, at a radial distance "O" from the center of the cathode, is located. The radial distance "I" of this intersection, divided by the distance "O," gives the magnification. To calculate this path Eq. (13) must be used.

A comparison of the results of the measurements and calculations for the fixed and variable focus type tubes is given by Figures 6 to 9. The relatively large deviations for very small image distances, v, may be ascribed to the interference of the screen with the field distribution within the lens. The closeness with which the magnification is given by $v/2u$ is striking for both types of tubes.

3. ABERRATIONS

The aberrations which detract from the quality of the electron image observed on the fluorescent screen can conveniently be separated into two classes; axial aberrations and field aberrations. The former, chromatic and spherical aberration in the customary nomenclature, affect the quality of the image on the axis, as well as in other parts of the field, while the latter, in first line astigmatism and curvature of field, become noticeable only in the outer portions of the image. It will be seen that these constitute the most serious defects of the systems here studied.

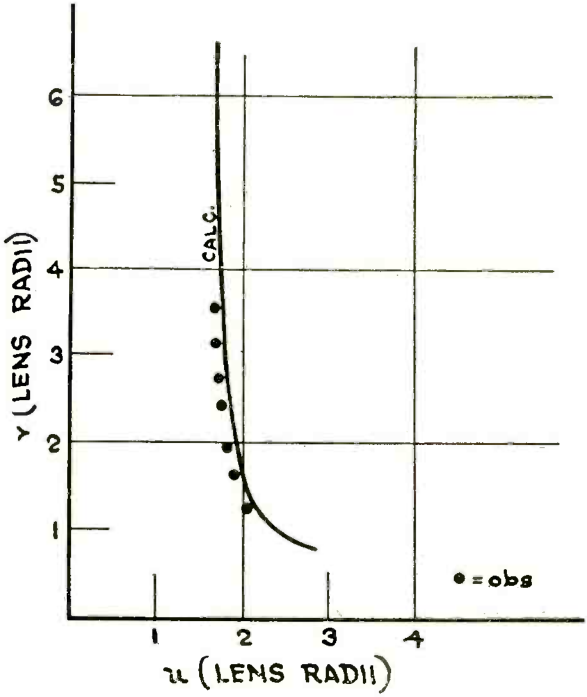

Fig. 6—Focusing relation (fixed focus).

An experimental investigation of all the image defects of electron optical systems has been carried out for a point source by Diels and Knoll,[4] to demonstrate their identity with the aberrations encountered in light optics. H. Johannson[5] has made

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[4] K. Diels and M. Knoll, Zeits. f. Tech. Physik 16, 617 (1935).

[5] H. Johannson, Ann. d. Physik 18, 385 (1933); 21, 274 (1934).

a special study of the aberrations of the electron microscope. On the theoretical side, Glaser[6] has developed the theory of electron optical aberrations very completely, though not in a form in which it is directly applicable to our case, where the electrons enter the refracting field with infinitesimal velocities. Henneberg and Recknagel[7] have, making suitable simplifying assumptions, given a theoretical treatment of the chromatic (and spherical) aberrations of various types of image tubes.

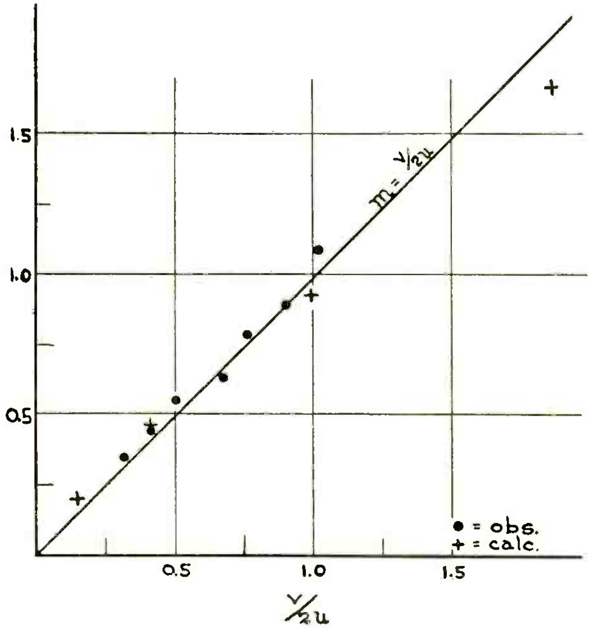

Fig. 7—Magnification (fixed focus)

It was not practical, in the present case, to carry out measurements of the axial aberrations, as these are not of sufficient magnitude to be readily determined except for so low accelerating voltages that no bright images could be obtained on the screen. For the measurement of the field aberrations, curvature and astigmatism, the procedure was the following. In the tube of Figure 2 the object distance was kept fixed at the value $u = 1.8$ and pictures were taken of the image on the fluorescent screen at various distances from the lens; such a series of photo-

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[6] W. Glaser, Zeits. f. Physik 80, 451; 81, 647; 83, 104 (1933); 97, 177 (1935); Ann. d. Physik 18, 557 (1933).

[7] W. Henneberg and A. Recknagel, Zeits. f. Tech. Physik 16, 230 (1935).

graphs is shown in Figure 10. The object consisted of a grid of fine vertical lines superposed on an array of black squares. The point along a vertical line through the optical axis of the system at which the fine lines appear sharpest, indicates the location of a sagittal, that along a horizontal line through the axis where they appear sharpest, that of a tangenital image point, just as in ordinary optics. Having located the sagittal and tangential image points in every plane, it is possible to construct also the sagittal and tangential image surfaces.

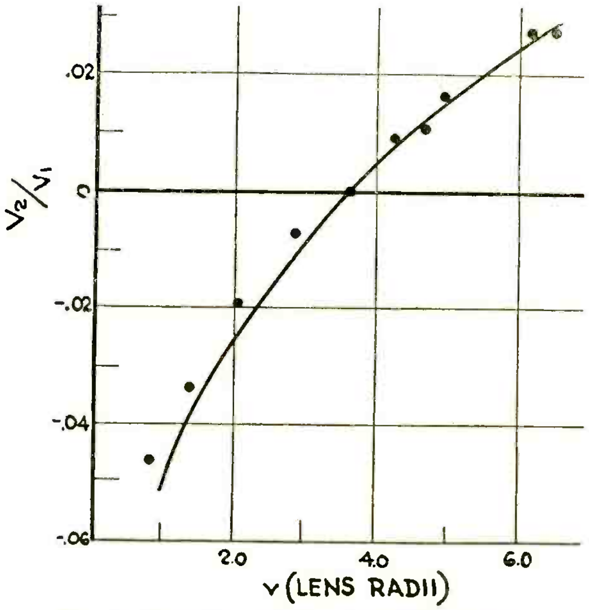


Fig. 8—Focusing relation (variable focus).

In order to calculate the axial aberrations, we consider pencils of rays leaving the center of the cathode with a fixed initial kinetic energy $e\Delta\Phi$ under different angles, e.g., 0°, 45° and 90°, and find their points of convergence on the axis.

To treat the first case, $\Theta = 0$, we replace Φ in Eq. (13) by $\Phi + \Delta\Phi$ and then introduce as new dependent variable (which vanishes for $z = 0$):

$$b = \frac{1}{2\left(\left[z + \frac{\Delta\Phi}{\Phi'(0)}\right] - \left[\frac{\Delta\Phi}{\Phi'(0)}\left[z + \frac{\Delta\Phi}{\Phi'(0)}\right]\right]^{\frac{1}{2}}\right)} - \frac{1}{r}\frac{dr}{dz}. \tag{16}$$

If b_0 is a solution of Eq. (15) corresponding to the case of zero initial velocity and $\triangle b = b - b_0$ is small up to the point where ray paths become substantially straight $(z = z_1)$, we can write for $\triangle b(z_1)$:

$$\Delta b(z_1) = \int_0^{z_1} B(z') \exp\left(\int_{z'}^{z_1} A(z'')dz''\right)dz', \qquad (17)$$

where $$A = -(1/z + \Phi/2\Phi) + 2b_0, \qquad (18)$$

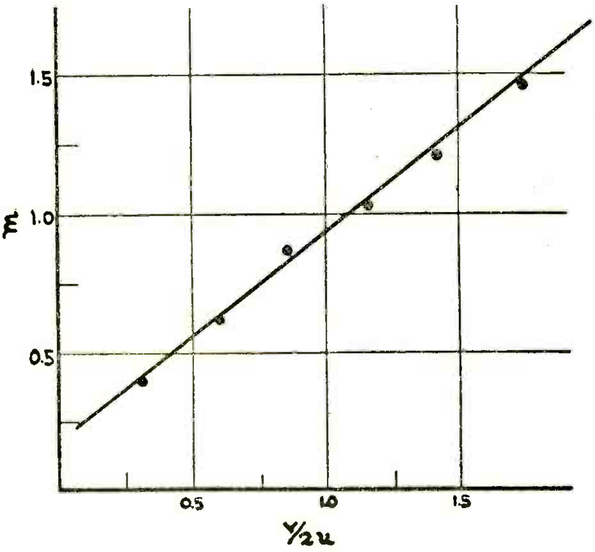
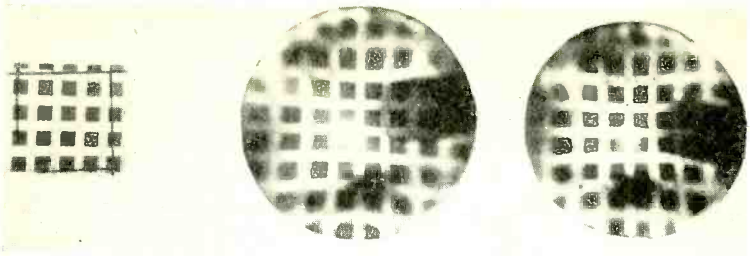


Fig. 9—Magnification (variable focus).

$$B = \frac{\Delta\Phi}{\Phi}\left(b_0{}^2 - \frac{db_0}{dz} - \frac{b_0}{z} - \frac{1}{4z^2}\right) - \frac{1}{4z^2}\left(\frac{\Delta\Phi}{\Phi'(0)z}\right)^{\frac{1}{2}}$$
$$\times\left(1 - \left(\frac{\Delta\Phi}{\Phi'(0)z}\right)^{\frac{1}{2}}\right) - \frac{b_0}{z}\left(\frac{\Delta\Phi}{\Phi'(0)z}\right)^{\frac{1}{2}}$$
$$+ \frac{\Phi'}{4z\Phi}\left(\frac{\Delta\Phi}{\Phi'(0)}\right)^{\frac{1}{2}}$$

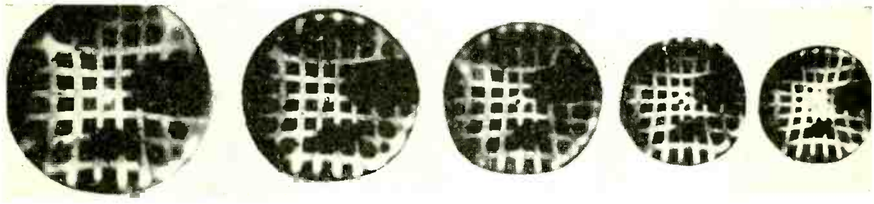
To find the solutions for rays with finite initial lateral velocity components, we introduce the variable $\triangle r = r - r_0$ where r_0 is



Object: $u = 1.7R$ Image: $v = 3.46\mathrm{R}$ $v = 3.33\mathrm{R}$

$R = 1.5''$

Fig. 10a.



$v = 2.96\mathrm{R}$ $v = 2.51\mathrm{R}$ $v = 2.18\mathrm{R}$ $v = 1.80\mathrm{R}$ $v = 1.57\mathrm{R}$

Fig. 10b.

Fig. 10—Sections through image space of flat cathode tube for various distances from lens v.

the solution of the paraxial Eq. (13) for an equal initial lateral velocity and integrate the equation

$$\begin{aligned}\Delta r'' = &-\frac{\Phi''}{4(\Phi+\Delta\Phi)}\Delta r - \frac{\Phi'}{2(\Phi+\Delta\Phi)}\Delta r' \\ &- r_0\frac{\Phi''}{4(\Phi+\Delta\Phi)}\left[r_0^2\left(\frac{\Phi''}{4(\Phi+\Delta\Phi)} - \frac{\Phi_{\mathrm{IV}}}{8\Phi''}\right) + 2r_0'^2\right] \\ &- r_0'\frac{\Phi'}{2(\Phi+\Delta\Phi)}\left[r_0^2\left(\frac{\Phi''}{4(\Phi+\Delta\Phi)} - \frac{\Phi'''}{4\Phi'}\right)\right. \\ &\qquad\left. - r_0 r_0'\frac{\Phi''}{2\Phi'} + r_0'^2\right] - r_0''\frac{\Delta\Phi}{\Phi+\Delta\Phi}. \qquad (19)\end{aligned}$$

This is obtained from Eq. (12a) if terms involving third powers of r and r' are retained. The proper initial conditions follow in every case from the form of the parabolic path described by the electron in the uniform accelerating field immediately in front of the cathode.

For the case of the fixed-focus tube with unity magnification and with $\triangle\Phi/V_1 = 0.0001$ (e.g., $\triangle\Phi = 0.4$ volt, $V_1 = 4000$ volts), the axial deviations from the focal point corresponding to infinitesimal initial velocities are found to be 0.44, 0.24, and -0.03 lens radii for $\Theta = 0°$, 45°, and 90°, respectively. As the solution of Eq. (13) for our particular case indicates that the vertex angle of a beam, with initial lateral velocity $[2(e/m)\triangle\Phi_r]^{\frac{1}{2}}$, is equal to 2.17 $(\triangle\Phi_r/V_1)^{\frac{1}{2}}$ the diameter $\triangle$ of the circle of least diffusion is found to be about 0.003 lens radii, or 0.004″ (= 0.1 mm), increasing approximately in proportion to the initial energy of the electrons. The formula given by Henneberg and Recknagel[7] yields $\triangle = 2m\triangle\Phi/\Phi'(0) = 0.004$ lens radii or 0.006″ (= 0.15 mm). It is based on considering the image tube field as consisting of a uniform initial field terminated by a short lens. It is seen that the axial aberrations, while not important in the present case, may be of significance when the field before the cathode is reduced (as when a very small image is desired), or in cases when the initial velocities are on the average substantially larger and the accelerating voltage is reduced.

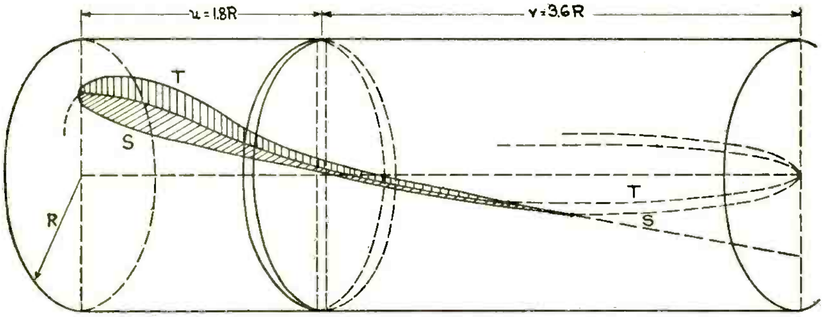


Fig. 11—Schematic diagram of lens structure and sagittal and tangential pencils.

Of greatest importance are, however, the field aberrations, image curvature and astigmatism. To calculate these, the paths of a set of principal rays, corresponding to electrons starting from rest on the cathode at various distances from the axis, must first be obtained by integrating the equation

$$r''=-\frac{r\Phi''}{4\Phi}\left[1+r^2\left(\frac{\Phi''}{4\Phi}-\frac{\Phi_{\mathrm{IV}}}{8\Phi''}\right)+2r'^2\right]$$

$$-\frac{r'\Phi'}{2\Phi}\left[1+r^2\left(\frac{\Phi''}{4\Phi}-\frac{\Phi'''}{4\Phi'}\right)-r\frac{r'\Phi''}{2\Phi'}+r'^2\right], \quad (20)$$

which is found by substituting Eq. (9) in Eq. (12a), retaining terms up to the third power in r and r'. Pencils of rays starting from the same point on the cathode, with infinitesimal lateral velocities, will in general come to a focus only if they lie either in the meridional plane or a plane normal thereto, the focal points being termed the tangential and sagittal image points, respectively. These image points, corresponding to all possible principal rays, form the tangential and sagittal image surfaces which are the object of the calculation. The separation of the two surfaces gives a measure of the astigmatism, their curvature determines the image curvature. Figure 11 illustrates the tangential and sagittal pencils belonging to a particular principal ray, as well as the two image surfaces T and S.

To obtain the tangential image point corresponding to a given principal ray $r_0(z)$, which is a solution of Eq. (20) for $r_0'(0)=0$, we introduce the difference variable $\Delta r=r-r_0$ and, furthermore, the convergence variable

$$b=1/2z-(1/\Delta r)\Delta r', \quad (21)$$

which obeys the equation

$$\frac{db}{dz}=-\frac{1}{4z^2}+\frac{\Phi''}{4\Phi}\left[1+3r_0^2\left(\frac{\Phi''}{4\Phi}-\frac{\Phi_{\mathrm{IV}}}{8\Phi''}\right)\right.$$

$$\left.+2r_0r_0'\left(\frac{\Phi'}{2\Phi}-\frac{\Phi'''}{2\Phi''}\right)+r_0'^2\right]$$

$$+\frac{\Phi'}{2\Phi}\left(\frac{1}{2z}-b\right)\left[1+r_0^2\left(\frac{\Phi''}{4\Phi}-\frac{\Phi'''}{4\Phi'}\right)\right.$$

$$\left.+r_0r_0'\frac{\Phi''}{\Phi'}+3r_0'^2\right]-\frac{b}{z}+b^2. \quad (22)$$

This can be integrated numerically in the same fashion as Eq. (15) giving the tangential image point on the principal ray.

The calculation of the tangential image curvature on the axis can readily be reduced to quadrature if $\triangle b = b - b_0$, where b_0 is the solution of Eq. (15), is introduced in Eq. (22).

To find the sagittal image point, the second Euler equation, (12b), is utilized, considering the displacement y as infinitesimal; then Eq. (12b) becomes

$$y'' = y'\left[\frac{r_0' r_0''}{1+r_0'^2} - \frac{1}{2\varphi}\left(\frac{\partial\varphi}{\partial r} r_0' + \frac{\partial\varphi}{\partial z}\right)\right] + \frac{(1+r_0'^2)}{2\varphi r_0}\frac{\partial\varphi}{\partial r} y. \quad (23)$$

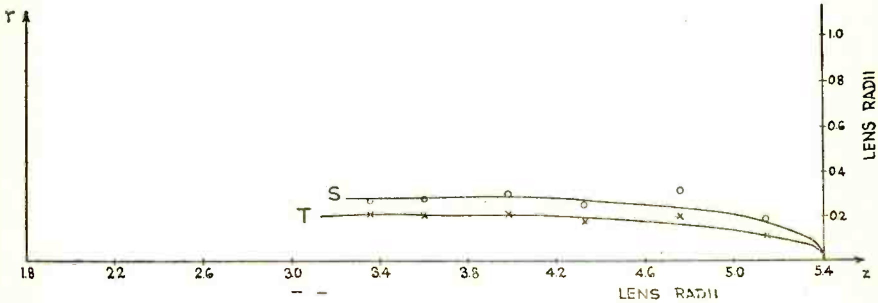


Fig. 12—Curvature of image field. *S*, calculated sagittal image surface; *T*, calculated tangential image surface; o, measured sagittal image points; ×, measured tangential points.

Introducing

$$b = 1/2z - (1/y)y', \quad (24)$$

as well as the expansion of the potential (9), a convergence equation analogous to (22) is obtained:

$$\frac{db}{dz} = -\frac{1}{4z^2} + \frac{\Phi''}{4\Phi}\left[1 + r_0^2\left(\frac{\Phi''}{4\Phi} - \frac{\Phi_{IV}}{8\Phi''}\right) + r_0'^2\right] - \frac{r_0' r_0''}{2z} + \frac{\Phi'}{2\Phi}\left(\frac{1}{2z} - b\right)\left[1 + r_0^2\left(\frac{\Phi''}{4\Phi} - \frac{\Phi'''}{4\Phi'}\right) - r_0 r_0' \frac{\Phi''}{2\Phi'}\right] + b r_0' r_0'' - \frac{b}{z} + b^2. \quad (25)$$

The numerical work and to obtain the sagittal radius of curvature on the axis proceed as in the case of the tangential pencil.

In Figure 12, the measured image points are compared with the calculated image surfaces, computations being made for object points on the cathode separated by 0.2, 0.4 and 0.6 lens radii from the axis, as well as for the radii of curvature on the axis. Vertical and horizontal scales are identical so that the figure gives a true picture of the appearance of the image surfaces. Figure 13 gives the corresponding large diameters of the ellipses of diffusion in the plane of the paraxial image point neglecting axial aberrations. The axial radii of curvature of the tangential and sagittal image surfaces are only 0.044 and 0.075 lens radii, or 1.7 and 2.9 mm, respectively.

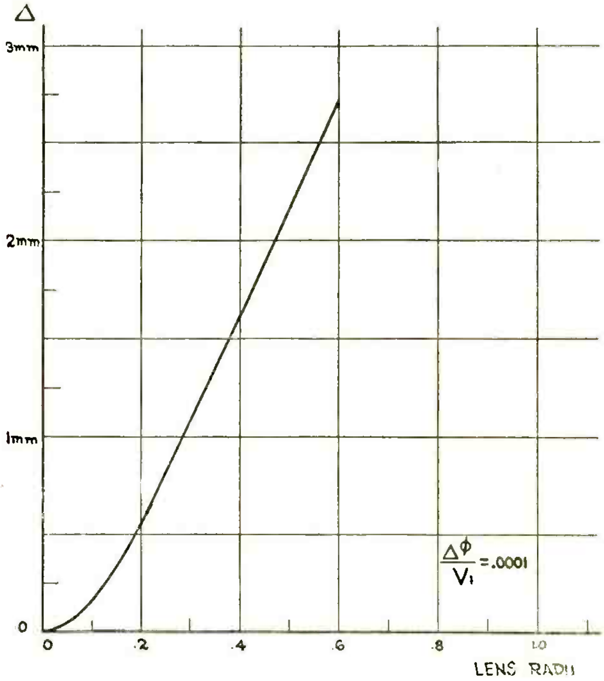
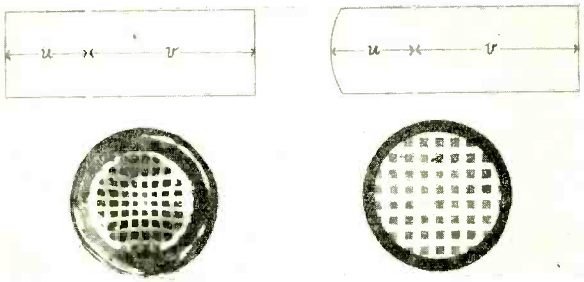


Fig. 13—Large diameter of ellipse of diffusion due to curvature of field as function of radial distance of object point.

It was found, as already reported in the earlier paper,[1] that this very serious defect could be largely removed by giving the cathode a curvature such that its center of curvature fell, approximately, into the center of the lens. The comparison of the images given by the flat and the curved cathode tube, shown in Figure 14, brings this out strikingly. Without, as yet, giving a quantitative treatment of the curved cathode tube, the main reason for the improvement may readily be pointed out. By curving the cathode in the above mentioned fashion, the principal rays are practically undeflected in the first part of their path, and the sagittal and tangential pencils of all the rays encounter practically identical variations of potential. As, due to the low velocities of the electrons in this region, their paths are most easily influenced in the early portion of their transit, it is clear that this must minimize the astigmatism, i.e., the difference between the convergence of the tangential and sagittal rays, and similarly reduce the curvature due to the similar conditions along different principal rays.



Flat Cathode Curved Cathode

Fig. 14—Comparison of images from tubes with flat (left side) and curved (right side) cathodes.

In conclusion, the authors wish to express their thanks to Dr. V. K. Zworykin, the director of the Electronic Research Laboratory, and to the members of the laboratory staff whose cooperation made this work possible.