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a technical journal

RADIO AND ELECTRONICS
RESEARCH • ENGINEERING

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FOREWORD

THE announcement concerning "TECHNICAL ARTICLES BY RCA AUTHORS" which appeared on page 135 of the March 1946 issue has been revised in several details, as follows:

(1) It has been found desirable to limit the listing to technical papers which have actually appeared in printed form in recognized periodicals;

(2) The publication date of RCA REVIEW makes it necessary that each issue contain a list of papers which were published in the *preceding* quarter.

In accordance with the above, the section "TECHNICAL PAPERS BY RCA AUTHORS" commences with this issue and includes a listing of papers published between January 1 and March 31, 1946. *Any requests for copies of the papers listed in this section should be addressed to the periodical concerned.*

All inquiries concerning papers published in RCA REVIEW and any comments or suggestions should be addressed to: Manager, RCA REVIEW, Radio Corporation of America, RCA Laboratories Division, Princeton, N. J.

Manager, RCA REVIEW.

AN EXPERIMENTAL COLOR TELEVISION SYSTEM*

By

R. D. Kell, G. L. Fredendall, A. C. Schroeder, R. C. Webb

Research Department, RCA Laboratories Division,
Princeton, N. J.

Summary—*A description is given of color television apparatus using an image orthicon in the color camera for direct pickup of studio scenes. A sequential three-color semi-mechanical system is used. Provision is made for demonstration of color pictures in three dimensions. The associated sound channel is transmitted on the edge of the picture during a portion of the horizontal blanking period.*

Introduction

LATE in 1945 and early in 1946, a series of demonstrations were given of television in color and of television images in three dimensions, also in color. These demonstrations were conducted to show the status and to point out the problems remaining to be solved before color television could be considered ready for development as a service. The remaining problems are such as to require much additional research and development. However, this article is not concerned with these aspects of the situation but rather with a description of the system and apparatus used during the demonstrations.

Work on broadcast television was interrupted by the war, but advances in electronic and radio techniques during the war period did have a direct influence on television, particularly monochrome television. In order to resume the studies of color television and to evaluate these advances as they applied to television in color, laboratory facilities for research on the various problems involved in the generation, transmission and reception of television images in color together with new studio facilities, new circuits and apparatus were developed and put in operation.

Camera Studio Setting

A small studio set was constructed in the laboratory to make possible small scale productions of colorful program material. The set is shown in Figure 1. Illumination is obtained from an overhead bank of 36 100-watt fluorescent lamps which provide an incident light of about 200 foot-candles. Two auxiliary banks of 24 100-watt lamps

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* Decimal Classification: R583

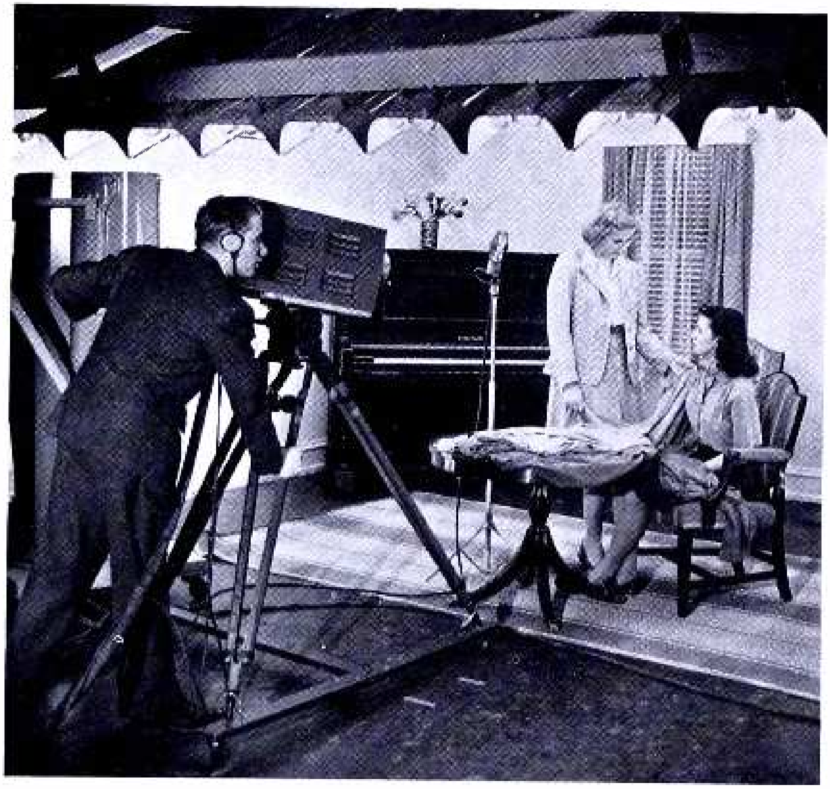

Fig. 1—Camera Studio Set.

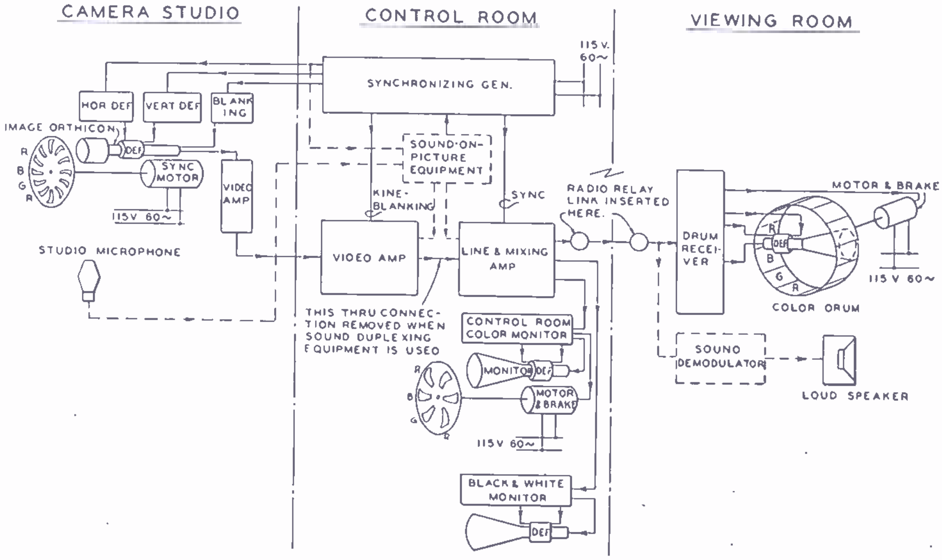

Fig. 2—Block Diagram of Color Television System.

each can be moved about as desired in front of the scene to bring the combined illumination up to more than 400 foot-candles. In order to obtain a more uniform light spectrum, half of the lamps are of the white type and half are of the daylight type. By distributing the lamps uniformly on the 3-phase 60-cycle power supply, no difficulty is experienced due to the lights operating on alternating current power.

CIRCUITS AND APPARATUS

A complete set of experimental equipment was constructed as shown in the block diagram of Figure 2. The system employs the latest and most suitable devices and circuits which have resulted from many years of extensive research in the field of electronic monochrome television. Added to these electronic components are two mechanically rotated tri-color filters so arranged that when the observer is viewing the picture on the kinescope through a red section of the filter in the receiver, for example, the pickup tube is being exposed to the televised scene through a red section of the filter in the camera. Similarly, when the blue and green filter sections, in turn, are in front of the kinescope, the blue and green sections are correspondingly in front of the pickup tube. The red, blue, and green images are repeated frequently enough so that the three are superimposed by the "persistence of vision" of the observer, to create the illusion of a single picture in multiple colors.[1,2,3,4,5]

The operating standards used are: 120 fields per second, 60 frames 2 to 1 interlaced, 525 lines, 40 single-color fields or 20 interlaced full color pictures per second. The color sequence is red, blue, green. With these operating standards, the resolution obtained with the overall system is about 250 lines.

The apparatus is designed so that by slight modification the transmission and reception of color pictures in three dimensions can be demonstrated. For this operating condition, polarizing light filters are incorporated with the rotating color filters at the camera and the kinescope. Special polaroid spectacles are provided for the observers to enable them to separate the right and left images.

During public demonstrations of the color equipment, when it was necessary to transmit the signal to a point several miles away by means of a microwave relay link, it was found convenient to transmit the asso-

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[1] J. H. Hammond, U. S. Patent No. 1,725,710.

[2] R. D. Kell, U. S. Patent No. 1,748,883.

[3] J. L. Baird, British Patent No. 473,323.

[4] P. C. Goldmark, J. N. Dyer, E. R. Piore and J. M. Hollywood, "Color Television, Part I", *Proc. I.R.E.*, Vol. 30, No. 4, pp. 162-182, April, 1942.

[5] CBS Engineers, "Color Television on Ultra High Frequencies", *Electronics*, Vol. 19, No. 4, pp. 109-115, April, 1946.

ciated sound on the same radio carrier as the picture by means of a time division duplexing circuit.[6]

CAMERA

One of the most outstanding new components incorporated in the color system is a special form of the image orthicon.[7] This camera tube is found to have sufficient sensitivity and a sufficiently uniform spectral response to make possible direct pickup of studio and outdoor scenes having an illumination level of from 150 to 300 foot-candles.

Equalization of the sensitivity of the orthicon to the three colors is accomplished by appropriately masking down the aperture on the filter disc for those colors to which the tube is most sensitive, thus reducing the time devoted to storing charges during those particular color fields. Computation of the degree of masking required is based upon measurements of photo-cathode current flowing when the rotating color disc is

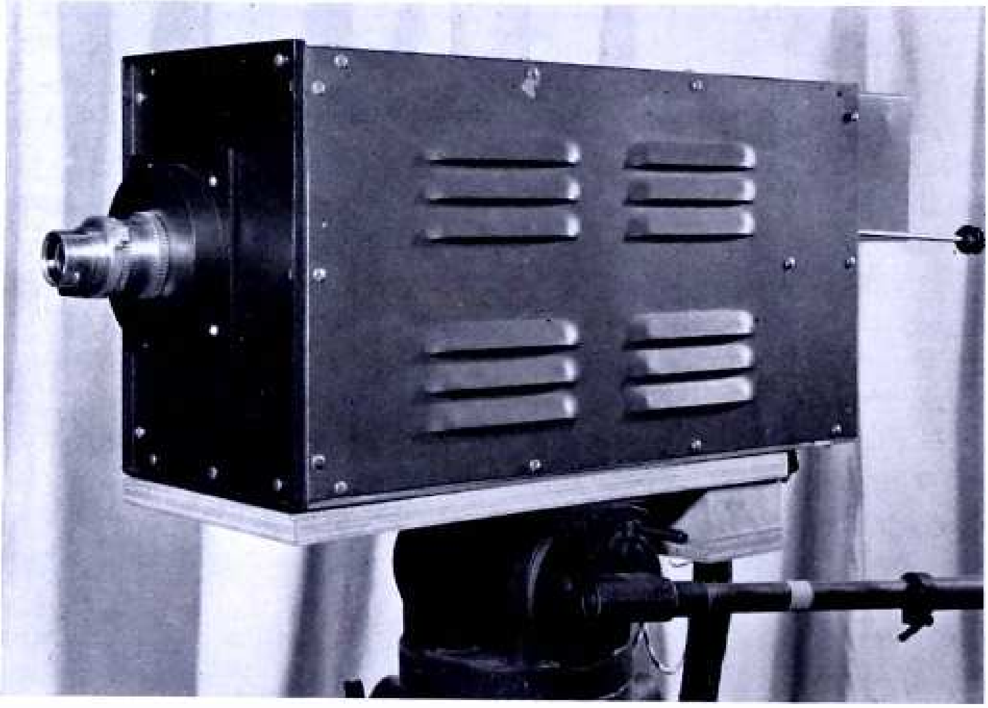

Fig. 3—Experimental Color Camera, Left Side.

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[6] G. L. Fredendall, Kurt Schlesinger, and A. C. Schroeder, "Transmission of Television Sound on the Picture Carrier", *Proc. I.R.E.*, Vol. 34, No. 2, pp. 49-61, Feb., 1946.

[7] Albert Rose and P. K. Weimer, "The Image Orthicon, a Sensitive Television Pickup Tube", presented at the I.R.E. Winter Technical Meeting on January 24, 1946 in New York, N. Y.

temporarily replaced by individual color filters. The subject for this test should be a white surface illuminated by the studio lights. After this first color balance has been obtained with a given camera tube, it is possible to operate the camera in much the same way as a conventional photographic camera. For televising scenes under illumination of different color temperature, the correction is made by the addition of a correcting filter over the lens.

The camera is used with either a 90 millimeter, f:3.5, or a 50 millimeter, f:1.9, Eastman Ektar lens. Both are color corrected. A lens aperture of about f:4.5 is required for the illumination present in the studio.

Side views of the camera are shown in Figures 3 and 4.

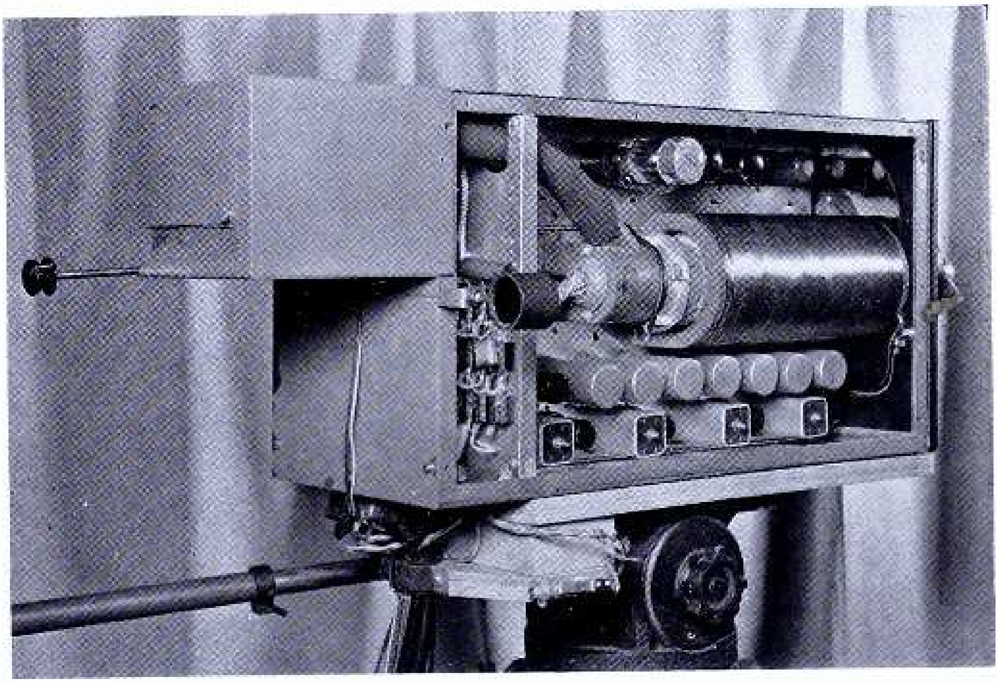

Fig. 4—Experimental Color Camera, Right Side.

The rotary color disc for the camera, Figure 5, is 6⅞ inches in diameter. It has twelve filter sectors clamped with the color balance mask between two plates of glass. The filters used are the conventional Wratten tri-color photographic filters, numbers 25 (red), 47 (blue), and 58 (green). The disc is rotated at 600 revolutions per minute by gearing from a small synchronous motor powered directly from the 60-cycle mains. The phase position of the motor with respect to vertical scanning is adjusted by manually rotating the motor frame. The disc is placed as close as possible to the face of the image orthicon in order to get it near the focal plane of the lens, thus minimizing any optical distortion that may be introduced. Since the image orthicon must operate in a uniform magnetic field of from 60 to 90 gauss, preferably extending beyond the image section of the tube, the focusing coil is made in two sections, with the smaller forward section being mounted in front of the color disc.

A multi-conductor cable connects the camera with the control room equipment which is mounted on racks of the conventional type. All electrical controls are on panels in the control room. The video amplifier and the deflection circuits are located inside the camera. All high voltage and plate supply units are located in the control room.

To overcome the difficulties in the camera and terminal equipment due to 60-cycle hum and crosstalk, special power supplies are required. The heaters of the various tubes in the camera are operated from the laboratory direct current power supply. The heaters of the tubes in the control racks are operated on 120-cycle power obtained by using selenium rectifiers across the output of special 60-cycle filament transformers. All plate voltage supplies are regulated and are operated from a 400-cycle source.

Fig. 5—Camera Color Filter Disc.

The video pre-amplifier used in the camera consists of five stages employing a combination of series and shunt peaking to obtain adequate bandwidth with sufficient gain to raise the signal level to approximately 1 volt peak-to-peak at the sending end of the camera cable.

CONTROL ROOM EQUIPMENT

A view of the control room equipment is shown in Figure 6. Here is located the synchronizing signal generator, the main video amplifier, the sync-mixing and output line amplifiers, the sound-on-picture terminal equipment, a black-and-white picture monitor, and the direct current power supplies with all camera controls. Control of the video signal amplitude is accomplished by a gain control circuit in the main video amplifier.

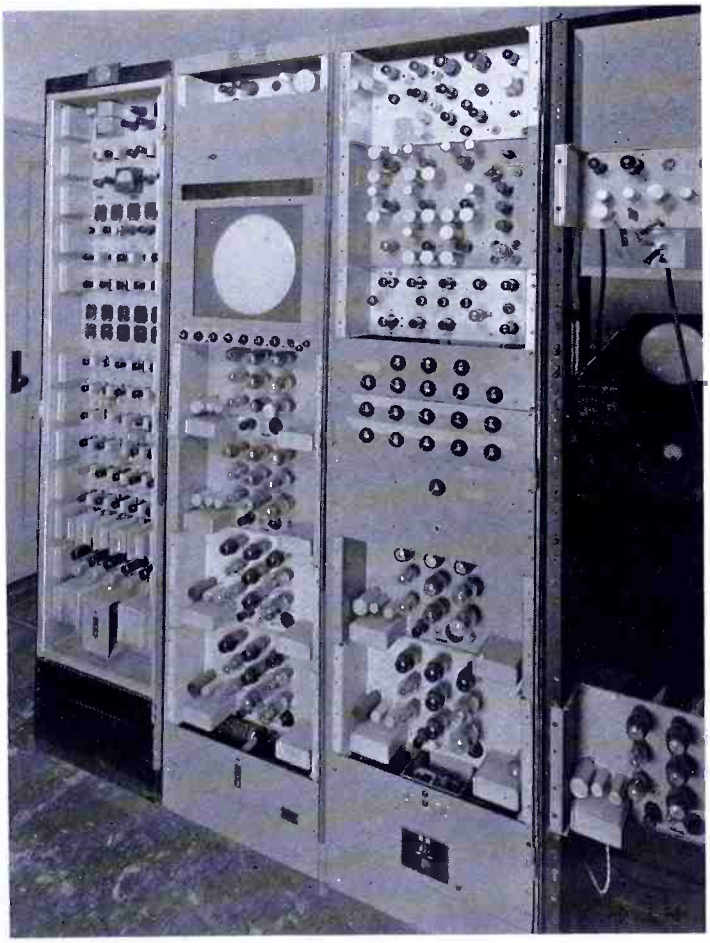

Fig. 6—View of Control Room Racks.

Both the synchronizing signal generator and the video amplifiers are standard black-and-white picture equipment modified to operate on color standards. All of the amplifiers used in the system are equalized to beyond 9 megacycles. This would make possible the same degree of horizontal resolution (at twice the scanning rate) ordinarily obtained with black-and-white standards using a 4.5 megacycle channel, provided the other limitations imposed by the color system did not exist.

CONTROL ROOM COLOR MONITOR

In addition to a standard 12-inch black-and-white monitor which is useful for checking camera focus, color phasing, scanning, etc., there is provided a color monitor using a 9-inch kinescope having an aluminized screen[8] and operating at a second anode voltage of 15 kilovolts. Front and rear views of this unit are shown in Figures 7 and 8. A 21¾″ diameter color disc is used in this receiver carrying six filter sections and rotating at a speed of 1200 revolutions per minute. Power to turn the disc is supplied from a ⅛ horsepower 60-cycle induction motor through a belt and pulley drive. This permits the motor with its disturbing magnetic fields to be located at a considerable distance from the cathode ray tube. Synchronization of the color disc speed with the color field repetition rate is accomplished by a magnetic brake. Proper color frame phasing is obtained by momentarily releasing the brake by manually switching off its controlling current.

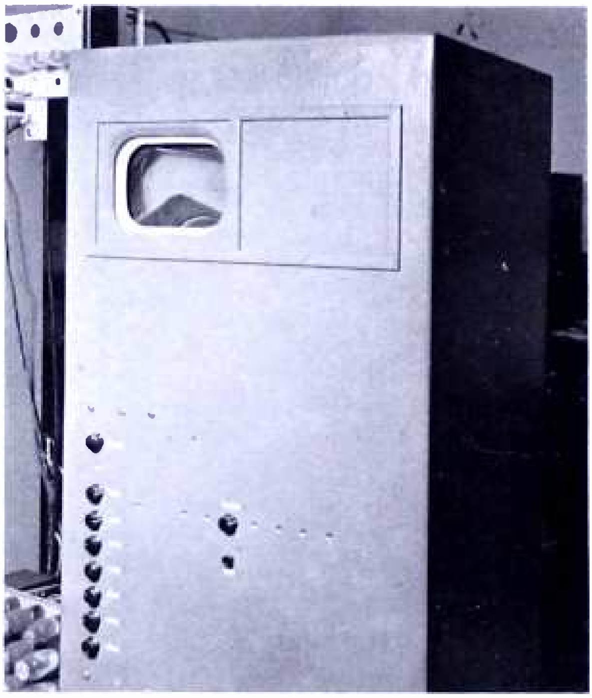

Fig. 7—Color Monitor, Front View.

DRUM COLOR RECEIVER

For best viewing by a large number of observers a demonstration

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[8] D. W. Epstein and L. Pensak, "Improved Cathode-Ray Tubes with Metal-Backed Luminescent Screens", RCA REVIEW, Vol. VII, No. 1, pp. 5-10, March, 1946.

receiver was built using a 12-inch, short persistence, aluminized-screen kinescope operating at a second anode potential of 17 kilovolts. Photographs of this receiver are shown in Figures 9 and 10.

The rotary color filter is in the form of a large drum, one end of which is open to allow the kinescope to be supported inside the drum and at right angles to the axis of the drum by a stationary bracket. The other end of the drum is closed to provide attachment to the drive shaft. The periphery of the drum consists of 12 rectangular red, blue, and green color filter sections clamped in a suitable framework. The drum is rotated at 600 revolutions per minute, in the direction of vertical scanning and in synchronism with the picture field repetition rate. The mechanical drive for the drum is similar to that used for the disc of the control room color monitor.

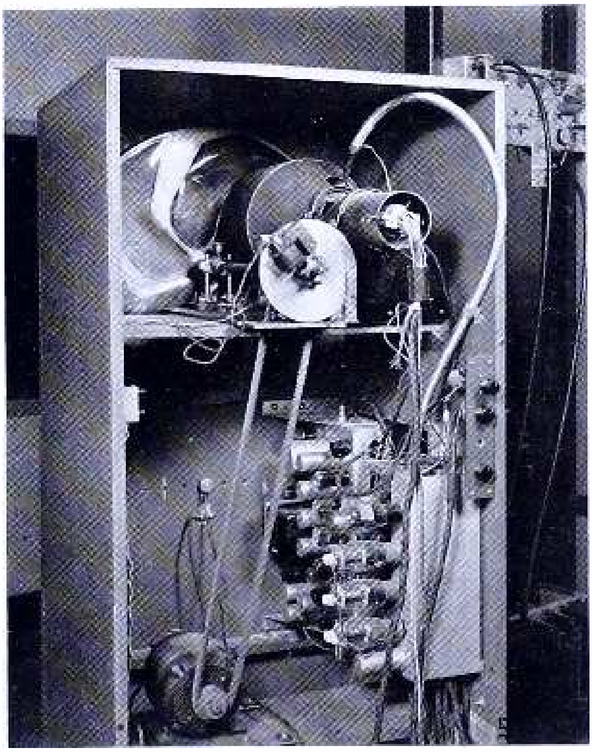

Fig. 8—Color Monitor, Rear View.

To overcome the difficulties due to 60-cycle interference in various components of the receiver, several precautions are taken. The kinescope is placed in a large mu-metal shield to protect it from the magnetic fields of the motor and power transformers. The power supply for the tube plates is obtained from a regulated source. All heater power is obtained from a full-wave selenium rectifier, High voltage for the kinescope accelerating electrodes is obtained from a pulse power supply in which the high voltage pulses developed in an auxiliary winding on the horizontal deflection transformer during the "fly back" time are used in a voltage-quadrupling rectifier to obtain 17 kilovolts at a current of several hundred microamperes. With this high anode voltage and the advantage of the aluminized kinescope screen, a screen brightness of 4.5 foot lamberts is obtained in the highlights of the pictures. Since a light loss of approximately 90 per cent is introduced by the color filters, the actual kinescope brightness is 45 foot lamberts. At present a minimum of 10 foot lamberts is considered satisfactory for monochrome television.

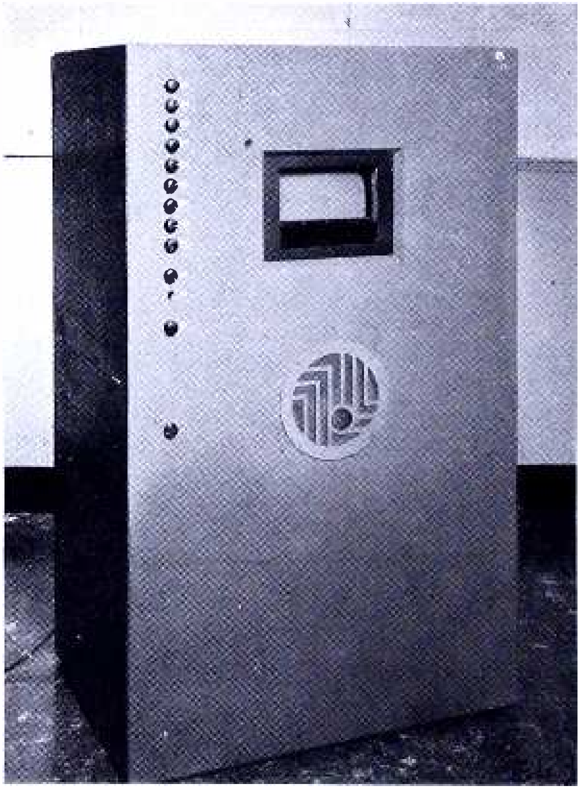

Fig. 9—Drum Receiver, Front View.

TELEVISION PICTURES IN THREE DIMENSIONS

In natural stereoscopic vision the distance to any object (and hence the sense of depth) in the scene is determined by three different properties of the views seen by the eyes. The first is the difference between the two images resulting from the different points of view of the two eyes; the second is the focusing of the individual eyes; and the third is the amount of convergence or toe-in of the two eyes to see a given object in the scene.

In the stereoscopic television system described here, the images intended for the right and left eyes, respectively, are reproduced on the kinescope screen in time sequence. The two images are separated by polarizing the light from them in planes at right angles to one another by means of sheets of polaroid filter material associated with the color filters on the rotating drum of the receiver as described previously. The observer wears a pair of special polaroid glasses, in which the plane of polarization of each lens is set to agree with the plane of polarization of the picture intended for the corresponding eye.

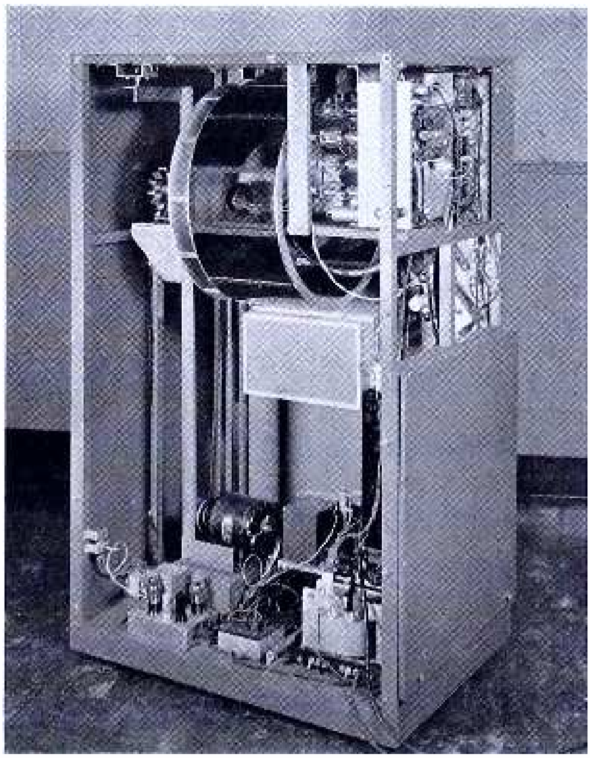

Fig. 10—Drum Receiver, Rear View.

At the camera, a light splitter is mounted in front of the lens. This attachment, shown in Figures 11 and 12, consists of a system of mirrors set at 45 degrees behind each of two windows which are spaced horizontally on centers 3½ inches apart. This spacing is a function of the normal interpupillary distance and the overall magnification of the system both optical and electrical. The factors are related by Rule[9] in the equation—

$$T = wed/sf$$

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[9] John J. Rule, "The Geometry of Stereoscopic Projection", *Jour. Opt. Soc. Amer.*, Vol. 31, No. 4, pp. 325-334, April, 1941.

where w = width of image on photo-cathode of camera; s = width of image on viewing screen; T = lens separation of the camera; e = human interocular distance; f = focal length of camera; d = distance of camera lens to plane of object which is intended to appear coincident with the plane of the viewing screen. Sequential separation of the two images is achieved by means of polaroid filters which are placed over each of the windows so that the light coming from the scene as viewed through the left "eye" is horizontally polarized, while that through the right "eye" is vertically polarized. Selection of the particular image to be transmitted during a given field is made possible by means of additional polaroid filters mounted on the rotating color disc with their planes of transmission arranged in quadrature and in alternate fashion. Thus the vertically polarized image is transmitted during

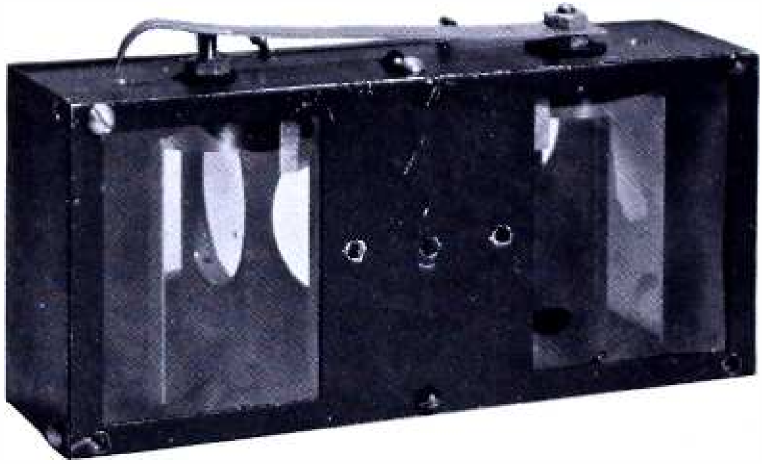

Fig. 11—Stereo Attachment for the Camera (Light Splitter).

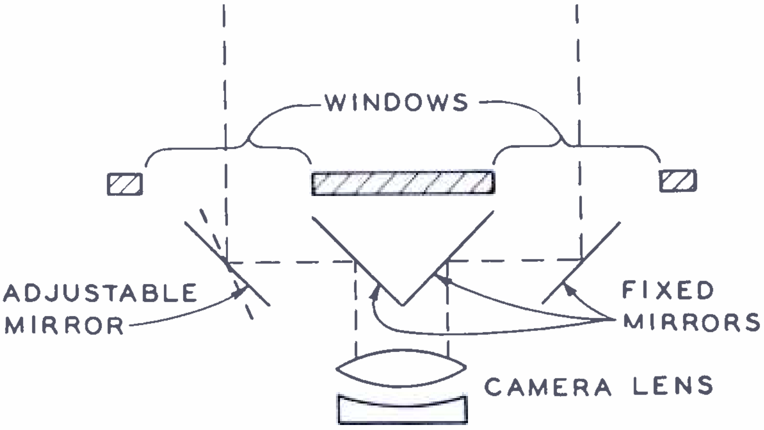

Fig. 12—Light Splitter.

one field and the horizontally polarized image during the next, the unwanted image being suppressed by crossed polarization.

The angular setting of one of the mirrors in the light splitter is adjustable so that the convergence of the camera "eyes" can be set to bring into register some object near the center of the useful depth of field. Observation of this point on the screen of the kinescope corresponds to the situation illustrated in Figure 13(A). In this case the object appears to be in the plane of the viewing screen since the angle of toe-in of the eyes is commensurate with the focal distance. The image of objects farther away from the camera will not fall at the same place on the screen, but will be separated horizontally a small amount, depending upon their position. Thus the horizontally polarized image intended for the left eye is displaced to the left as indicated in Figure 13(B). This condition gives the impression that the object is behind the screen as a result of the angle that the eyes must take in order to obtain fusion of the two images. Conversely, objects nearer to the camera are displaced horizontally in the opposite direction on the screen as shown in Figure 13(C) and thus appear to the observer to be located in front of the screen.

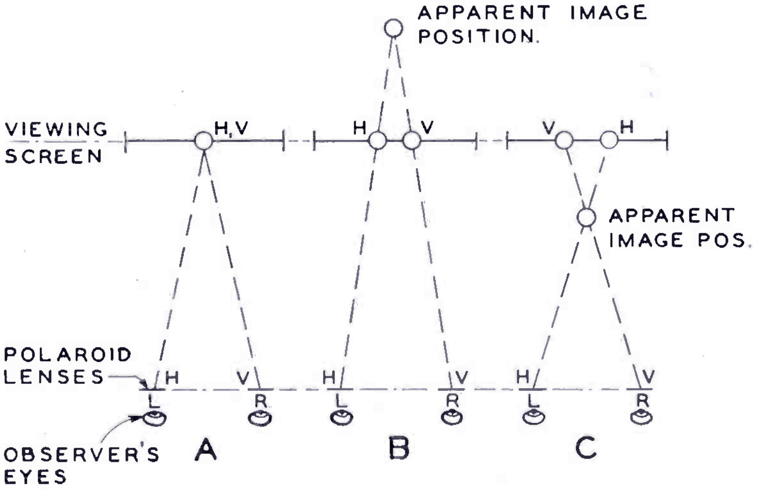

Fig. 13—The Geometry of Stereo Viewing.

The optical adjustments of the system can be made to give orthostereoscopic pictures only for one viewing distance and screen size. When more than one receiver is to be operated from a given camera, and if different amounts of magnification are to be used, some correction for the depth and perspective distortion can be obtained by keying the horizontal positioning circuit field by field thus changing the horizontal displacement of a given object on the screen, and hence its apparent position relative to the observer.

SOUND-ON-PICTURE EQUIPMENT

During certain public demonstrations of the color television apparatus the receiving equipment was in another building several miles from the studio. A microwave relay link operating on a frequency of 10,000 megacycles was employed on these occasions for transmission. The associated sound signal was transmitted on the picture carrier by means of a time division duplexing system.[6]

The essential elements of the sound-on-picture equipment are shown in dotted lines on the diagram of Figure 2. The sound modulator is inserted between the video amplifier and the output line and mixing amplifier and keys a rectangular pulse into the "back porch" of the horizontal blanking. This pulse is of constant amplitude extending down to white level and is adjustable in width in accordance with the audio modulation amplitude. In fact, the variable width modulation system is similar in many respects to the variable area sound track as commonly used for sound motion pictures.

Demodulation of the duplexed sound channel is accomplished at the receiver by means of a synchronized electronic switch which serves to exclude all but the sound carrier pulses. An amplitude limiter removes amplitude noise. This sound system has the basic theoretical limitation that the maximum audio frequency that can be transmitted is one-half the horizontal line scanning rate, or 15,750 cycles for the color system employed. A further minor reduction in the available bandwidth is due to the cutoff characteristic of the low-pass filter which is required to exclude frequencies above 15,750 cycles.

WIDE RANGE LOUDSPEAKER DEVELOPMENTS*

By

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Princeton, N. J.

Summary—Two unit direct-radiator loudspeakers may be constructed in many different ways. In order to determine some of the characteristics, a number of experimental designs were built and tested. As a result of these experiments, it appeared that the duo-cone loudspeaker, consisting of two coaxial, congruent, separately driven cones, possessed many constructional, theoretical and experimental advantages. Consequently, a detailed theoretical and experimental investigation of the due-cone loudspeaker was carried out to determine the optimum values for the constants of the system from the standpoint of the following characteristics; pressure response, directional pattern, distortion and transient response. The results of these investigations are included.

Introduction

THE almost universal use of the direct-radiator loudspeaker is due to its simplicity of construction, small space requirements and the relatively uniform response frequency characteristic. Uniform response over a moderate frequency band may be obtained with any simple direct-radiator loudspeaker. However, reproduction over a wide frequency range is restricted by practical limitations. The portion of the speech range required for intelligibility falls in the mid-audio band. The range of the fundamental frequencies of most horn, reed and string instruments also falls within this band. This is rather fortunate because it is a very simple task to build mechanical and acoustical vibrating systems to cover only this mid-frequency band. The two extreme ends of the audio-frequency band are the most difficult to reproduce with efficiency comparable to the mid-frequency range. Inefficiency at the low frequencies is primarily due to a small radiation resistance. Inefficiency at the high frequencies is primarily due to large mass reactance.

The volume range is another factor involved in sound reproduction. In the middle frequency band the ear has a volume range of a million to one in pressure, or a trillion to one in energy. To build linear reproducing apparatus for this tremendous range is practically impossible today. As a matter of fact, it is not practical to reproduce the volume range of all musical instruments.

An increase in the volume and frequency ranges of the loudspeaker

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* Decimal Classification: R365.2

multiplies the problems connected with obtaining the proper directional pattern, low nonlinear distortion and suitable transient response. The directional characteristics of the conventional direct-radiator loudspeaker are quite adequate for the frequency range of the present-day broadcast receivers. However, when the high frequency range is increased by one to two octaves, the directional pattern becomes quite narrow and some consideration must be given to this problem. The problem of nonlinear distortion is multiplied several times by the addition of one or two octaves. The additional volume range, of course, complicates the problem of nonlinear distortion. It has been found that poor transient response is not objectionable in the case of a loudspeaker with a limited frequency range—in some cases it actually enhances the reproduction. However, a wide-range high-fidelity loudspeaker should exhibit good transient response. From the above discussion it will be seen that additional volume and frequency ranges increase the complexity of the technical problems in loudspeaker design and manufacture.

Wide frequency range, low distortion loudspeakers are required for monitoring in radio and television broadcasting, phonograph and sound motion picture recording and high quality sound systems. The direct radiator loudspeaker is particularly suited for these applications because the acoustic power required is relatively low and the space requirements rather limited.

It is the purpose of this paper to describe the following: the development work on a wide range direct radiator loudspeaker; the performance of an experimental duo-cone direct-radiator loudspeaker.

TWO-UNIT LOUDSPEAKERS

Two-unit loudspeakers may be constructed in many different ways. In order to determine some of the characteristics, a number of experimental designs were built and tested. Some of the theoretical and practical advantages and disadvantages will be described.

The simplest two-unit direct-radiator loudspeaker consists of a small cone unit and a large cone mounted on the front face of a flat baffle as shown in Figure 1. If the response covers the frequency range from 40 to 15,000 cycles the natural overlap region will be somewhere between 1000 and 2000 cycles. A system of the type depicted in Figure 1 consists of a cone fifteen inches in diameter in the low frequency unit and two inches in diameter in the high frequency unit. Due to the mounting arrangements of the two units the spacing between the two units in the baffle was fifteen inches. The middle of the overlap region was placed at 1500 cycles. The directional pattern at 1500 cycles

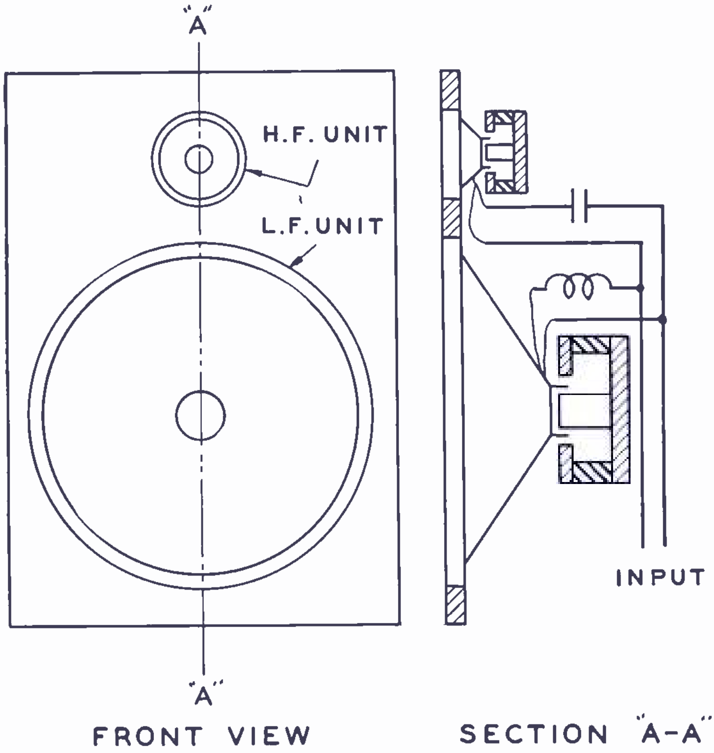

Fig. 1—A coplaner combination of low and high frequency direct-radiator loudspeaker units.

is shown in Figure 2. Complete destructive interference occurs when the distance between the two units is one-half wavelength and odd multiples of one-half wavelength. The type of directional characteristic shown in Figure 2 introduces frequency discrimination for points removed from the axis in a very important frequency band.

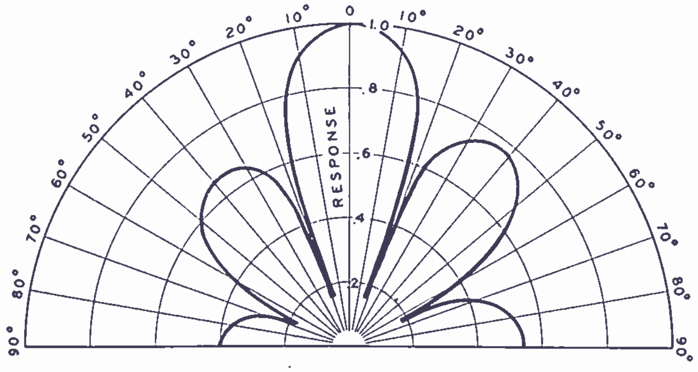

Fig. 2—The directional characteristics in the overlap region of the coplaner combination of low and high frequency direct-radiator loudspeaker units shown in Figure 1.

In the next experiment, the high frequency loudspeaker unit was placed coaxially inside the low frequency unit as shown in Figure 3. This construction improved the directional pattern in the overlap region. However, the sound which was diffracted around the high frequency unit and reflected from the low frequency cone interfered with the direct radiation. The result of this process is a nonuniform response

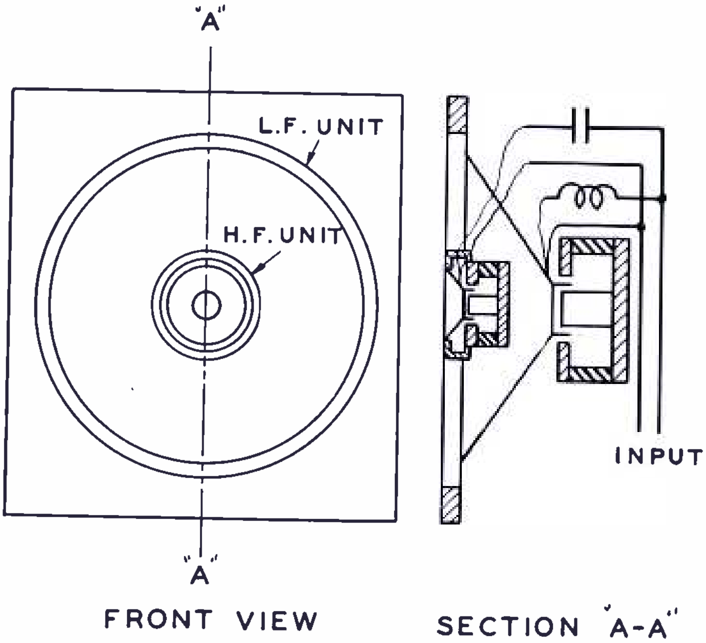

Fig. 3—A coaxial combination low and high frequency direct-radiator loudspeaker units.

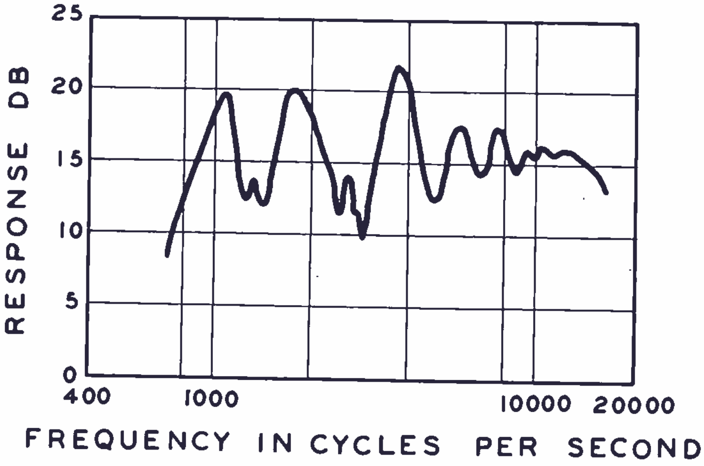

Fig. 4—The response frequency characteristic of the high frequency unit of the coaxial combination of low and high frequency direct-radiator loudspeaker units shown in Figure 3.

frequency characteristic as shown in Figure 4.

In the next experiment a small cellular horn loudspeaker was used as the high frequency loudspeaker. The horn loudspeaker was placed in a baffle above the low frequency unit as shown in Figure 5. This system exhibited the same type of directional pattern in the overlap frequency region as the system of Figure 1.

Following the above experiment the cellular horn loudspeaker was arranged coaxially with respect to the low frequency loudspeaker as shown in Figure 6. This system exhibited diffraction characteristics similar to those of Figure 3. There was an additional factor, namely, the source of the high frequency sound was several inches behind the source of the low frequency sound. This path amounts to almost a wavelength in the overlap frequency region. This is an undesirable feature,

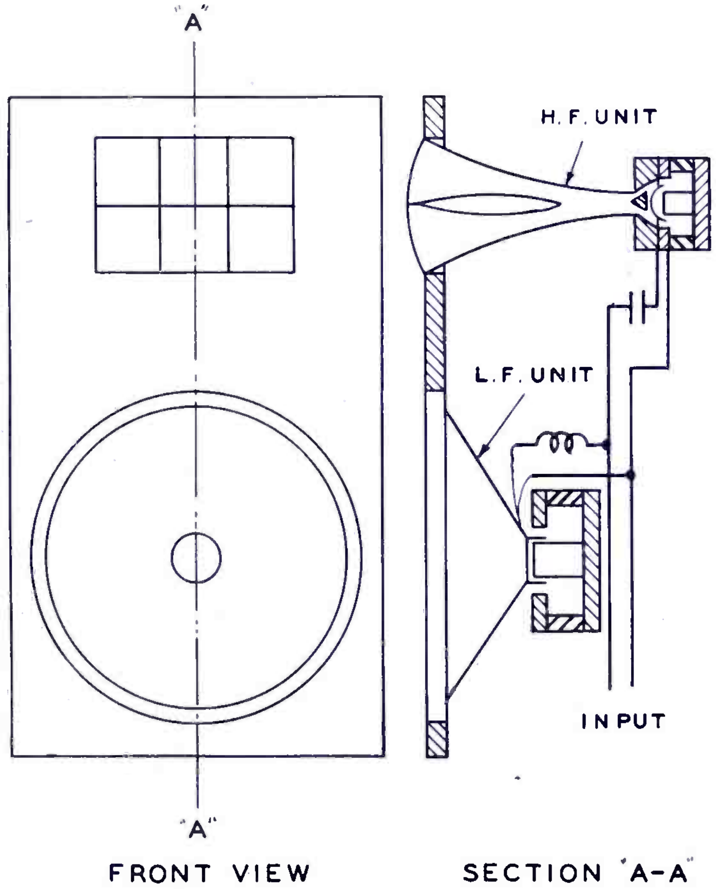

Fig. 5—A coplaner combination of a direct-radiator low frequency loudspeaker unit with a cellular horn high frequency loudspeaker unit.

particularly, in the case of the reproduction of transient sounds.

From the above experiments it appeared undesirable to place the high frequency unit in front of the low frequency unit. This feature can be obviated by making the pole for the low frequency unit a portion of the high frequency horn as shown in Figure 7. The response frequency characteristic obtained on this system was smooth. In addition,

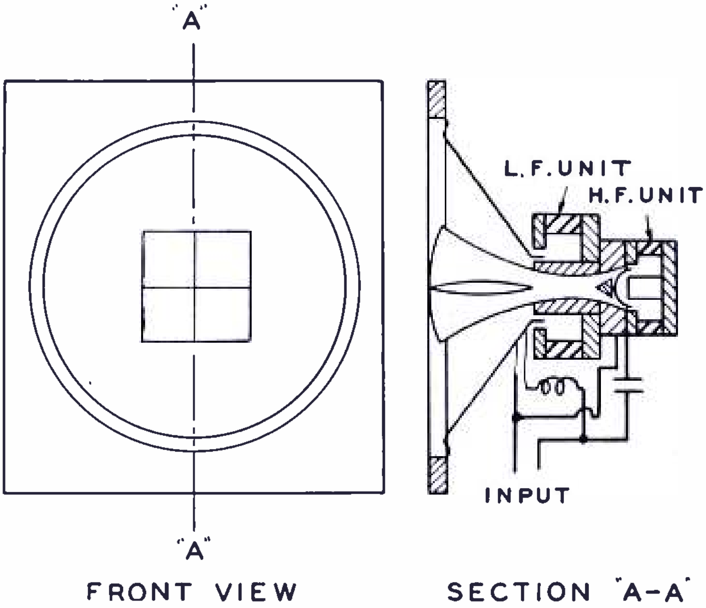

Fig. 6—A coaxial combination of a direct-radiator low frequency loudspeaker unit with a cellular horn high frequency loudspeaker.

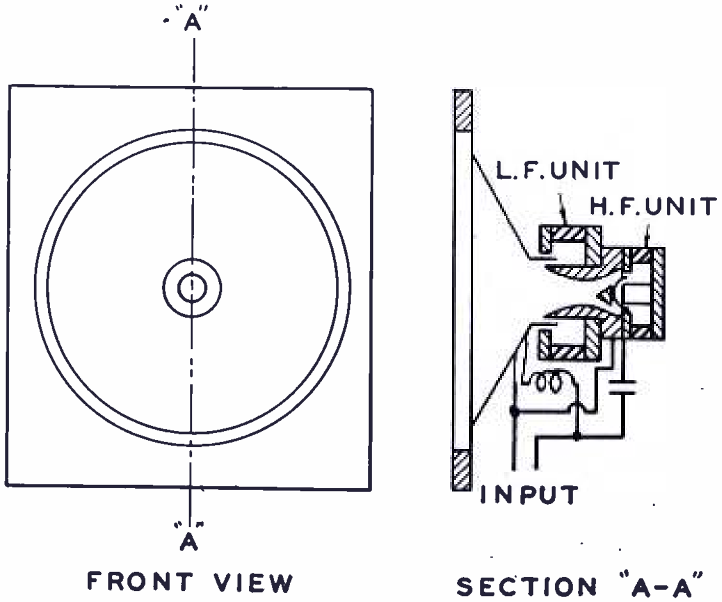

Fig. 7—A coaxial combination of a direct-radiator low frequency loudspeaker unit with a horn high frequency loudspeaker unit.

the directional pattern was acceptable particularly when a wide angle low frequency cone was used. The difference in path length between the source of the low and high frequency units was still an undesirable feature.

There is another problem when a horn and direct-radiator loudspeaker are combined, namely, the difference in efficiency. The efficiency of a horn loudspeaker is from 10 to 20 decibels greater than the direct radiator loudspeaker. This means that an attenuation network must be used with the horn unit to obtain comparable efficiencies and uniform response from the combination of the two units.

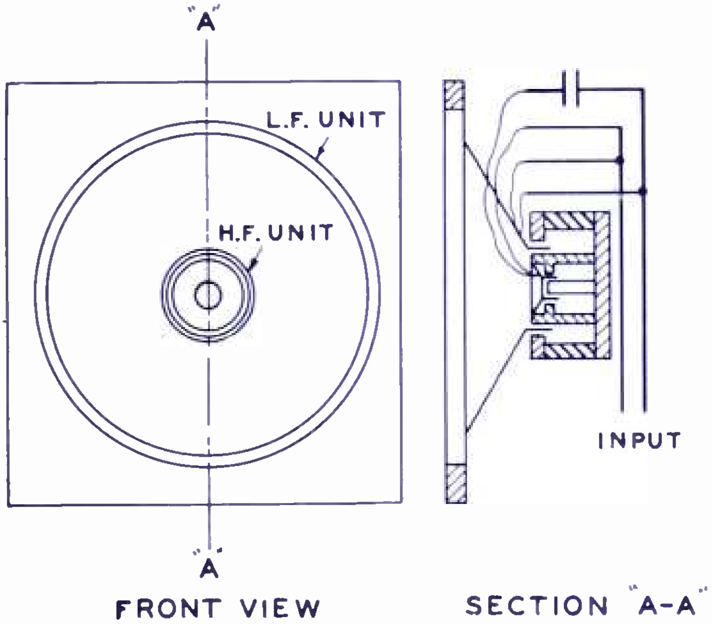

Fig. 8—A congruent coaxial combination of low frequency and high frequency direct-radiator loudspeaker units.

In the next experiment two cone loudspeaker units were combined so that the large cone was a continuation of the small cone as shown in Figure 8. This system has been termed a duo-cone loudspeaker. The combination system shown in Figure 8 eliminates the path difference factor because in the overlap region the two cones vibrate together as a single cone.

As a result of the above experiments it appeared that the duo-cone loudspeaker possessed many constructional, theoretical and experimental advantages. In view of this, it was decided to make a detailed investigation of the duo-cone loudspeaker. It is the purpose of the sections which follow to describe in detail some of the characteristics of the duo-cone loudspeaker.

THEORETICAL CONSIDERATIONS

The performance of a direct-radiator loudspeaker may be obtained from theoretical considerations.[1] Theoretical investigations are useful in determining the dimensions of the units, the masses of the voice coils and cones, the air gap flux, the fundamental resonant frequencies and other relevant factors. Proper evaluation of these factors is important in obtaining a scientifically coordinated loudspeaker system. It is the purpose of this section to outline theoretically the action of the duo-cone loudspeaker consisting of two congruent, coaxial direct-radiator loudspeaker systems.

A cross-sectional view, voice coil circuit and the mechanical circuit of the low frequency unit of the duo-cone loudspeaker is shown in Figure 9. The total mechanical impedance of the vibrating system at the voice coil is

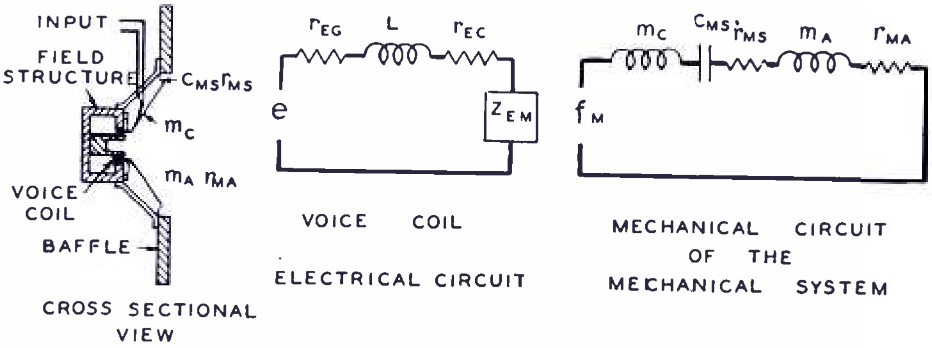

Fig. 9—Cross-sectional view, electrical circuit and mechanical circuit of the low frequency portion of a duo-cone loudspeaker. In the electrical circuit: r_{EG}, the internal electrical resistance of the generator; r_{EC} and L, the electrical resistance and inductance of the voice coil; z_{EM}, the electrical motional impedance, e, the voltage of the electrical generator. In the mechanical circuit: m_C, the mass of the cone and voice coil; C_{MS}, the compliance of the suspension system; r_{MS}, the mechanical resistance of the suspension system; m_A and r_{MA}, the mass and mechanical resistance of the air load; f_M, the mechanomotive force in the voice coil.

$$z_{MT} = r_{MS} + r_{MA} + j\omega m_C + j\omega m_A - \frac{j}{\omega C_{MS}} \qquad (1)$$

where r_{MS} = mechanical resistance of the suspension system, in mechanical ohms,

r_{MA} = mechanical resistance of the air load, in mechanical ohms,

m_C = mass of the cone and the voice coil, in grams,

m_A = mass of the air load, in grams, and

C_{MS} = compliance of the suspension system, in centimeters per dyne.

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[1] H. F. Olson, "ELEMENTS OF ACOUSTICAL ENGINEERING," D. Van Nostrand Company, Inc., New York, New York, 1940.

Equation (1) may be written as follows:

$$z_{MT} = r_{MS} + r_{MA} + jx_{MC} + jx_{MA} - jx_{MS} \tag{2}$$

where r_{MS} = mechanical resistance of the suspension system, in mechanical ohms,

r_{MA} = mechanical resistance of the air load, in mechanical ohms,

$x_{MC} = \omega m_C$ = mechanical reactance of the voice coil and cone,

$x_{MA} = \omega m_A$ = mechanical reactance of the air load, in mechanical ohms, and

$x_{MS} = \dfrac{1}{\omega C_{MS}}$ = mechanical reactance of the suspension system, in mechanical ohms.

The mechanical resistance and mechanical reactance of the air load may be obtained from Figure 10.

The motional impedance,[2] in abohms, of the mechanical system is

$$z_{EM} = \frac{(Bl)^2}{z_{MT}} \tag{3}$$

where B = flux density in air gap, in gausses,

l = length of the conductor in the voice coil, in centimeters and

z_{MT} = mechanical impedance of the mechanical system, in mechanical ohms.

The efficiency of the loudspeaker is the ratio of the sound power output to the electrical input. The efficiency may be obtained from the voice coil circuit of Figure 9 and expressed as follows,

$$\mu = \frac{r_{ER}}{r_{EC} + r_{EM}} \times 100\% \tag{4}$$

where r_{ER} = component of the motional resistance due to the radiation of sound, in abohms,

r_{EM} = total motional resistance, in abohms,

r_{EC} = damped resistance of the voice coil, in abohms.

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[2] H. F. Olson, "DYNAMICAL ANALOGIES," D. Van Nostrand Company, Inc., New York, New York, 1943.

The components r_{ER} and r_{EM} may be obtained from equations (1), (2) and (3).

From equations (2), (3) and (4) the efficiency, in per cent, of the loudspeaker is

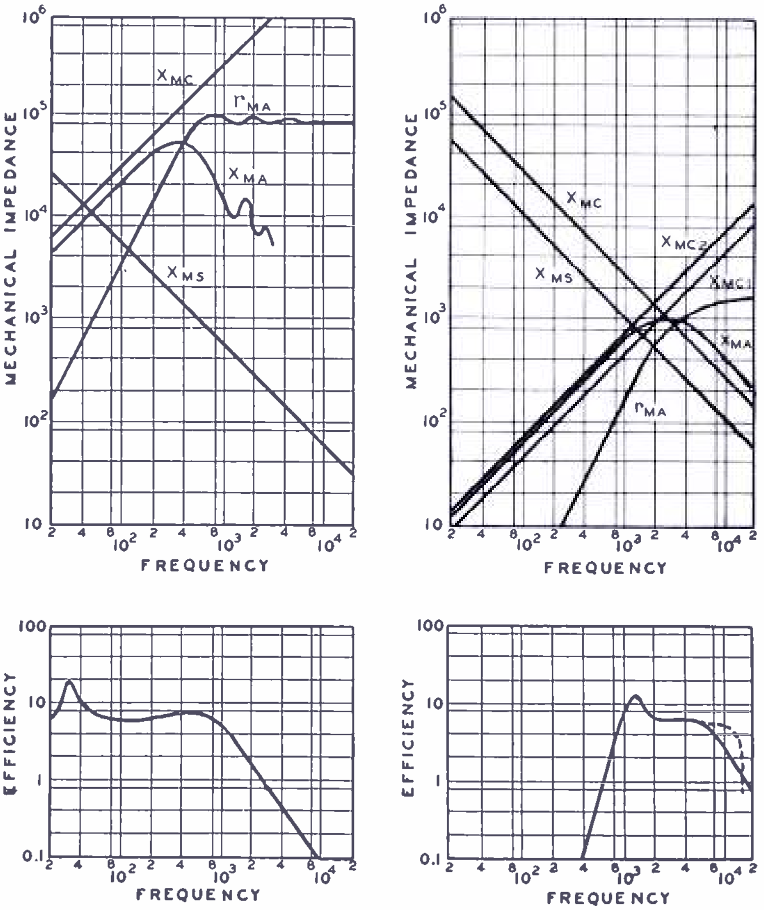


Fig. 10—Mechanical impedance and efficiency frequency characteristics of the low and high frequency units of the duo-cone loudspeaker. In the low frequency unit: x_{MC}, the mechanical reactance of the cone and coil; x_{MA} and r_{MA}, the mechanical reactance and mechanical resistance of the air load; x_{MS}, the mechanical reactance of the suspension system. In the high frequency unit: x_{MC1} and x_{MC2}, the mechanical reactances of the voice coil and cone; x_{MA} and r_{MA}, the mechanical reactance and mechanical resistance of the air load; x_{MS}, the mechanical reactance of the suspension system; x_{MC}, the mechanical reactance of the air cavity behind the cone.

$$\mu = \frac{(Bl)^2\, r_{MA}}{(Bl)^2\,(r_{MS} + r_{MA}) + r_{ED}\,[(r_{MC} + r_{MA})^2 + (x_{MA} + x_{MC} - x_{MS})^2]\, 10^9} \times 100 \qquad (5)$$

Above the fundamental resonant frequency the mechanical reactance due to the suspension system is small compared to the mechanical reactance of the cone and coil. Since r_{MA} is small compared to x_{MA} and x_{MC}, equation (5) becomes

$$\mu = \frac{(Bl)^2 \, r_{MA}}{r_{EC} \, (x_{MA} + x_{MC})^2 \, 10^9} \times 100 \tag{6}$$

In terms of the resistivity and density of the voice coil, equation (6) becomes,

$$\mu = \frac{B^2 \, r_{MA} m_1}{\rho K_r \, (x_{MA} + x_{MC})^2} \times 100 \tag{7}$$

where m_1 = mass of the voice coil, in grams,

ρ = density of the voice coil conductor, in grams per cubic centimeter, and

K_r = resistivity of the voice coil conductor, in ohms per cubic centimeter.

The relation between the efficiency and the ratio of the mass of the coil to the mass of the cone and air load may be obtained from equation (7). The maximum efficiency occurs when the mass of the cone is equal to the mass of the coil.

The cone diameter of the low frequency unit used in the duo-cone loudspeaker is 15 inches. The mechanical resistance and reactance characteristics of the elements of the vibrating systems are shown in Figure 10. For the air load on the large cone it is assumed that it is mounted in an infinite baffle.

The efficiency in which all the elements of the vibrating system are included may be obtained from equation (5). The resistance r_{MC} due to the suspension system is also a factor in the efficiency in the region of resonance. The mechanical resistance, r_{MS}, of the suspension system of the large cone is 2400 mechanical ohms.

The efficiency characteristic is shown in Figure 10. It will be noted that the efficiency is higher at the resonant frequency. However, when coupled to a vacuum tube driving system the motional impedance is also increased which produces the power input to the voice coil. For this reason, the response is not accentuated to the degree depicted by the peak in the efficiency characteristic. It will be seen that the efficiency decreases very rapidly below the resonant frequency. Therefore, in a direct-radiator loudspeaker the response limit at the low frequency end of the frequency range is determined by the resonant frequency of the system.

The motional impedance of a dynamic loudspeaker is given by equation (3). The normal impedance, in abohms, of voice coil is given by

$$z_{EN} = z_{EM} + z_{ED} \qquad (8)$$

where z_{EM} = motional electrical impedance, in abohms, and

z_{ED} = electrical impedance of the voice coil in the absence of motion, that is blocked, in abohms.

A cross-sectional view, voice coil circuit and mechanical circuit of the high frequency unit of the duo-cone loudspeaker is shown in Figure 11. In the case of the high frequency unit there are two additional compliances as contrasted to the low frequency unit, namely, the compliance of the chamber behind the cone and the compliance between the coil and cone. The mechanical impedance at the voice coil, assuming the latter compliance, to be zero is given by

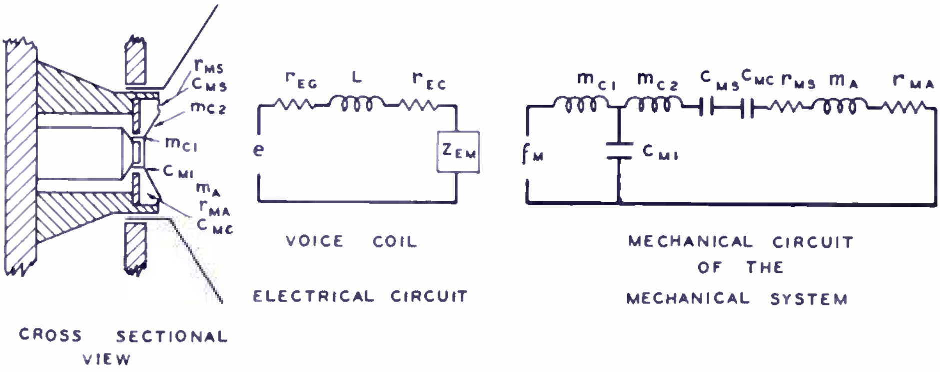


Fig. 11—Cross-sectional view, electrical circuit and mechanical circuit of the high frequency portion of a duo-cone loudspeaker. In the electrical circuit: r_{EG}, the internal electrical resistance of the generator; r_{EC} and L, the electrical resistance and inductance of the voice coil; z_{EM}, the electrical motional impedance, e, the voltage of the electrical generator. In the mechanical circuit: m_{C1}, the mass of the voice coil; m_{C2}, the mass of the cone; C_{MS}, the compliance of the suspension system; r_{MS}, the mechanical resistance of the suspension system; m_A and r_{MA}, the mass and mechanical resistance of the air load; C_{MC}, the compliance of the air cavity behind the cone; C_{M1}, the compliance between the voice coil and cone; f_M, the mechanomotive force in the voice coil.

$$z_{MT} = r_{MS} + r_{MA} + j\omega m_{C1} + j\omega m_{C2} + j\omega m_A - \frac{j}{\omega C_{MS}} - \frac{j}{\omega C_{MC}} \qquad (9)$$

where r_{MS} = mechanical resistance of the suspension system, in mechanical ohms,

r_{MA} = mechanical resistance of the air load, in mechanical ohms,

m_{C1} = mass of the voice coil, in grams,

m_{C2} = mass of the cone, in grams,

m_A = mass of the air load, in grams,

C_{MS} = compliance of the suspension system, in centimeters per dyne, and

C_{MC} = compliance of the air chamber behind the cone, in centimeters per dyne.

The efficiency, from equations (3), (4) and (9), is

$$\mu = \frac{(Bl)^2 r_{MA}}{(Bl)^2 (r_{MC} + r_{MA}) + r_{ED} \left[(r_{MC} + r_{MA})^2 + x_{MA} + x_{MC1} + x_{MC2} + x_{MS} - x_{MC} \right] 10^9} \times 100 \qquad (10)$$

where r_{MS} = mechanical resistance of the suspension system, in mechanical ohms,

r_{MA} = mechanical resistance of the air load, in mechanical ohms,

$x_{MA} = \omega m_A$ = mechanical reactance of the air load, in mechanical ohms,

$x_{MC1} = \omega m_{C1}$ = mechanical reactance of the voice coil, in mechanical ohms,

$x_{MC2} = \omega m_{C2}$ = mechanical reactance of the cone, in mechanical ohms,

$x_{MS} = \dfrac{1}{\omega C_{MS}}$ = mechanical reactance of the suspension system, in mechanical ohms,

$x_{MC} = \dfrac{1}{\omega C_{MC}}$ = mechanical reactance of the air chamber behind the cone, in mechanical ohms.

The cone diameter of the high frequency unit used in the duo-cone loudspeaker is 2 inches. The mechanical resistance and reactance characteristics of the elements of the vibrating system are shown in Figure 10. For the air load upon the cone it is assumed that the large cone forms a conical horn. The mechanical resistance of the suspension system is 3600 mechanical ohms. It will be seen that mechanical reactance due to the air chamber behind the cone is three times the mechanical reactance due to the suspension system. Therefore, in the range where the compliances are the controlling mechanical reactances the compliance due to the air chamber is the controlling compliance. This expedient reduces the distortion due to a nonlinearity of the suspension system. The efficiency characteristic is shown in Figure 10. It will be seen that the efficiency falls off about 10,000 cycles. This is due to the fact that the system is mass controlled and the radiation resistance does not increase as the square of the frequency above 10,000 cycles. By introducing a compliance, C_{M1}, between the voice coil and cone the effective mass of the system is reduced and uniform efficiency is maintained to 15,000 cycles as shown by the dotted efficiency characteristic of Figure 10.

The combination of the low and high frequency units as outlined should yield uniform output from 30 to 15,000 cycles. A photograph of an experimental duo-cone loudspeaker having the constants given in this section is shown in Figure 12.

Fig. 12—A photograph of a duo-cone direct-radiator loudspeaker.

RESPONSE FREQUENCY CHARACTERISTICS

The measured response frequency characteristics of the low and high frequency units of the duo-cone loudspeaker mounted in a large flat baffle are shown in Figure 13. These characteristics are in substantial agreement with the efficiency characteristics of Figure 10. The response frequency characteristics in a phase inverter cabinet will be considered in a later section.

CROSS-OVER NETWORK

The cross-over network is an important consideration in a direct radiator loudspeaker. In the design of any two-unit loudspeaker, when there is considerable path length between the two units, a relatively sharp cross-over network is required in order to prevent destructive interference between the two units in the cross-over region. In the duo-cone loudspeaker, since the large cone is a continuation of the small cone, the cross-over frequency range need not be confined to a narrow band because the two cones vibrate as a single cone in this frequency region. This fact makes it possible to use a very simple cross-over network. The electrical impedance characteristics of the low and high frequency units of the duo-cone loudspeaker are shown in Figure 14. The inductance of the large low frequency voice coil is large. As a consequence, it is not necessary to use an inductance in series with the low frequency unit to reduce the current at the high frequencies. The only external element required for the cross-over network is a condenser in series with the high frequency unit to limit the current through the high frequency unit at the low frequencies. The cross-over frequency in this system extends over about two octaves. However, as pointed out

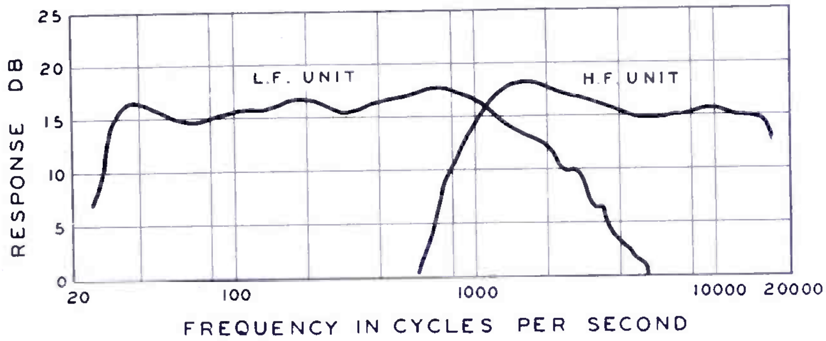


Fig. 13—Response frequency characteristics of the low and high frequency units of the duo-cone loudspeaker mounted in a large baffle.

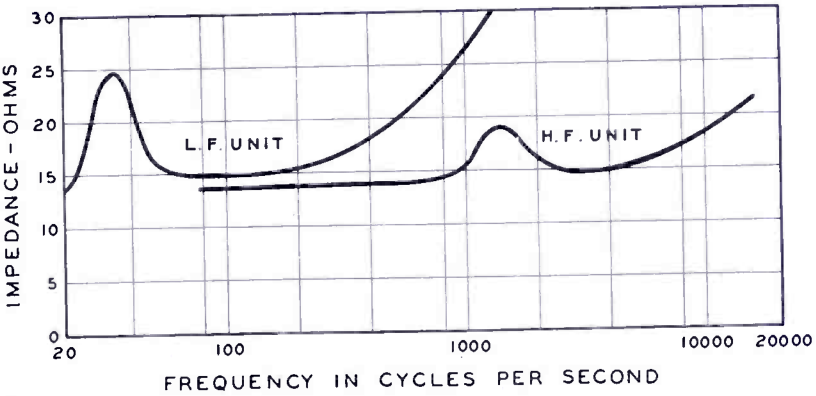


Fig. 14—The electrical impedance frequency characteristics of the low and high frequency units of the duo-cone direct-radiator loudspeaker.

before this is not objectionable because in the overlap region the two cones vibrate as a single cone.

PHASE INVERTER WITH A VARIABLE PORT

The preceding considerations have been concerned with the performance of the duo-cone loudspeaker operating in a large flat baffle. The large flat baffle is not a practical mounting arrangement for general applications. A cabinet is the conventional housing for direct radiator loudspeaker systems. It is the purpose of this section to consider a phase inverter type cabinet suitable for the duo-cone loudspeaker.

The term, phase inverter loudspeaker, is used to designate a system consisting of a loudspeaker mechanism mounted in a closed cabinet with an opening or port which augments the low frequency response by the addition of the sound radiated from the port. The reason that the addition of the port augments the low frequency response is because the particle velocity of the air in the port is in phase with the velocity of the cone.

The amount of low frequency accentuation required for a particular condition of reproduction depends upon the program material, the room in which the sound is reproduced, etc. Therefore, it is desirable to provide a variable means for adjusting the low frequency response to a loudspeaker. It is the purpose of this section to describe a phase inverter type cabinet with a variable port.

The acoustic circuit of the system shown in Figure 15 shows the action of the acoustic phase inverter. When the port is closed, the inertance $M_2 = \infty$, the action is the same as that of a completely enclosed cabinet. If the inertance of the port is approximately equal to the inertance of the cone the low frequency response will be accentuated. The performance can be deduced from the acoustic circuit as follows:

The volume current in z_{A1} is given by

$$\dot{X}_1 = \frac{p(z_{A2} + z_{A3})}{z_{A1}\, z_{A2} + z_{A1}\, z_{A3} + z_{A2}\, z_{A3}} \tag{11}$$

where $z_{A1} = r_1 + j\omega M + \dfrac{1}{j\omega C_{A1}}$

r_{A1} = acoustic radiation resistance on the cone,

M_1 = inertance of the cone and the air load, and

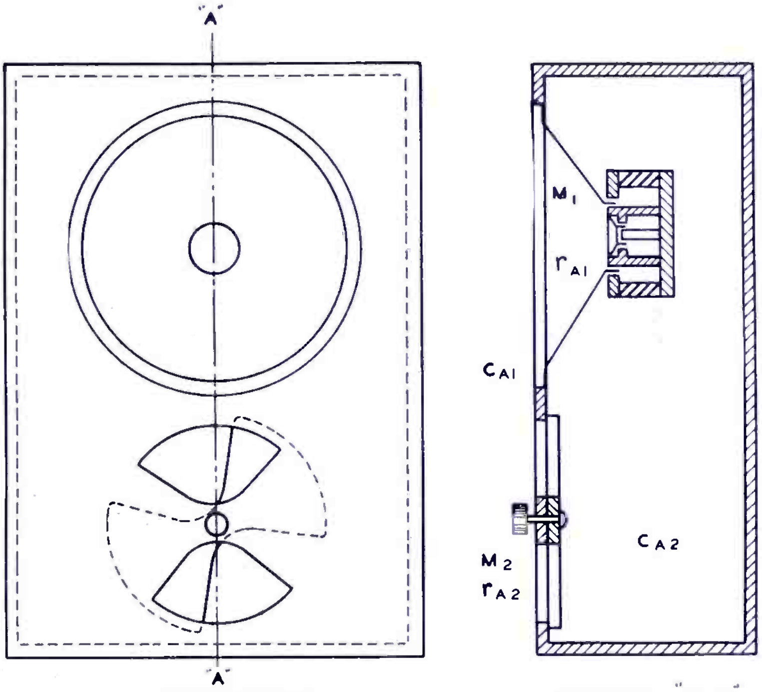
C_{A1} = acoustic capacitance of the cone,

$$z_{A2} = \frac{1}{j\omega C_{A2}}$$

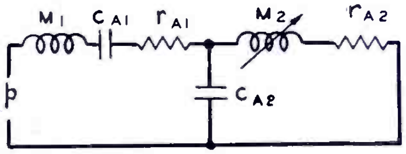
C_{A2} = acoustic capacitance of the cabinet volume,

$z_{A3} = r_{A2} + j\omega M_2$

r_{A2} = acoustic radiation resistance of the cone,



FRONT VIEW SECTION "A-A"



ACOUSTIC CIRCUIT

Fig. 15—Front and sectional views and the acoustic circuit of the acoustic phase inverter used with the duo-cone loudspeaker. In the acoustic circuit: M_1, C_{A1} and r_{A1}, the inertance, acoustic capacitance and acoustic resistance of air load and cone and coil of the loudspeaker unit; M_2 and r_{A2}, the inertance and acoustic resistance of the port; C_{A2}, the acoustic capacitance of the cabinet volume.

M_2 = inertance of the port,

$p = ABli$ = sound pressure which drives the acoustic system,

B = flux density in the air gap,

l = length of conductor in the air gap,

i = current in the voice coil, and

A = area of the cone.

The volume current in z_{A3} is

$$\dot{X}_3 = \frac{p\, z_{A2}}{z_{A1}\, z_{A2} + z_{A1}\, z_{A3} + z_{A2}\, z_{A3}} \tag{12}$$

The total power radiated is given by real part of

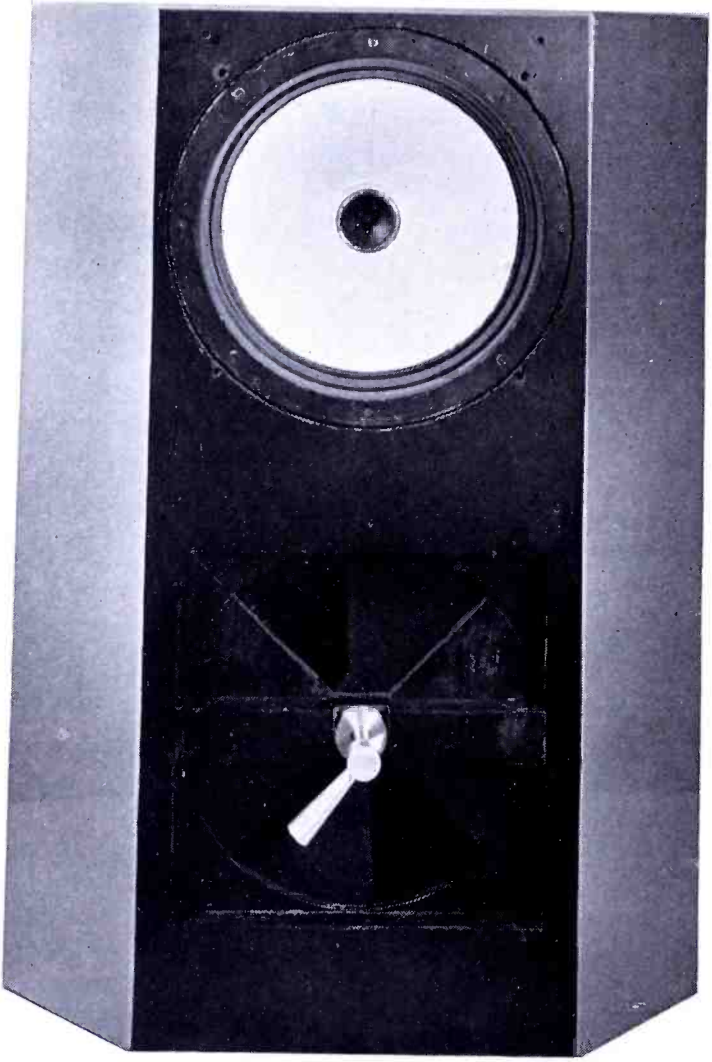


Fig. 16—Photograph of the due-cone direct-radiator loudspeaker mounted in a phase inverter cabinet with the variable port with the grill removed.

$$P = r_{A1}\, \dot{X}_1{}^2 + r_{A2}\, \dot{X}_3{}^2 \tag{13}$$

Equation (13) shows the effect of the port in altering the response in the low frequency range.

A photograph of the duo-cone loudspeaker mounted in a phase inverter cabinet with the grill removed is shown in Figure 16. The same cabinet with the grill in place is shown in Figure 17.

The measured response frequency characteristics of the duo-cone loudspeaker operating in a phase inverter cabinet is shown in Figure 18. These characteristics show the effect of the port opening upon the response and also show that the response is uniform in the overlap region.

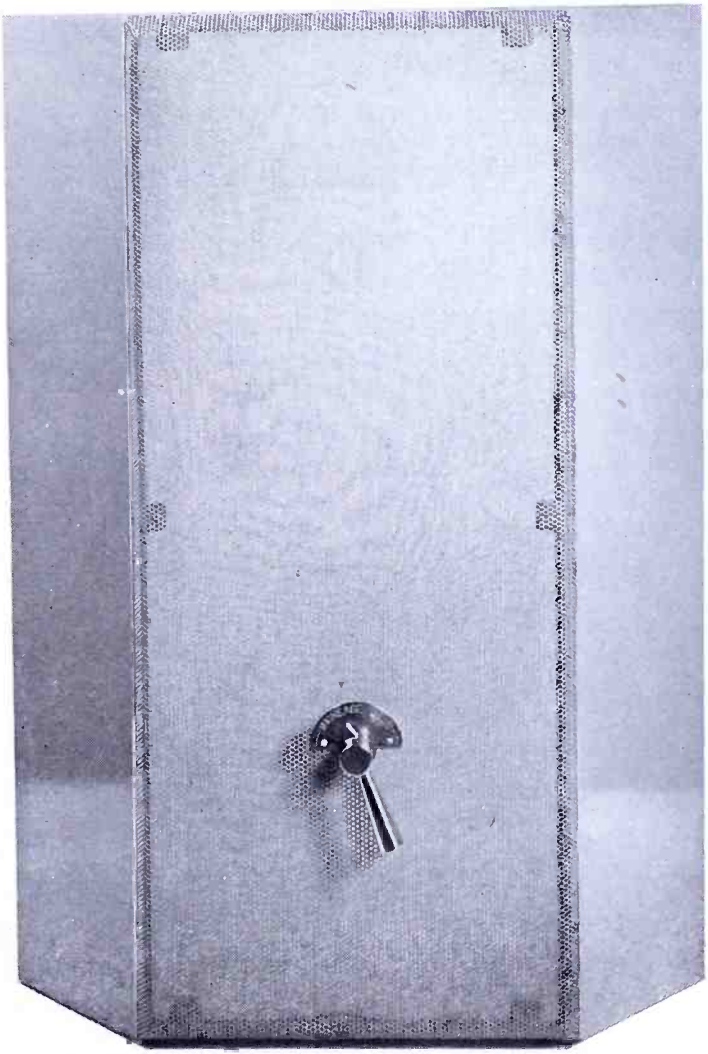


Fig. 17—Photograph of the complete duo-cone loudspeaker.

DIRECTIONAL CHARACTERISTICS

The directional characteristics of a loudspeaker used for monitoring and high quality sound reproduction should be substantially independent of the frequency over at least a total of 90°. The directional characteristics of a cone loudspeaker are a function of the frequency. At the low frequencies where the dimensions are small compared to the wavelength the system is nondirectional. When the dimension of the

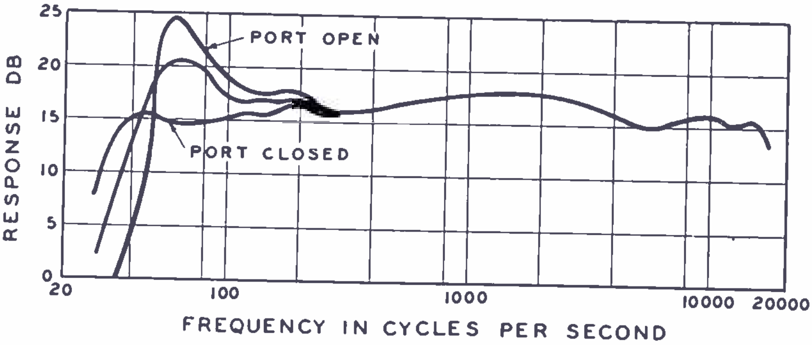


Fig. 18—Response frequency characteristics of the duo-cone direct-radiator loudspeaker unit operating in the phase inverter cabinet of Figure 15 for various openings of the port.

cone becomes comparable to a wavelength the system becomes directional. Above this frequency the directional pattern becomes progressively sharper with increase in the frequency. The directional pattern of a cone is also a function of the cone angle. This is due to the finite

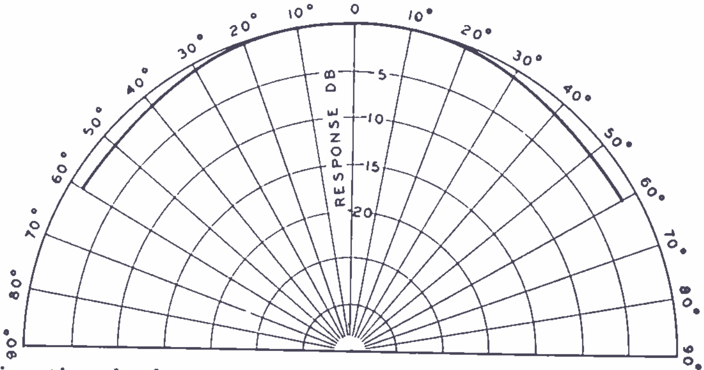


Fig. 19—Directional characteristic of the duo-cone direct-radiator loudspeaker at 1000 cycles.

transmission of sound in the cone. By increasing the angle of the cone the directional pattern becomes broader at the higher frequencies. Relatively wide angle cones were used in both the low and high fre-

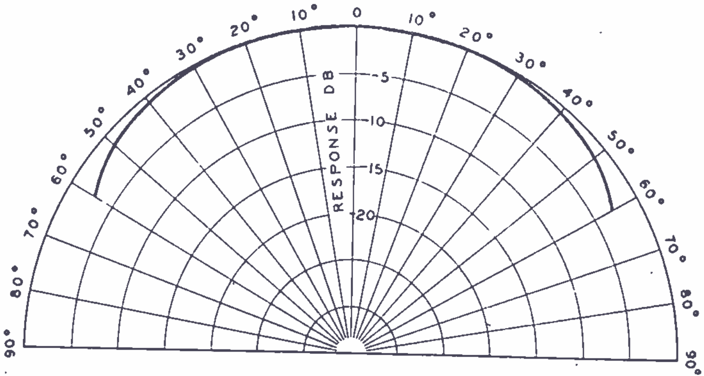


Fig. 20—Directional characteristic of the duo-cone direct-radiator loudspeaker at 3000 cycles.

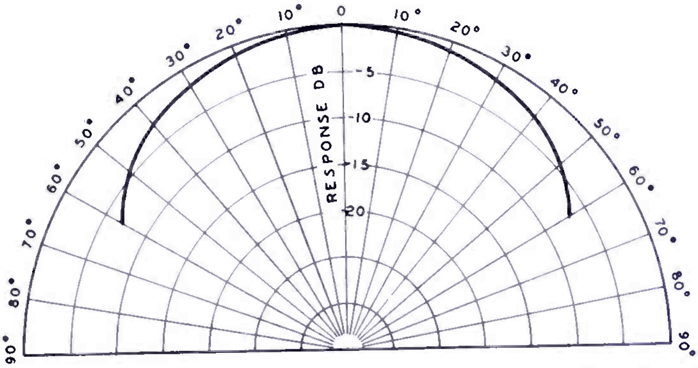


Fig. 21—Directional characteristic of the duo-cone direct-radiator loudspeaker at 6000 cycles.

quency units of the duo-cone loudspeaker in order to obtain uniform response over a total angle of 90° up to 15,000 cycles. The directional patterns for 1000, 3000, 6000, 10,000, 13,000 and 15,000 cycles are

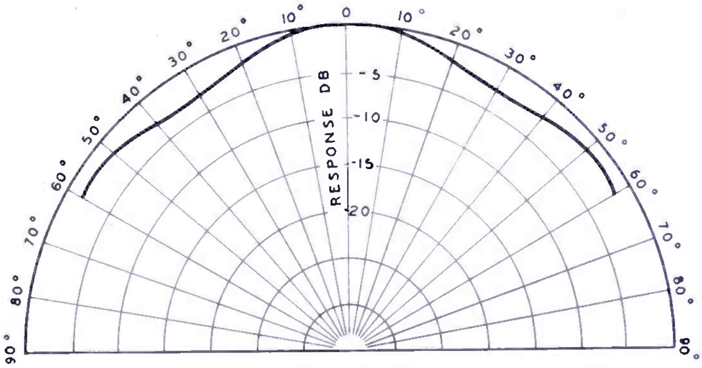


Fig. 22—Directional characteristic of the duo-cone direct-radiator loudspeaker at 10,000 cycles.

shown in Figures 19, 20, 21, 22, 23 and 24. The directional pattern is practically nondirectional over the 90° angle below 1000 cycles. Referring to the directional characteristics it will be seen that the directional patterns show very little variation over an angle of 90° over the frequency range to 15,000 cycles.

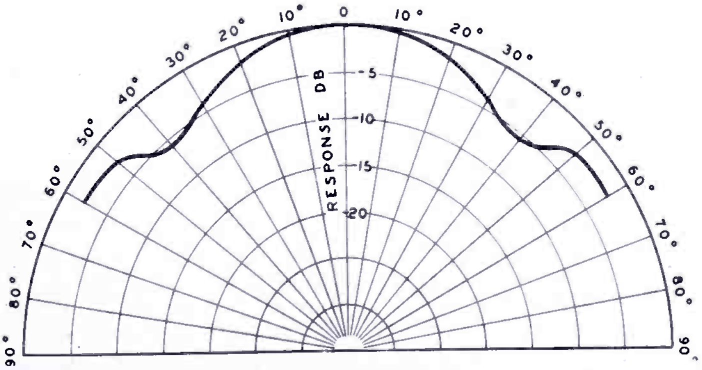


Fig. 23—Directional characteristic of the duo-cone direct-radiator loudspeaker at 13,000 cycles.

Nonlinear Distortion

Nonlinear distortion occurs when a nonlinear element is present in a vibrating system. The outside suspension system is one nonlinear element in a direct-radiator loudspeaker. The stiffness is not a constant but is a function of the amplitude and, in general, increases with larger amplitudes. The theoretical and experimental considerations of nonlinearity in a direct-radiator loudspeaker have been considered elsewhere[3] and will not be repeated here. The conclusion of this investigation was that the nonlinear distortion due to the suspension system may be eliminated by placing the fundamental resonant frequency of the loudspeaker at the lower limit of the reproduction frequency range.

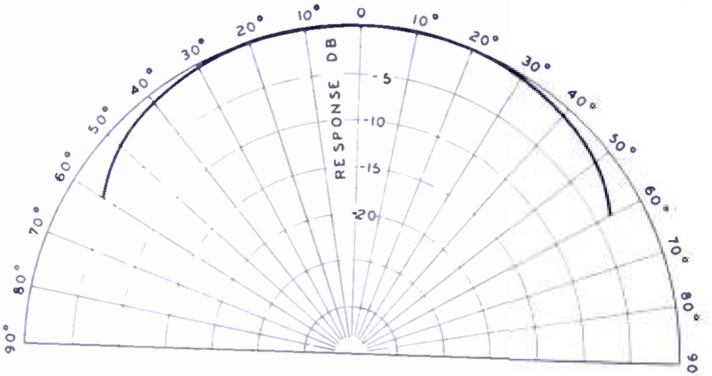


Fig. 24—Directional characteristic of the duo-cone direct-radiator loudspeaker at 15,000 cycles.

Above the fundamental resonant frequency, the velocity of the cone is not appreciably affected by the suspension system because the mechanical reactance due to the compliance of the suspension system is small compared to the mechanical impedance of the remainder of the system. In this loudspeaker the fundamental resonant frequency of the low frequency unit of the duo-cone loudspeaker was placed at 30 cycles. Under these conditions, the nonlinear distortion due to the suspension system was minimized. Another nonlinear element is the cone. In the range from 100 cycles to 1000 cycles nonlinearity of the cone produces both harmonic and subharmonic distortion. Since the range from 100 to 800 cycles contains the maximum power in both speech and music it is very important that the distortion be reduced to a minimum in this range. This can be done by employing a very rigid cone. In order to obtain sufficient rigidity to insure low distortion it was necessary to make the thickness of the cone about two and one-half times that of the conventional cone. This increased the rigidity by a factor of about 15 times.

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[3] H. F. Olson, "The Action of a Direct Radiator Loudspeaker with a Non-Linear Cone Suspension System," *Jour. Acous. Soc. Amer.* Vol. 16, No. 1, pp. 1-4, July, 1944.

Inhomogeneity of the flux density through which the voice coil moves is another source of distortion. This type of distortion can be eliminated by making the summation of the product of each turn and the flux density associated with that turn independent of the amplitude. This requirement was satisfied by making the voice coil large and slightly longer than the air gap. In order to obtain reasonable efficiency with the heavy cone it is necessary to employ a heavy voice coil. A voice coil of 25 grams was used in this loudspeaker which is about 25 times the mass of the voice coil used in console type radio loudspeakers.

In the case of the high frequency unit of duo-cone loudspeaker, the nonlinear distortion due to the suspension system was minimized by making the stiffness of the space behind the cone the controlling mechanical impedance. (See section on THEORETICAL CONSIDERATIONS). For example, the resonance of the high frequency unit without the back enclosure occurs at 750 cycles. With the back enclosure as used in the duo-cone loudspeaker the resonant frequency is 1500 cycles.

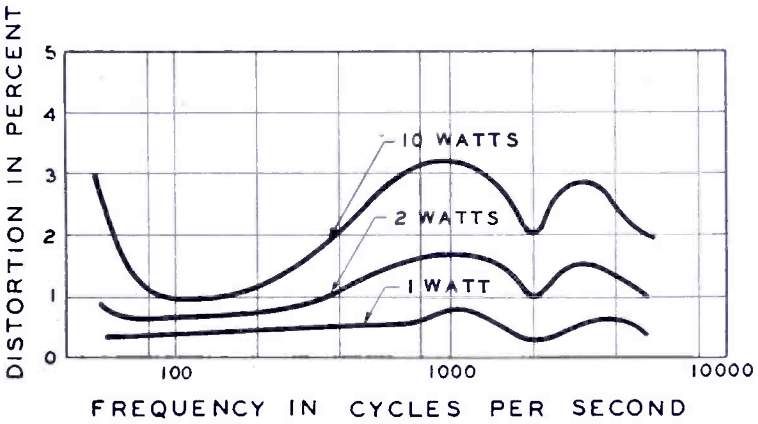

Fig. 25—Second harmonic distortion frequency characteristics for 1, 2 and 10 watts input.

With the above expedients the nonlinear distortion in the duo-cone loudspeaker is quite low as shown in Figures 25 and 26. The average input for normal monitoring and listening use is about 100 to 200 milliwatts which means that under these conditions the distortion is very small.

TRANSIENT RESPONSE

The sounds of speech and music are of a transient rather than a steady-state character. Therefore, practically all the sounds which are reproduced by a loudspeaker may be considered to be of a transient nature. In view of this, the transient response of a loudspeaker is an important factor in sound reproduction. One way of testing the transient response of a loudspeaker is to apply a square wave current to the voice coil and record the output by means of a microphone and cathode ray oscillograph. For a test of this type it is very important that the microphone be capable of reproducing square waves. The velocity microphone is a mass controlled system in the frequency range above 15 cycles. Since the driving force is proportional to the frequency, the system can be replaced by a constant driving force and a resistance instead of mass element. The transient response of this system is perfect. A special velocity microphone was built in which the free field response as determined by reciprocity calibrations was uniform to within one decibel from 25 cycles to 16,000 cycles. The important frequency region from the standpoint of transient response in double unit loudspeakers is near or below the overlap frequency band. The response of the duo-cone loudspeaker to a square wave having a fundamental component of 900 cycles is shown in Figure 27. It is not a perfect reproduction of a square wave but is quite comparable to other audio elements covering this frequency range. It may be mentioned in passing that to obtain a semblance of square waves from a loudspeaker requires a very good acoustical system.

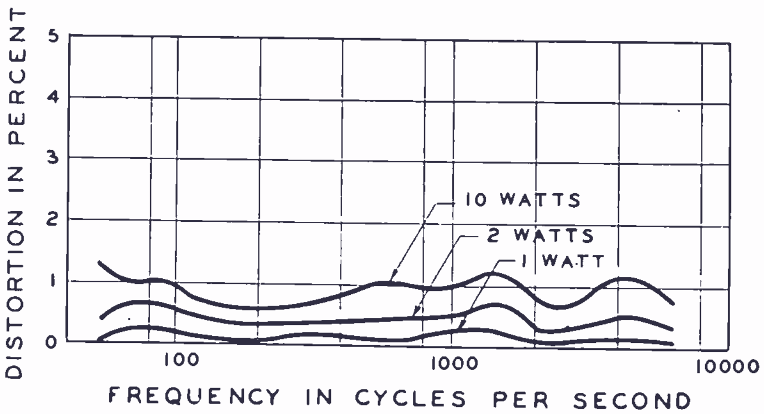

Fig. 26—Third harmonic distortion frequency characteristics for 1, 2 and 10 watts input.

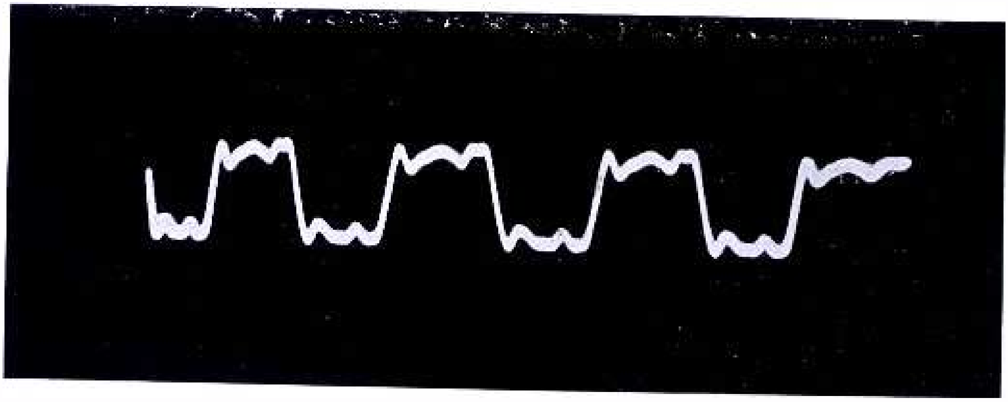

Fig. 27—Acoustic output of the duo-cone direct-radiator loudspeaker with an electrical square wave input of "900 cycles".

A MULTI-CHANNEL VHF RADIO COMMUNICATIONS SYSTEM*

By

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***Summary**—The planning and installing of a multi-channel Very High Frequency radio communications network on the Pacific Coast of Canada are described. Preliminary propagation tests are considered, and the conclusions drawn from these discussed. Profiles of both test and operative circuits are shown. The equipment used is described briefly. Results obtained on the operating circuits are analyzed and discussed.*

INTRODUCTION

DURING the recent war, a comprehensive network of communication facilities, involving both radio and landline circuits, was constructed in the Pacific Coast region of Canada. This paper describes the planning, installation, and operation of the radio circuits. These totalled 537 miles, involving seven terminals, three radio-to-radio relays and three radio-to-landline relays.

GENERAL

Population of any considerable density in this region is largely confined to the south east portion of Vancouver Island and the area immediately surrounding the city of Vancouver. Consequently, peacetime facilities for communication with the more northerly portions of the coast and with the Queen Charlotte Islands, were not capable of handling the heavy traffic loads resulting from military activity in these regions. These facilities comprised a network of high frequency radio telephone circuits operated by the British Columbia Telephone Company and several government and privately owned radio telegraph circuits.

The map of Figure 1 shows the general layout of the system. It will be noted that this comprises a landline network extending north from Vancouver along the Fraser River valley and to the coast at Bella Coola and Prince Rupert. Vancouver Island is connected with the mainland by submarine cable and the system is carried along the

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* Decimal Classification: R423.15

east coast of the island by landline, with an extension to the west coast at Tofino. Radio circuits are used to extend the system from the landline terminals at Prince Rupert, Bella Coola and Tofino to the points shown on the map. Table 1 lists the radio circuits, with some geographical information and shows the services carried over each circuit.

The terrain over which the radio circuits operate is extremely rugged, and for the most part heavily wooded. Rainfall is heavy, as high as 200 inches per year in some places. These characteristics, coupled with the fact that almost all of the locations are relatively

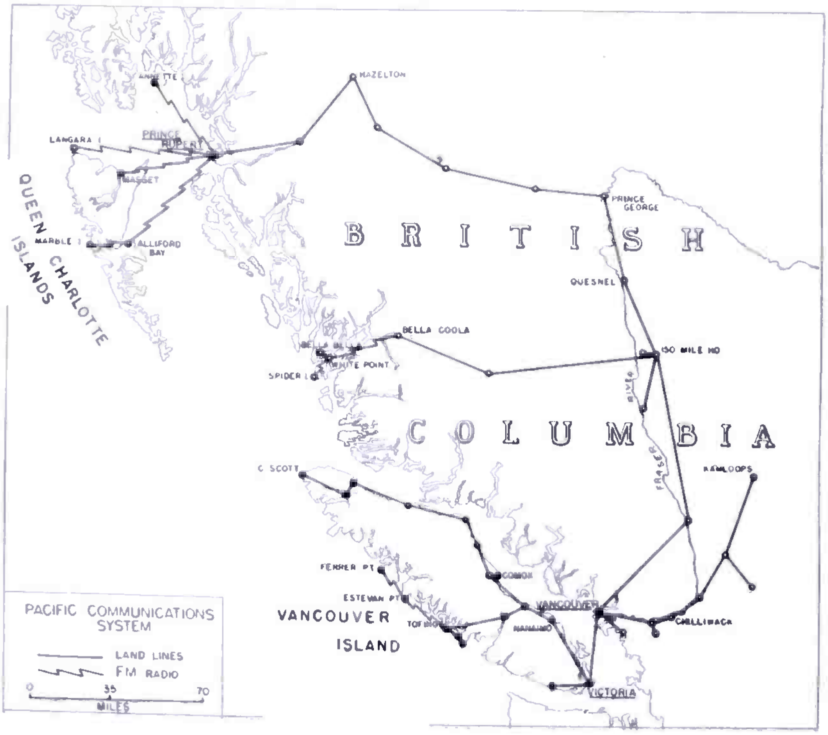

Fig. 1—Map Showing Pacific Communications System Landline and Radio Circuits.

Table 1

Circuit A		Circuit B	Respective Site Altitudes		Distance	Tele-phone	Teletype
Prince Rupert	—	Annette	1300 (Trans.) 1500 (Rec.)—	50 ft.	72 Miles	2	2
Prince Rupert	—	Langara Is.	1300 (Trans.) 1500 (Rec.)—	400	108	1	-
Prince Rupert	—	Massett	1300 (Trans.) 1500 (Rec.)—	15	76	1	2
Prince Rupert	—	Alliford Bay	1300 (Trans.) 1500 (Rec.)—	1100	98	2	4
Alliford Bay	—	Marble Is.	1100	390	30	1	-
Bella Coola	—	White Pt.	400	750	54	2	2
White Pt.	—	Bella Bella	750	50	7	1	2
White Pt.	—	Spider Is.	750	25	20	1	
Tofino	—	Estevan Pt.	30	10	40	2	
Estevan Pt.	—	Ferrer Pt.	10	80	32	1	

remote from civilization and difficult of access, imposed severe handicaps on both the initial exploratory work, and the installation. These very features, however, made radio particularly attractive, because, while the installation of the radio circuits was difficult, the installation of landline or submarine cable under similar circumstances would have been infinitely more so.

Planning and Propagation Tests

At the time the system was planned, information on propagation of 40 to 50 megacycle frequencies over mountainous terrain was extremely scarce. The theoretical methods necessarily deal with highly idealized conditions, and records of actual experience were not available. Consequently, it was decided to conduct a series of tests in a relatively accessible area over paths which, as nearly as could be ascertained, were representative of those which would be encountered in the actual system. A 250 watt transmitter operating on 44.5 megacycles was installed on the southern slopes of Hollyburn Ridge, north of the city of Vancouver. The elevation of the site was 1300 feet above sea level. The antenna used was a single vertical dipole, 0.2 wavelengths in front of a wire screen reflector. It was so oriented that the axis of the lobe lay slightly west of south. Spot measurements of field intensity were made at points in the north-western corner of the State of Washington and on southern Vancouver Island. Measurements were made with a Type 301-A field intensity meter. Profiles of the most interesting circuits over which measurements were made are shown in Figures 2 to 19. Test circuit profiles are given in Figures 2-9, actual circuit profiles in Figures 10-19. The measured value of field intensity is indicated on each. It should be noted that these profiles are plotted on a basis of 4/3 earth's radius, to correct for average refraction.

It was noted, at the time these measurements were made, that quite wide variations in field intensity could be obtained by moving the receiving antenna about a wavelength horizontally. Regardless of the profile, no change in polarization was observed, the received signal being polarized in the same direction as the transmitted signal in each case. It was observed that, in the case of measurements made at the edge of a cliff, moving the antenna a few feet back from the edge caused a marked reduction in field intensity. Although these were essentially spot measurements, an attempt was made to observe each for a sufficient period for short-time fading to show up.

Attempts to correlate calculated and measured values of field intensity met with little success. In some instances, where the profiles

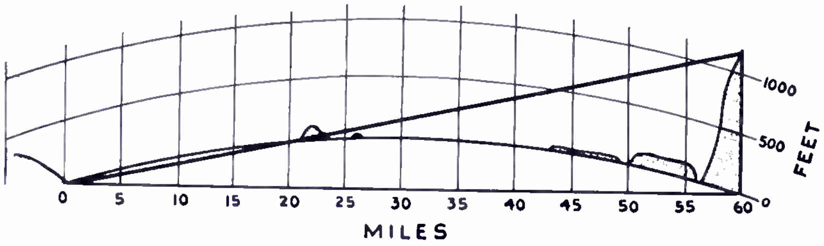

Fig. 2—Test Profile, Vancouver—Cadboro Point (4/3 Earth's Radius). Measured Field Intensity—100 Microvolts per Meter.

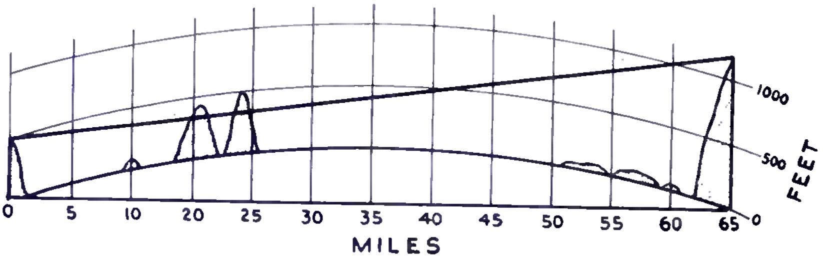

Fig. 3—Test Profile, Vancouver—Mount Douglass (4/3 Earth's Radius). Measured Field Intensity—500 Microvolts per Meter.

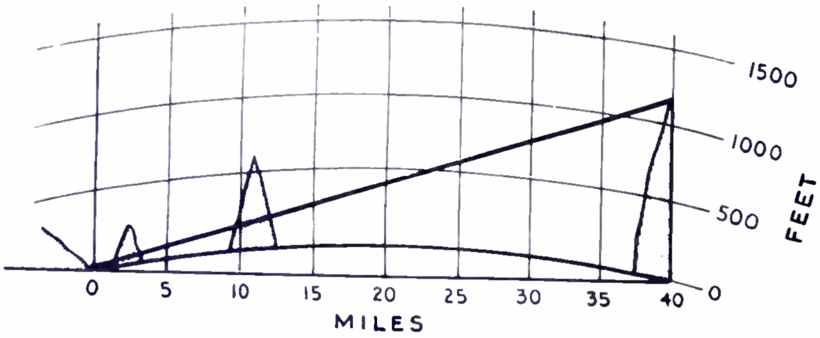

Fig. 4—Test Profile, Vancouver—Ladysmith (4/3 Earth's Radius). Measured Field Intensity—100 Microvolts per Meter.

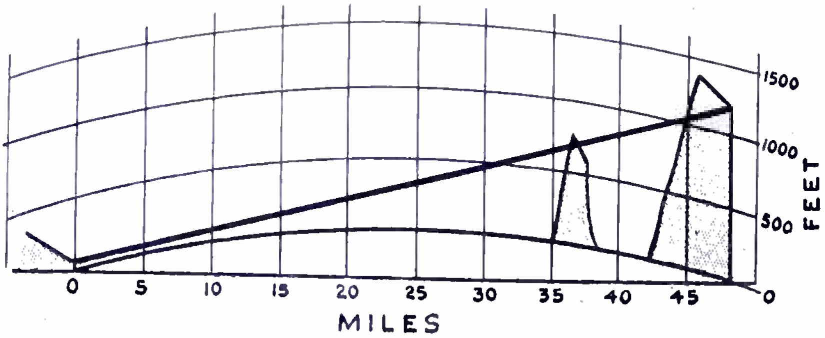

Fig. 5—Test Profile, Vancouver—Nanoose (4/3 Earth's Radius). Measured Field Intensity—3 to 4 Microvolts per Meter.

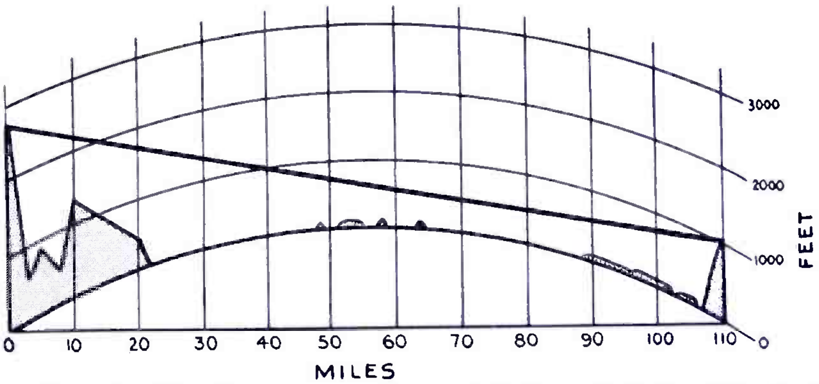

Fig. 6—Test Profile, Vancouver—Mount Walker (4/3 Earth's Radius). Measured Field Intensity—350 Microvolts per Meter.

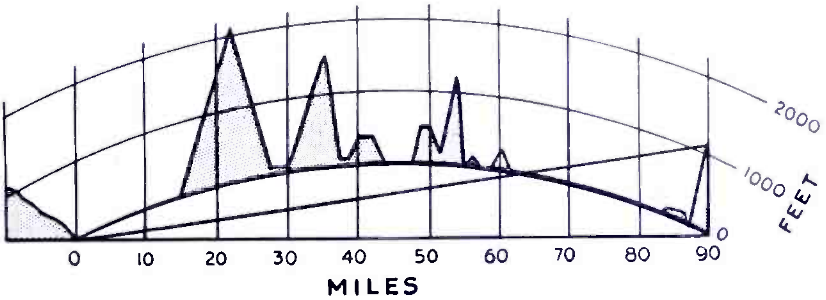

Fig. 7—Test Profile, Vancouver—Twin Rivers (4/3 Earth's Radius). Measured Field Intensity—12 Microvolts per Meter.

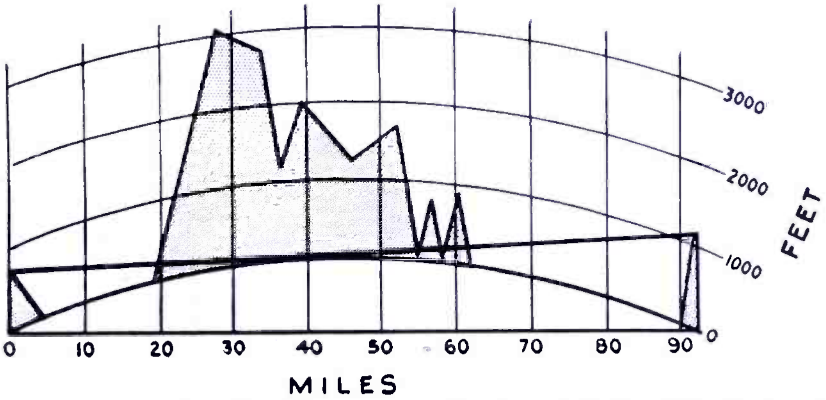

Fig. 8—Test Profile, Vancouver—Pysht (4/3 Earth's Radius). Measured Field Intensity—13 Microvolts per Meter.

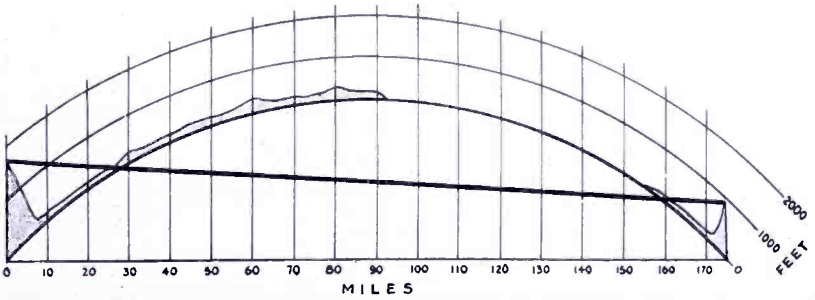

Fig. 9—Test Profile, Vancouver—Chop (4/3 Earth's Radius). Measured Field Intensity—8 Microvolts per Meter.

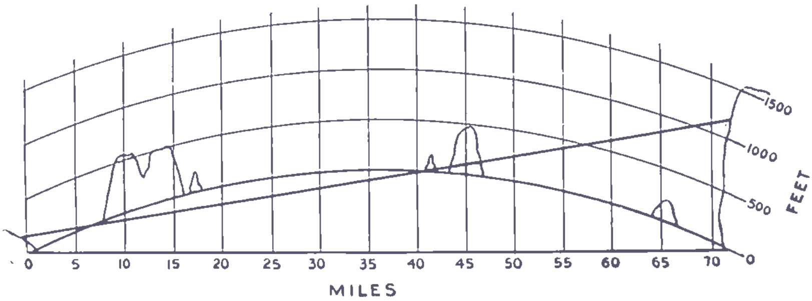

Fig. 10—Profile (4/3 Earth's Radius) of Prince Rupert—Annette Circuit.

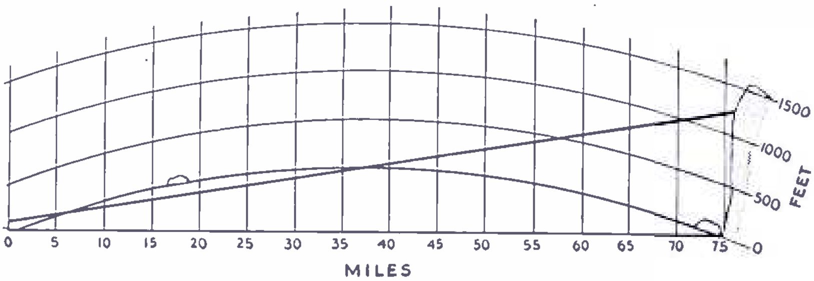

Fig. 11—Profile (4/3 Earth's Radius) of Prince Rupert—Massett Circuit.

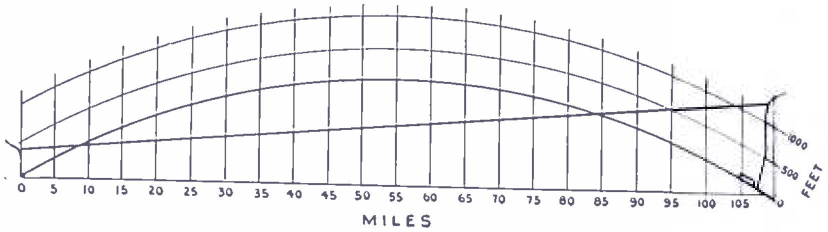

Fig. 12—Profile (4/3 Earth's Radius) of Prince Rupert—Langara Island Circuit.

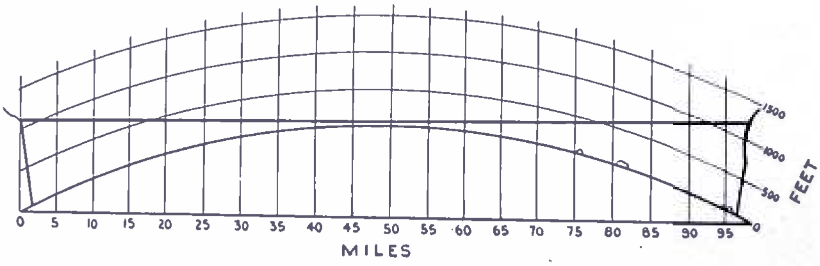

Fig. 13—Profile (4/3 Earth's Radius) of Prince Rupert—Alliford Bay Circuit.

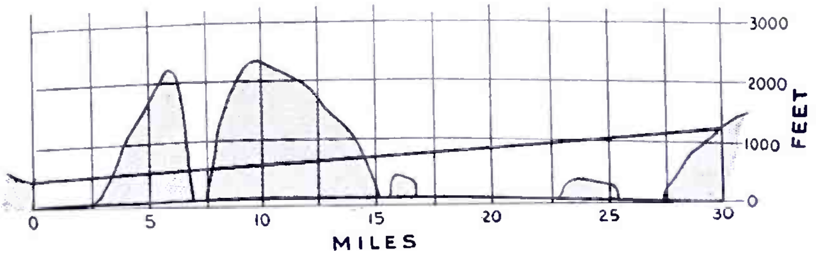

Fig. 14—Profile (4/3 Earth's Radius) of Alliford Bay—Marble Island Circuit.

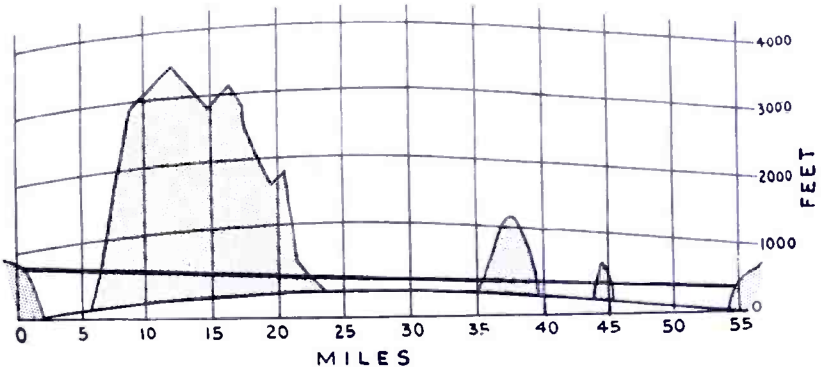

Fig. 15—Profile (4/3 Earth's Radius) of Bella Coola—White Point Circuit.

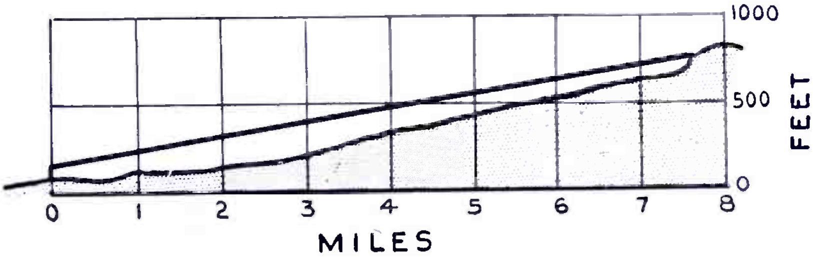

Fig. 16—Profile (4/3 Earth's Radius) of White Point—Bella Bella Circuit.

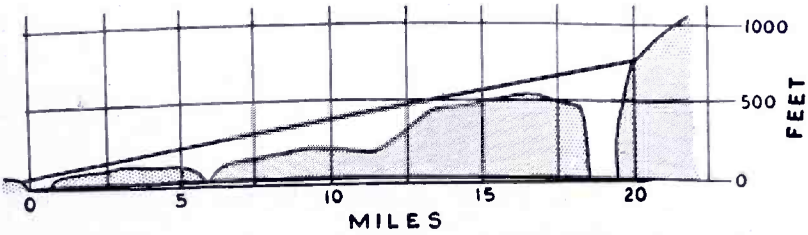

Fig. 17—Profile (4/3 Earth's Radius) of White Point—Spider Island Circuit.

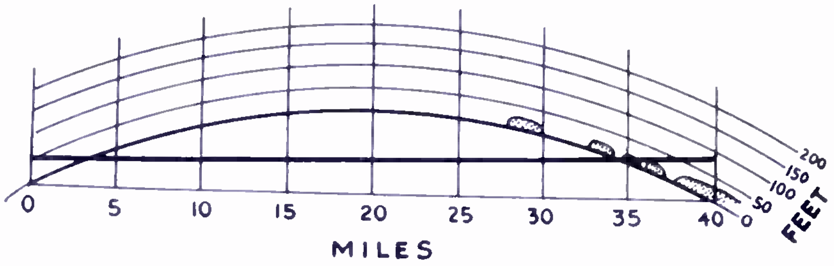

Fig. 18—Profile (4/3 Earth's Radius) of Tofino—Estevan Point Circuit.

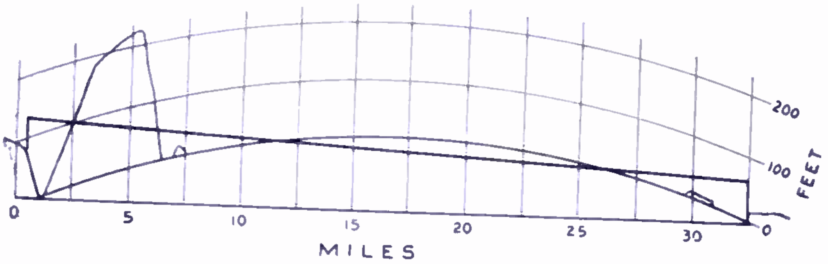

Fig. 19—Profile (4/3 Earth's Radius) of Estevan Point—Ferrer Point Circuit.

approached the idealized conditions assumed in the calculations, fair agreement was obtained. In others in which the profiles seemed equally close to ideal, no agreement at all could be found.

A qualitative analysis of the results obtained from these measurements led to the formulation of several empirical rules, which were found to be of considerable value.

1. Where clear line of sight conditions exist, satisfactory results are practically assured.

2. In the case of a circuit where the line of sight is unobstructed by the earth's curvature, but is blocked by intervening land masses such as mountains, satisfactory results can be expected provided these do not extend over more than about 50 percent of the path, and are not close to either antenna.

3. An obstruction close to either antenna has an extremely deleterious effect.

4. The antenna locations should be as high as possible above the general level of the terrain.

5. The ground immediately in front of the antenna should drop away as steeply as possible.

6. Satisfactory results can be obtained on circuits which are well below line of sight, provided the conditions in (4) and (5) are met.

Although it was felt that the information obtained from the above tests provided an effective means of predicting the operation of the various circuits, it was considered desirable, wherever possible, to check the signal over each circuit before proceeding with the installation of equipment. This was done by making temporary transmitter installations at one end, and checking the received field intensity at the other end of the circuits concerned.

Survey and Installation

A preliminary survey of the northern end of the system was first made, and sites were established, permanently at Prince Rupert, and tentatively at Alliford Bay and Annette Island. Because the system required that four circuits terminate at Prince Rupert, it was considered desirable to separate the transmitter and receiver locations, to minimize interaction. The receiving site was actually located about a quarter of a mile behind, and 200 feet above the transmitter site. Construction work was immediately started on the Prince Rupert site, and when it was sufficiently far along, a test transmitter was installed.

Originally, it had been planned to use twenty-four element arrays for both transmitting and receiving on all circuits. However, when the test transmitter at Prince Rupert was operating, and the field intensity at Alliford Bay was checked, it was found that the signal was strong enough to justify a considerable reduction in antenna size. Four element arrays were installed for this circuit.

As the angle between the Prince Rupert-Massett and Prince Rupert-Langara Island circuits is small, it was felt that one receiving and one transmitting antenna at Prince Rupert would suffice for both. Moreover, the service requirements of the two places permitted the use of a single transmitter to handle both. Two receivers were used, connected to the single receiving antenna. The antennas on these circuits are twenty-four element arrays oriented so that the major lobes are directed towards Langara Island. Field intensity measurements made at Langara Island and Massett after the installation of the transmitting antenna at Prince Rupert indicated that considerable antenna gain would be necessary at the former location, whereas a moderate gain would suffice at the latter. The antennas installed at Langara are eighteen element arrays, the reduction from twenty-four being dictated by limited pole heights. Four element arrays were sufficient at Massett.

Twenty-four element arrays were installed at Prince Rupert for the Annette Island circuit, also. Field intensity measurements showed that four element arrays would be sufficient at the Annette end.

As the profile (Figure 14) shows, the Alliford Bay-Marble Island circuit is badly obstructed. Predicting its performance was difficult in that no very good analogy could be found with any of the test circuits, although it seemed reasonable to expect that with sufficient antenna gain it could be made to work. Four element horizontal arrays were installed initially for trial. The circuit was found to be quite satisfactory, and no changes were made.

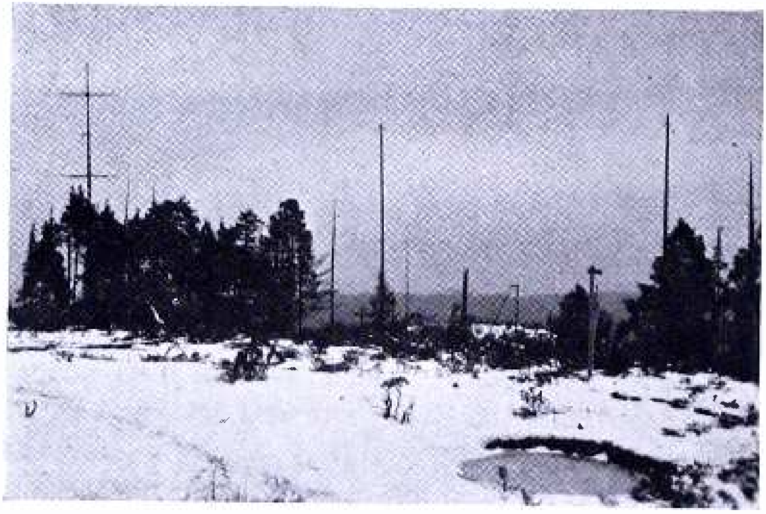

Fig. 20—Prince Rupert Transmitting Site. One twenty-four element Antenna (Massett) and one four-element Antenna (Alliford Bay) visible.

The obvious solution to the problem of establishing the circuits from Bella Coola to Bella Bella and Spider Island, considering the mountainous nature of the terrain, was to site the radio stations at a sufficient elevation to permit direct working. However, careful con-

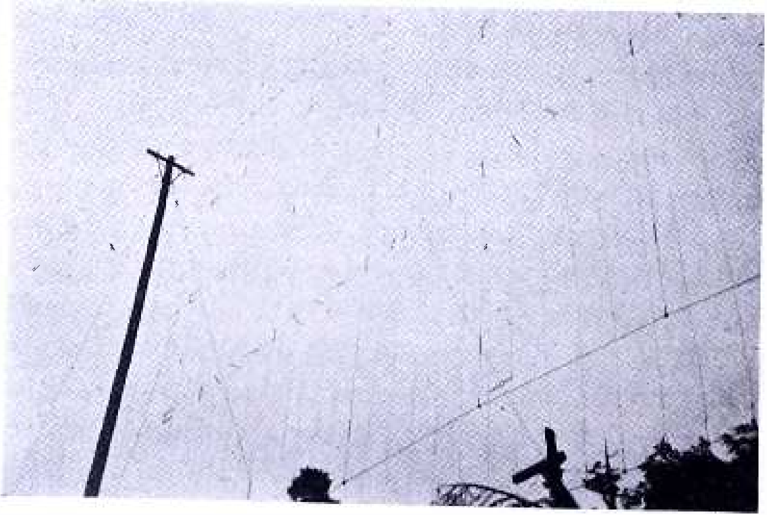

Fig. 21—Twenty-Four Element Antenna Array.

sideration showed that the cost in time and money of developing high elevation sites was such as to make this impractical. Tests were conducted to ascertain the possibility of direct working between low level sites at Bella Coola and Bella Bella, and it was found that this was impossible. This indicated the necessity of at least one relay station, and the site at White Point was selected for trial. Two four-element antenna arrays, one vertical and one horizontal, were erected at Bella Coola, and field intensities of eight to ten microvolts per meter were measured at White Point, with no observable difference between the two polarizations and with considerable fading on both. The feasibility of the circuit still seemed open to question, and in view of the extreme difficulty of locating an additional relay east of King Island along Burke Channel, it was decided to erect twenty-four element horizontal arrays and to examine stability and signal-to-noise ratio. It was found that, under these circumstances, the fades were not deep enough to be troublesome and the average signal-to-noise ratio was satisfactory. The circuit was installed on this basis. A single transmitter is used at White Point for Bella Bella and Spider Island. The antenna comprises two co-linear vertical dipoles 0.4 wavelengths in front of a reflecting screen. This gives a two-lobed pattern, one lobe being oriented on Bella

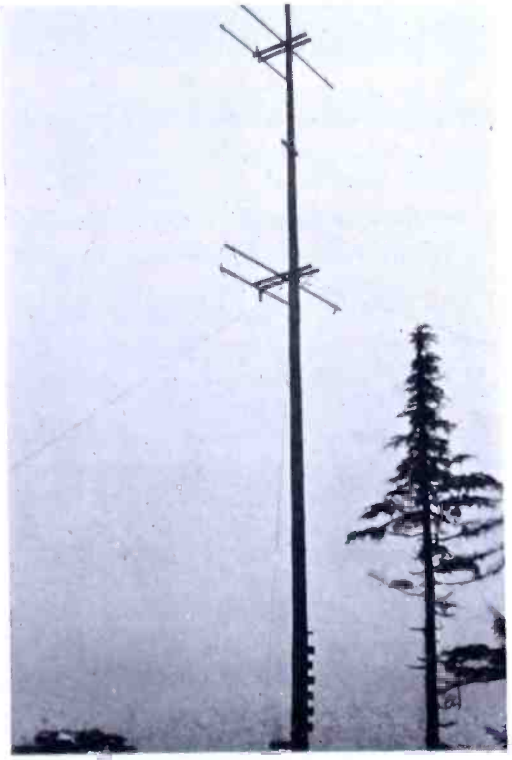

Fig. 22—Four-Element Antenna Array.

Fig. 23—View From Bella Coola Site Towards White Point.

Bella and the other on Spider Island. Single dipoles 0.2 wavelengths in front of reflecting screens are used for receiving at White Point from Bella Bella and Spider Island, and throughout at the latter two locations.

On the Tofino-Ferrer Point circuit no elevation could be readily attained at either terminal, and a relay was thus necessary. Estevan Point was an obvious choice. Four element vertical antenna arrays are used throughout.

Figures 20 to 24 show photographic views of several of the installations.

Fig. 24—Bella Coola Site. Pre-Fabricated Equipment Building.

EQUIPMENT

General

In the planning of a radio telephone circuit, either as a separate entity or as a part of a system, established landline performance standards can be used to great advantage. Telephone performance is judged, basically, on "subjective intelligibility", which is dependent upon the following factors:

1. Cross talk	(a) intelligible	60 decibels below signal.
	(b) babble	
2. Circuit noise	(a) periodic (hum)	
	(b) fortuitous	
3. Distortion	(a) frequency	within 2 decibels in voice range.
	(b) phase	
	(c) harmonic	5%
4. Background (noise other than circuit noise)		
5. Level		− 15 to + 5 Volume Units

The figures shown at the right are approximate minimum commercial telephone standards. It is necessary, of course, that equipment for use on radio telephone circuits be capable of meeting these.

Transmitters

Circumstances, among which availability was paramount, dictated the use of standard 250-watt FM broadcast transmitters operating in the 42-50 megacycle band. The transmitters were 250 watt General Electric 4GF1A1 units. These employ a frequency modulated master oscillator, the center frequency of which is controlled by automatically adjusted bias on the reactance modulator. The control voltage is developed by applying the difference frequency of the master oscillator controlled carrier and a reference frequency derived from a quartz crystal to a discriminator.

Transmitter Specification

Frequency Range:	42-50 megacycles
Output:	250 watts constant signal power from 0-100 percent modulation.
Percentage Modulation:	± 75 kilocycles swing represents 100 per cent modulation.

Audio Frequency Response: ± 1 decibel to the standard pre-emphasized characteristic, as required by Federal Communications Commission in the U. S., from 30-16,000 cycles.

Audio Input level: Normal level 0 Volume Units to 600 ohm input for ± 75 kilocycles deviation.

Harmonic distortion: Less than 1.5 per cent at modulation frequencies between 30-15,000 cycles for carrier swing of ± 75 kilocycles; less than 2 per cent for carrier frequency swing up to ± 100 kilocycles.

Receivers

The receivers were Kaar Type FM38A which were specially designed for this project. These are single conversion crystal controlled super-heterodynes, employing a single radio frequency amplifier stage and an input band pass filter.

Receiver Specifications

Frequency range: 42-50 megacycles.

Sensitivity: 20 microvolts signal to fully saturate 2nd limiter.

Selectivity: 80 decibels down, 300 kilocycles off frequency for combined radio frequency and intermediate frequency stages.

Output Level: Approximately + 20 Volume Units maximum for 75 kilocycles swing.

Output attenuator: Capable of reducing output to zero in 3 decibel steps.

Output impedance: 600 ohms.

Distortion: Maximum distortion 3 per cent, 150-10,000 cycles with 75 kilocycles swing.

Hum Level: 60 decibels down related to reference level ± 75 kilocycles at full audio gain.

Fidelity: The transmission quality between 100 cycles and 10,000 cycles must be such that within the transmission bands 100 to 3,000 cycles, 4,000 to 7,000 cycles and 7,000 to 10,000 cycles, the variation must not exceed ± 1 decibel with respect to 1,000 cycles, 6150 cycles and 8150 cycles respectively.

Undesired Response: 100 decibels.

HF Oscillator:	To be controlled by low temperature coefficient quartz plates.
Antenna input:	Inputs for 600 ohm balanced and 70 ohm unbalanced transmission lines.
Power Supply:	115 volts 60 cycles.
Mechanical:	Rack mounting, panel 19 inches by 8¾ inches. Screw driver adjustment of tuning controls.

Antennas

Directional antenna arrays were used on all installations. On the simpler circuits, these comprise a single dipole located 0.2 wavelength in front of a ground screen reflector. Four element arrays with reflectors and 24 element arrays with reflectors are also used. These latter types were constructed for both horizontal and vertical polarization. Figure 25 indicates the general arrangement of a 24 element vertically polarized array. Spacing between radiator elements is 0.5 wavelengths, and the reflector curtains are spaced 0.2 wavelength from the radiator curtain. Adjacent reflector wires are spaced 0.1 wavelength. Two-wire open transmission line of 525 ohm impedance is used throughout. Transmission line terminations are effected by means of stubs.

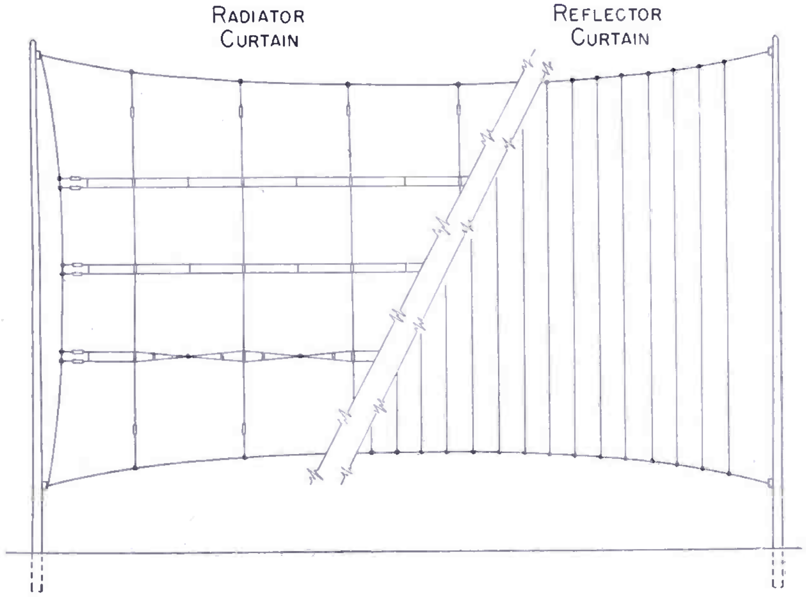

Fig. 25—Twenty-Four Element Vertically Polarized Antenna Array. The Reflector Curtain is approximately 0.2 Wavelengths behind the Radiator Curtain.

Broadside arrays were decided upon in place of long wire arrays principally because the latter require a flat area of substantial proportions for erection, whereas the former require only locations for two poles. As a consequence, the problem of finding a site for a broadside array is much easier, less timber clearing is required and full advantage can be taken of terrain drop-away.

Antenna and transmission line conductors are No. 10 Copperweld wire, 30 per cent conductivity. Steatite insulators and spreaders are used. Wherever possible standard pole line hardware and technique are used.

Primary Power Supply

In all but two locations, primary power is obtained from the adjoining military establishment. This necessitated construction of power lines, the maximum distance required being about 3¼ miles. At the other two sites diesel-powered alternators were installed to provide power.

Carrier Equipment

Where more than a single telephone channel is required, Northern Electric Modified H1 carrier equipment is used. This equipment in its original form provides two telephone channels over a single pair. The modifications provide for four wire operation, with three channels.

Northern Electric (Western Electric) Type 40C voice frequency telegraph equipment is used for teletype operation. Where teletype operation is required, one voice channel is used for this purpose.

Adjustments

Radio frequency and intermediate frequency receiver adjustments are made with the associated transmitter in each case. Receiver discriminators are adjusted for minimum distortion. Distortion indication was obtained by applying a 2700 cycle tone to the transmitter and measuring the level in the first carrier channel—that is, measuring the second harmonic level.

Level adjustments are made such that with zero level (1 milliwatt) applied to the transmitter, it is fully modulated. Receiver output level is adjusted to feed zero level to the terminal equipment. Reduction of levels of each carrier channel and each telegraph channel (to prevent over-modulation from the combined signals) is taken care of in the terminal equipment.

RESULTS

Recordings of receiver input voltage were made on those circuits where it was considered that this information would be most interesting and valuable. These extended over a period of about one week for each circuit. The original recordings were analyzed and the results plotted to show hourly maximum and minimum values (Figures 26 to 30, inclusive). A statistical analysis was also made, the results of which are shown in Figures 31 to 35.

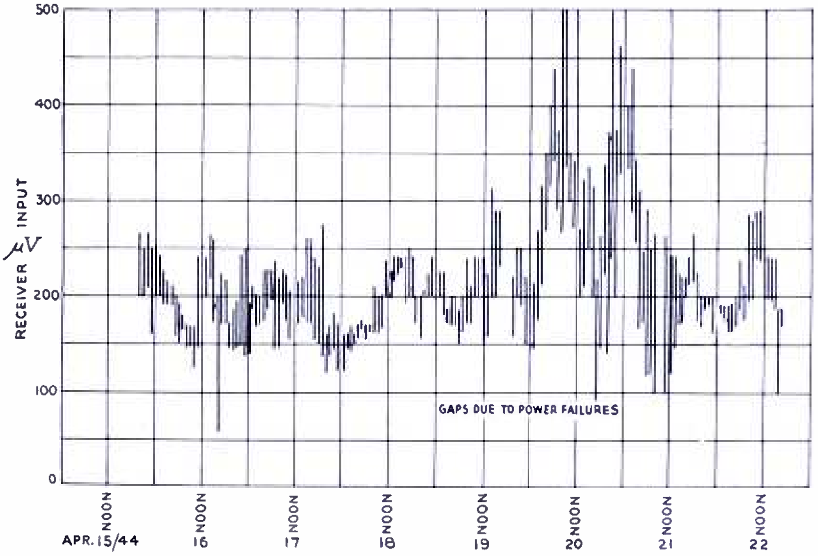

Fig. 26—Hourly Range of Receiver Input Signal, Prince Rupert—Massett.

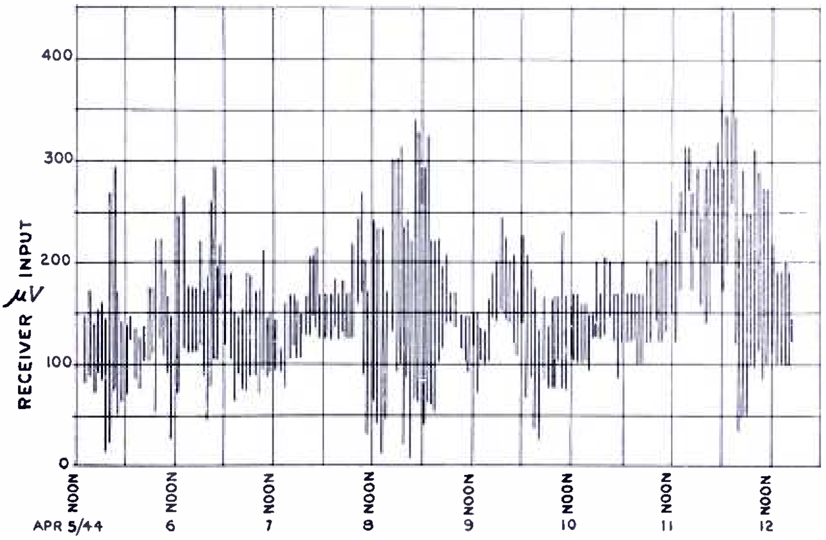

Fig. 27—Hourly Range of Receiver Input Signal,
Prince Rupert—Langara Island.

An examination of the recordings and of the analyses in Figures 26 to 30 fails to reveal anything in the way of a diurnal pattern on the obstructed circuits. On the Prince Rupert-Alliford Bay circuit, the average value of the signal seems to be lower, and the fades less severe,

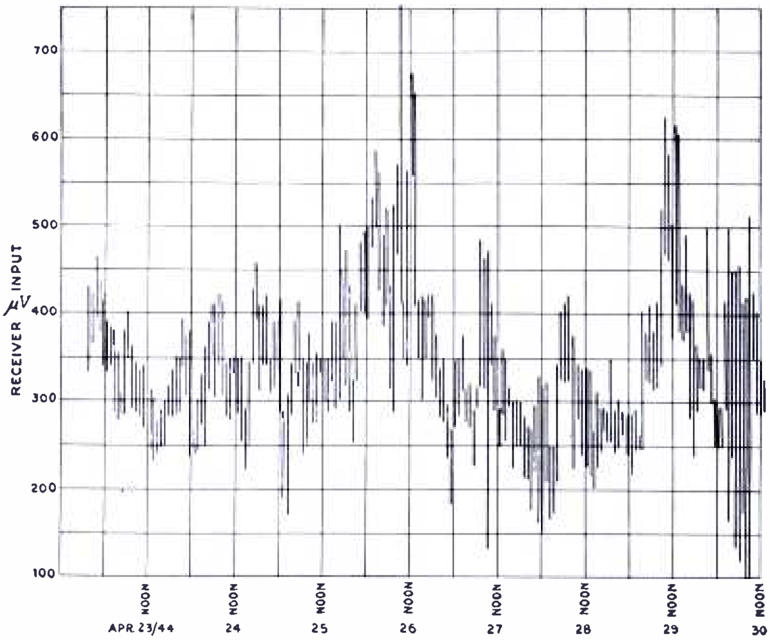

Fig. 28—Hourly Range of Receiver Input Signal, Prince Rupert—Alliford Bay.

at noon than at midnight. It is likely that one week's recording is insufficient to show diurnal variations.

The signal summaries, Figures 31 to 35, show that on all of the circuits recorded, the receiver input remained well above the value

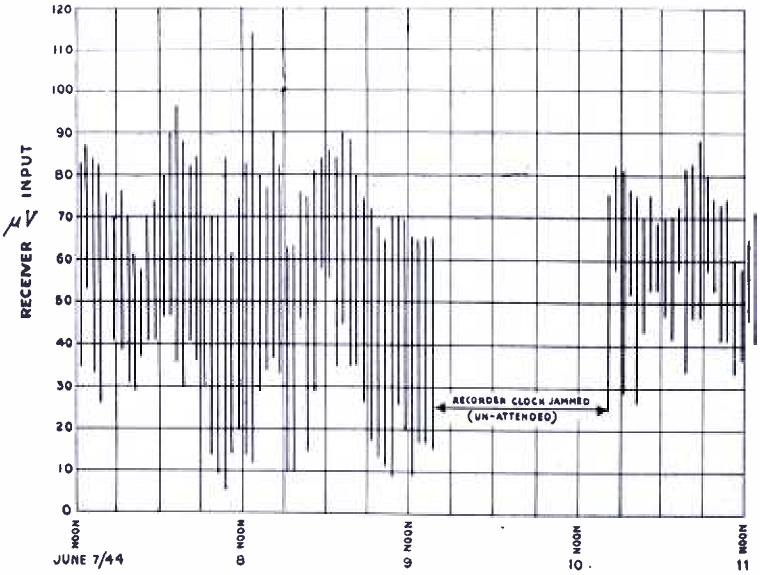

Fig. 29—Hourly Range of Receiver Input Signal, Alliford Bay—Marble Island.

required for full limiter action, 20-microvolts, for all but an extremely small percentage of the time.

In operation, the radio circuits have proven very satisfactory. In comparison with the landline portions of the systems, their performance is decidedly better. A large proportion of the outages on the radio circuits have been due to failure of the power and communication lines leading to the radio stations.

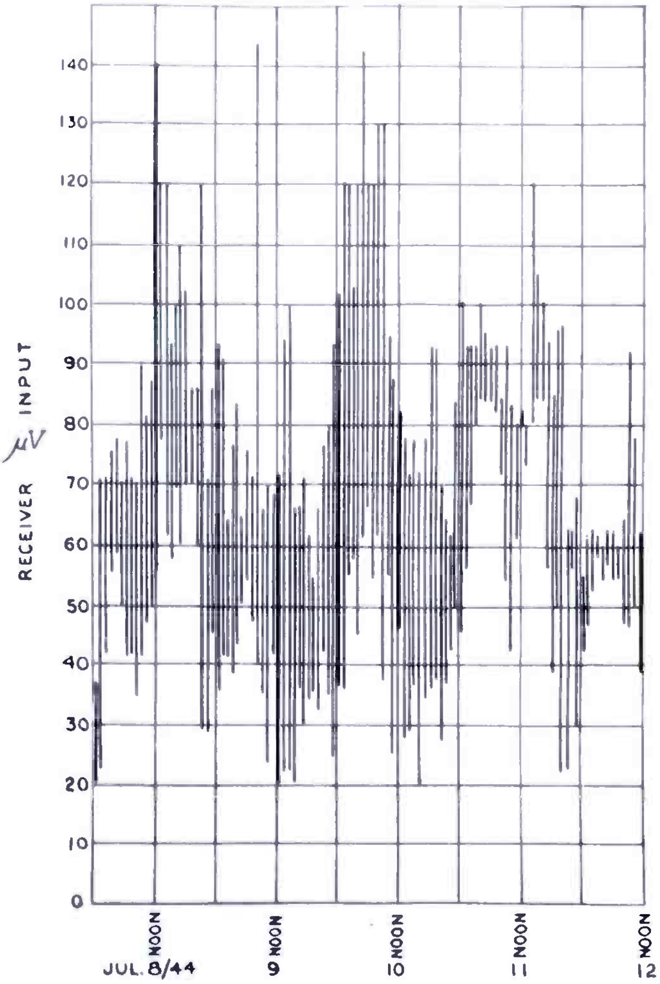

Fig. 30—Hourly Range of Receiver Input Signal, Bella Coola—White Point.

ACKNOWLEDGMENTS

The project described herein was the result of the collaborate efforts of the following organizations: the Royal Canadian Air Force, the British Columbia Telephone Company and its associate, the North West Telephone Company, and the RCA Victor Company Limited. Im-

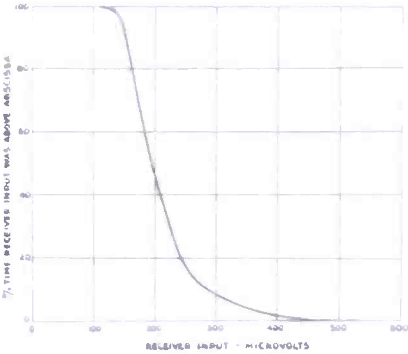

Fig. 31—Receiver Input Signal Summary, Prince Rupert—Massett.

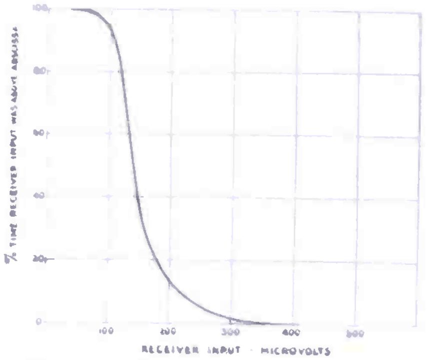

Fig. 32—Receiver Input Signal Summary, Prince Rupert—Langara Island.

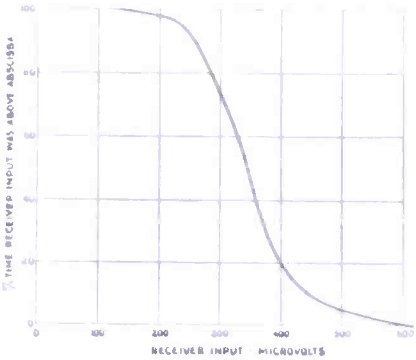

Fig. 33—Receiver Input Signal Summary, Prince Rupert—Alliford Bay.

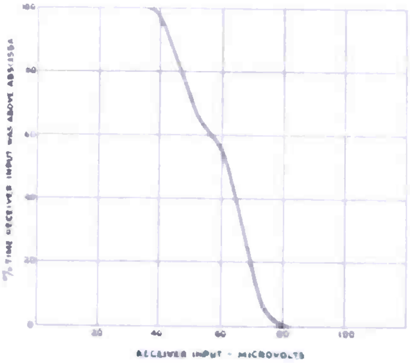

Fig. 34—Receiver Input Signal Summary, Alliford Bay—Marble Island.

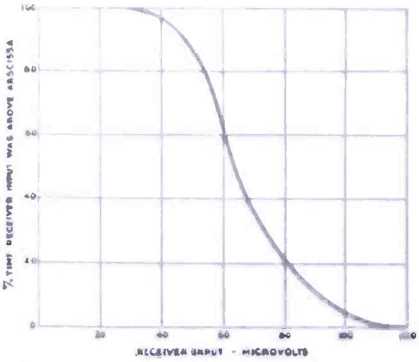

Fig. 35—Receiver Input Signal Summary, Bella Coola—White Point.

portant contributions were made by many individuals from all of these. In particular, the authors wish to acknowledge the collaboration of Mr. B. R. Tupper, of the North West Telephone Company, Flight Lieutenant A. G. McKeen of the Royal Canadian Air Force, and Mr. E. A. Laport, now Chief Engineer of RCA International Division.

LUMINESCENCE AND TENEBRESCENCE AS APPLIED IN RADAR*, †-a, †-b

By

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Summary—*One of the principal technical problems in World War II was to devise radar apparatus which would afford tactical advantages over the enemy. It was especially desirable to have a panoramic map, completely resketched every few seconds, simultaneously showing the locations of distant objects at all points of the compass, or sectors thereof, and over a wide range of elevation angles. To provide such a map it was necessary to devise indicators which would: (1) instantaneously transform megacycle-frequency electrical fluctuations into visible image traces (blips), (2) retain the visible blips, which were produced in microseconds, for a number of different fixed scan intervals up to 30 seconds, and (3) dissolve (clear, or "forget") the previously retained blips at the end of the particular radar scan interval to avoid confusing subsequent images.*

Cathode-ray tubes (CRT),[†-c] *which had been developed for electronic television, were found to be the only practical means for providing radar*

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* Decimal Classification: R138.31

[†-a] The terms "tenebrescence" and "scotophor" are derived from Latin and Greek sources to correspond to the terms "luminescence" and "phosphor." The broad definitions are:

luminescence is any emission of light not ascribable directly to thermal radiation;

tenebrescence is any absorption of light not intrinsic to the materials involved;

a *phosphor* is a luminescent material, usually a crystalline inorganic material, whose luminescence persists for times longer than the normal lifetime of isolated excited non-metastable atoms (approx. 10^{-8} sec);

a *scotophor* is a tenebrescent material, usually a crystalline inorganic material, which may be made to tenebresce reversibly, i.e., visibly darken and bleach (irrespective of chromaticity), under suitable irradiations.

[†-b] This paper is based in part on work done for the Office of Scientific Research and Development (OSRD) under Contract NDCrc-150, and is largely an abbreviated version of the "Final Report on Research and Development leading to new and improved Radar Indicators," NDRC-14-498, covering work done under Contracts NDCrc-150 and DIC-193471 (Jan. 1941-Aug. 1945). A copy of the Final Report, which contains many unpublished data obtained prior to the contract work, is on file in the Office of the Publication Board, Department of Commerce, Washington, D. C. Photographic copies of the final report, and of interim reports Nos. 14-103, 14-249, 14-369, and 14-492, will be available through the Publication Board.

[†-c] This abbreviation will be used throughout this paper.

images. Stratosphere conditions and logistics limited radar CRT voltages to about 5 kilovolts. This restricted radar cathode-ray beam energy densities to values below those used for television CRT's, while radar blips were required to remain visible for time intervals up to 1000 times as long as those used in television.

The chief burden of improvement was placed upon the CRT screen and several new and improved cathodosensitive screens had to be devised, especially for panoramic [†-d] *radars whose bulky antennae necessitated scan intervals much longer than the persistence of vision (approx. 0.1 sec.). The most important radar CRT-screen problems were solved by the introduction of cascade cathodoluminescent screens which could be operated at low luminances by using the enhanced sensitivity of the dark-adapted human eye. Cascade screens, such as the P7 and P14, comprise stratified layers of different phosphors which afford an increase in phosphorescence and a reduction in initial luminescence (flash) of radar blips. The duration of visible persistence of present cascade screens may be adjusted to retain visible blips for many radar scan intervals from about 1 to 30 seconds.*

Attempts were made to provide large persistent images, having dark traces (DT) on a bright field, using: (1) negative modulation of luminescence (so-called "CR-burn" method), and (2) tenebrescent screens of scotophors. The P10 DT screen (KCl scotophor) was found to have possibilities for a few radars operating with scan intervals longer than about 10 seconds per scan, but was limited by low sensitivity, low contrast, and unduly long persistence.

A number of cathodoluminescent CRT screens have been devised with persistences ranging from about one microsecond to over 30 seconds, but none of the present CRT screens gives entirely satisfactory performance in the intermediate-persistence region from about 2 to 20 scans per second where flicker phenomena are most troublesome. One screen material, an exponential-decay fluoride (P12), was developed for use in fire-control radars at scans faster than about 4 per second, but the present fluorides do not maintain their desirable characteristics well during operational life.

Tabular summaries of some of the more useful CRT screens are given as an aid to radar indicator designers.

I. INTRODUCTION

AT the outset of World War II there were six CRT screens, P1 to P6, coded by the Radio Manufacturer's Association. Of these six, only one screen (P2) had visible phosphorescence at times longer than the 0.1-second persistence of vision. The prewar market

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[†-d] In this paper, radars are broadly classified as:

a. *searchlighting radars*, whose antenna beams may be fixed or scanning, but whose indicators show only information included in the instantaneous paths of their beams (these radars may be likened to telescopes which afford information only within a limited solid angle), and

b. *panoramic radars*, whose antenna beams scan continuously and whose indicators show all the information gained during a scanning cycle which is usually longer than the 0.1-second persistence of vision (these radars may be likened to panoramic cameras whose over-lapping images may be combined to provide a complete view of a region in every direction or in certain sectors).

for P2-screen CRT was so small that it was considered uneconomical to develop and manufacture a domestic phosphor to supplant a German phosphor, de Haën "Grün N",[1] then being imported and stocked in lots of 5 lbs. or less for use in theatrical effects and in P2-screens. One of the first effects of the war was to place the United States in short supply of the de Haën phosphor. Coincidentally there was a quickened demand for P2-screen CRT's and these laboratories undertook to synthesize a suitable phosphor for P2 screens.

The de Haën phosphor was equalled by co-crystallizing about two percent of zinc oxide with copper (Cu)-activated zinc sulphide (ZnS) at temperatures above 1020° C.[2, 3] The resultant phosphor may be symbolized as β^*-ZnS:O:Cu.[†-e] This phosphor has appreciably greater cathodophosphorescence[†-f] than non-oxygen-containing β^*-ZnS:Cu, but the increase was small when assessed by the human eye which responds logarithmically to change in stimulus. A greater increase in phosphorescence was achieved by applying the *cascade principle,* i.e., using cathodoluminescence[4] to excite photoluminescence.[†-g] The cascade principle was applied in this case by *dual activation* of β^*-ZnS with both copper and silver (Ag). In operation, the blue cathodoluminescence occasioned by the Ag-activator centers excites green photoluminescence from the Cu-activator centers. Table 1 shows the greater cathodophosphorescence and lesser cathodoluminescence (during excitation) of β^*-ZnS:Ag:Cu, embodying the cascade principle, as contrasted with the best obtainable de-Haën phosphor, β^*-ZnS:O:Cu.

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[1] M. Schilling, "Spektralphotometrische Untersuchungen an einer technischen Leuchtfarbe", *Zeits. f. techn. Physik,* Vol. 21, pp. 232-239, 1940; *Zeits. f. Instrumentenkunde,* Vol. 63, No. 1, pp. 37-38, 1943.

[2] The influence of oxidation on increasing phosphorescence of ZnS is mentioned by A. A. Guntz, "Etude Sur Les Sulfures De Zinc Phosphorescents", *Ann. de Chimie,* Vol. V, No. 10, pp. 157-198, 363-420, 1926.

[3] A. Wakenhut, U. S. patent 2,136,871, 11/15/39; S. Rothschild, Brit. patent 550,800, 1/25/43; M. Goodman, U. S. patents 2,310,424 and 2,310,425, 2/9/43.

[†-e] To achieve uniformity, the low-temperature modifications of crystals are here designated as α —, and successively higher-temperature modifications are denoted by β —, γ —, etc. Where this symbolism is variant with established (haphazard) notations, the symbol is starred. In the cited case, β^*-ZnS refers to the hexagonal (wurtzite) form of ZnS.

[†-f] Cathodophosphorescence is phosphorescence following excitation by cathode rays.

[4] H. W. Leverenz, "Cathodoluminescence as applied in Television", RCA REVIEW, Vol. V, No. 2, pp. 131-176, Oct. 1940; *Jour. Tele. Soc. (London),* Vol. 3, pp. 160-166, 1941.

[†-g] Photoluminescence is luminescence excited by undulatory radiant energy such as ultraviolet or visible light.

Table 1.

Cathodophosphorescences of long-persistence zinc sulphides.

Measured By:	Visual		931 Photomultiplier (unfiltered)									
	Cathode Ray Luminescence		Phosphorescence (t in seconds)								Main	Aux.
		$t = 0$	.25	.5	1	2	4	8	16	20	Peak Å	Peak Å
β*-ZnS:Ag:Cu (33-Z-22)	130	2,920	46	26	16	7.6	4.4	2.5	1.4	1.1	5200	4500
β*-ZnS:O:Cu (de Haën)	190	2,850	30	14.5	8.2	4.1	2.3	1.4	.7	.5	5200	——

Excitation by one second of 6-kilovolts, 4-microamperes per square centimeter cathode ray.

Dual-activation of ZnS:CdS phosphors had previously been proposed to provide a specific white-emitting fast-decay phosphor for television,[5] but the cathodoluminescence efficiency (during excitation) of such dual-activated phosphors is lower than the efficiency obtainable with a single activator.[†-h] This is shown in Figure 1 for ZnS(86):CdS:Ag:Cu which is compared with the dual-activated β*-ZnS:Ag:Cu listed in Table 1.

While the dual-activated β*-ZnS:Ag:Cu phosphor utilized cascading to achieve improved phosphorescence, the cascade action was not as effective as it would be if the Ag-activator centers alone were excited by cathode rays and the Cu-activator centers were subsequently excited solely by the blue cathodoluminescence from the Ag-activator emission band. A more clear-cut cascading was required to minimize the oft-observed rapid decay of cathodophosphorescence contrasted with the slower decay of photophosphorescence for the same phosphor. This *differential effect* of corpuscular vs. undulatory excitation energies on the phosphorescences of two typical phosphors is exemplified in Figures

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[5] A. Wakenhut, Ger. patent 640,056, 12/21/36.

[†-h] This has been mentioned on Page 142 of reference 4. It is conceivable that improved efficiency during excitation might be obtained from multiple-activation if the different activators occupied structurally dissimilar sites in the crystal. For example, one activator might occupy interstitial sites and another be located in normal (substitutional) sites.

2 and 3.[6] The differential effect is attributable to the lower efficiency of cathodoluminescence which leaves in the phosphor a larger residue of heat per emitted light quantum and, hence, accelerates the release of trapped electrons or, to a lesser extent, the collapse of metastable states.[7] The greater local heating by corpuscular excitation is aggravated when the corpuscular excitants have lower penetrating power than the undulatory excitants. Low-voltage cathode rays (below about

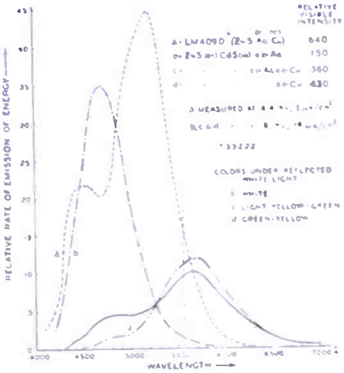

Fig. 1—Cathodoluminescence emission spectra of several single- and dual-activated sulphide phosphors.

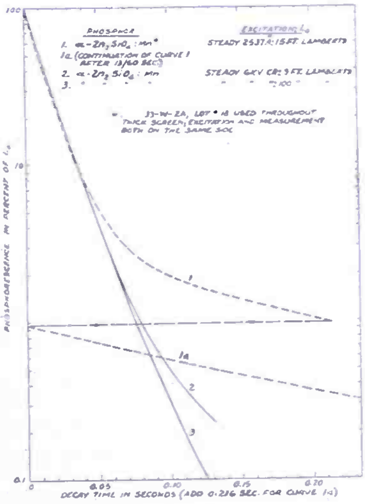

Fig. 2—Relative phosphorescences of α-Zn_2SiO_4:Mn(P1) after excitation by cathode rays and by ultraviolet.

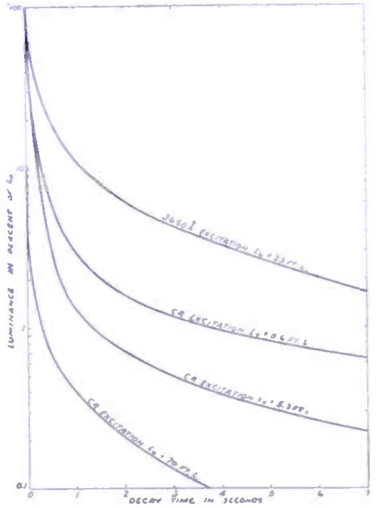

Fig. 3—Relative phosphorescences of ZnS(86%):CdS:Cu(0.0073%) (P7/2) after excitation by cathode rays and by ultraviolet.

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[6] The differential effect for a similar ZnS:CdS:Cu phosphor is shown also in: G. R. Fonda, "Factors affecting Phosphorescence Decay of the Zinc Sulphide Phosphors", *Trans. Electrochem. Soc.*, Vol. 87, pp. 69-82, 1945.

[7] H. W. Leverenz, "Corpuscular vs. Undulatory Excitation of Phosphors", Paper F10, *Bulletin of the American Physical Society*, Cambridge Meeting, Vol. 21, No. 2, page 17, April 26, 1946.

10 kilovolts) penetrate less than the 2537-Å or 3650-Å ultra-violet normally used to excite phosphors and, hence, low-voltage cathode-ray excitation leaves its larger heat residue in a smaller excited volume than would be the case for a particular phosphor excited to the same luminescence by near ultraviolet.[8, 9] At high velocities of corpuscular radiations, the average excitation density in the phosphor is quite low, especially when secondary radiations of high penetrating power are produced. This decrease in excitation density partly accounts for the observed increase of efficiency of cathodoluminescence with increasing voltage[10] and possibly for the reportedly high efficiency of radioluminescence.[11]

Since the differential effect is quite large, especially with sulphide-(selenide-) type phosphors which have predominantly power-law decays ($L \propto t^{-n}$), efforts were made to devise ultraviolet-emitting cathodoluminescent materials whose emissions would cascade-excite photoluminescent materials. This procedure is attractive as a means of utilizing some of the better photophosphorescent materials such as the alkaline-earth-sulphide and boric-acid (+ organic dyes) phosphors, which are inefficient under cathode ray excitation. Several of the ultraviolet-emitting cathodoluminescent materials were reported previously,[4] and further examples are given in Figure 4. While the cited ultraviolet-emitting phosphors were too inefficient for immediate practical application, they were used in early 1940 to demonstrate clear-cut cascading of phosphors.

One experiment involved coating one side of a thin fused-silica disc with an Al_2O_3 (1600° C.) phosphor and coating the other side of the

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[8] Approximate cathode ray penetrations as a function of voltage are given in: H. W. Leverenz, "Problems Concerning the Production of CRT Screens", *Jour. Opt. Soc. Amer.*, Vol. 27, pp. 25-35, 1937. The voltages shown in the left column of Table III of the referenced article should be multiplied by 2.14 to bring them into closer agreement with the experimental results of H. M. Terrill, X-RAY TECHNOLOGY, D. Van Nostrand Company, Inc., New York, N. Y., 1930. Terrill's equation for the penetration, x, of electrons accelerated by V_o volts to impinge on material of density σ, is: $x = 2.5 \times 10^{-12} V_o^2/\sigma$ cm.

[9] Ultraviolet penetration data are given by W. de Groot, "Luminescence Decay and Related Phenomena", *Physica*, Vol. VI, pp. 275-239, 1939, Vol. VII, pp. 432-446, Vol. VIII, pp. 805-809, 1941. See also C. K. Lui, "Absorption and Excitation of Zinc-silicate Phosphors", *Jour. Opt. Soc. Amer.*, Vol. 35, pp. 492-494, 1945.

[10] W. B. Nottingham, "Electrical and Luminescent Properties of Willemite under Electron Bombardment", *Jour. Appl. Phys.*, Vol. 8, pp. 762-778, 1937. S. T. Martin and L. B. Headrick, "Light Output and Secondary Emission Characteristics of Luminescent Materials", *Jour. Appl. Phys.*, Vol. 10, pp. 116-127, 1939.

[11] N. Riehl, PHYSIK UND TECHNISCHE ANWENDUNGEN DER LUMINESZENZ, J. Springer Pub. Co., Berlin, Germany, 1941. K. Birus, "Kristallphosphore", *Ergeb. d. exakten Naturw.*, Vol. 20, pp. 183-268, 1942.

disc with α-Zn_2SiO_4:Mn, α^*-ZnS:Ag, and ZnS:CdS:Ag (in separate patches). The coated disc was placed in a demountable CRT where the Al_2O_3 phosphor, under cathode-ray excitation, emitted sufficient ultraviolet to excite all the phosphors on the reverse side of the disc. The fused-silica disc was an effective selective barrier which transmitted ultraviolet and visible light, but absorbed all the residual primary cathode rays which traversed the Al_2O_3 phosphor. Further experiments were carried out by constructing two sealed-off CRT, made of Corning 970HW ultraviolet-transmitting glass, with Al_2O_3-phosphor screens. The cathodoluminescence from these CRT was found to excite all the photoluminescent materials placed nearby, since few phosphors have excitation bands which do not overlap the broad-band emission of Al_2O_3 (Figure 4). Although the cascade principle was demonstrated to be feasible for exciting photoluminescent materials by intermediately converting cathode-ray energy into ultraviolet or blue light, it did not achieve practical significance until the advent of panoramic radars which tolerated very low luminances to gain image retention during long scan intervals.

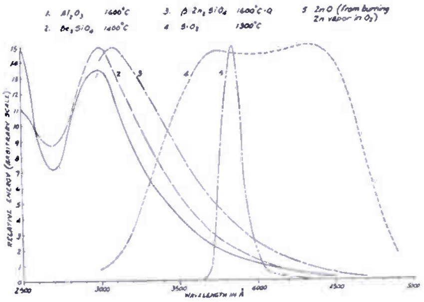

Fig. 4—Cathodoluminescence emission spectra of some ultraviolet-emitting phosphors. All peak energies set at an arbitrary maximum of 15.

II. Radar Images (Displays)

Radar determines the locations of distant objects by *objective measurement* of the time required for directed microsecond pulses or frequency-modulated patterns of electromagnetic radiation to travel from the radar antenna and echo back.[12, 13] An illustration of the general mechanism of a land-based radar is shown in Figure 5. Radar information, especially in the case of pulse radars, is usually presented as map-like images showing azimuth, elevation, and/or range of remote

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[12] E. Appleton, "The Scientific Principles of Radiolocation", *Jour. Inst. of Elec. Eng. (London)*, I. Vol. 92, No. 57, pp. 340-354, 1945.

[13] J. H. DeWitt Jr., "Technical and Tactical Features of Radar", *Jour. Frank. Inst.*, Vol. 241, pp. 97-125, 1946.

objects. Interpretation of radar images is a matter of *subjective discernment* which is accomplished by observers specially trained in the fine art of "blipology." It is apparent from Figure 5, that radar indicators must transform *objective* radar information, gathered and assembled with invisible kinds of energy, into visible maps designed to be most useful to the *subjective* physiological and psychological processes of the observer.

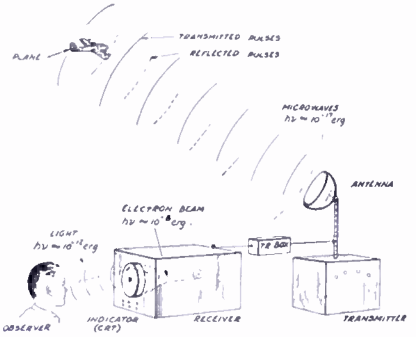

Fig. 5—Schema of radar. The CRT screen transforms objective data into subjectively perceptible information.

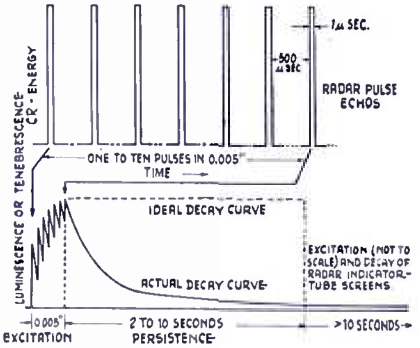

Fig. 6—Exemplary excitation and decay of a radar CRT screen in PPI operation.

The energy-versus-time relationships of typical radar pulses and ideal-vs.-real indicator-screen persistence characteristics are sketched in Figure 6. Noise and clutter[†-1] are omitted for simplicity. The time between transmission of a pulse and the reception of its echo is used to determine range; 10 microseconds corresponding roughly to one mile.

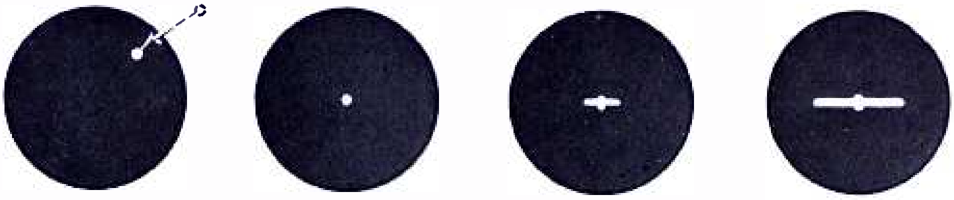

Fig. 7—A nightfighter airplane radar image. Center of image is center of gunfire. Length of simulated wings proportional to nearness of the target.

Several typical radar displays (image types) are shown schematically in Figures 7 and 8. Figure 7 shows a type of searchlighting nightfighter airborne radar image which indicates the position of another plane with reference to the observer's line of flight. When the target

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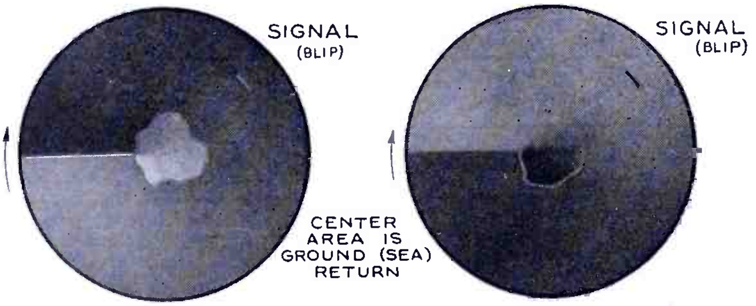
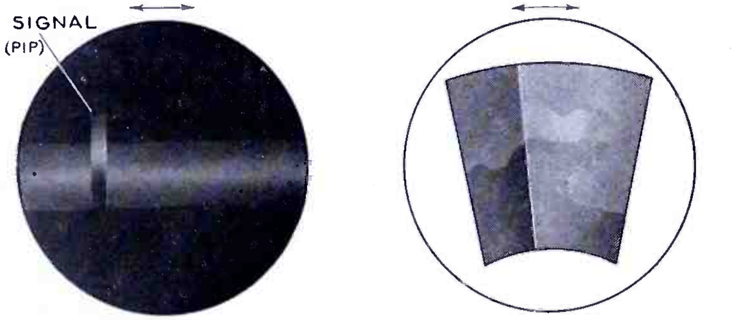
[†-1] Clutter is a collective term including visible indications of: (1) fixed echos such as ground or sea-returns; (2) countermeasures interferences, such as from "chaff" or "window" (metallised strips dropped from aircraft to obfuscate radar detection in that region); and (3) vestigial blips from previous images.

has been brought into the dead-ahead position, the length of the simulated "wings" (proportional to signal strength) indicates relative nearness. Figures 8(a) and 8(b) show the panoramic radial-scan plan-position-indicator (PPI) which may be displayed as bright traces (BT) on a dark background or by the opposite effect of dark traces (DT) on a bright background. The radial length normally indicates range while the angular displacement of the blip from a fiducial direction usually indicates azimuth. Figure 8(c) shows the searchlighting type-A scan which usually shows range alone, but may be arranged to indicate elevation angle. In the latter case, the elevation indicator plus a range-azimuth PPI affords the three-dimensional information which is necessary to locate a distant object in space with range accuracy up to ± 5 yards (independent of range), and angular accuracy of the order of 3 degrees.[†-j] Figure 8(d) shows a panoramic airborne Eagle scan which virtually displays a sector of a PPI scan; more exactly, this is



BT, PPI (a) CASCADE-PHOSPHOR (P7)
DT, PPI (b) DARK-TRACE (P10)
(ANGLE = AZIMUTH; RADIUS = RANGE)



BT, TYPE-A SCAN (c) P1 OR P7 (ABSCISSA = RANGE; ORDINATE = SIGNAL STRENGTH)
BT, EAGLE SCAN (d) CASCADE-PHOSPHOR (P14) (ABSCISSA = LATERAL DISTANCE; ORDINATE = RANGE)

Fig. 8—Sketches of typical radar images.

[†-j] The angular accuracy in radians is proportional to the wavelength of the radiation (in cm) divided by the diameter (in cm) of the radar "dish" (antenna).

a sector of an annulus. Many other display types exist, mostly based on the original rectilinear scans listed in Table 2.

Table 2.

Radar Scan Types		
Scan	Ordinate	Abscissa
A	Signal Strength	Range
B	Range	Azimuth
C	Elevation	Azimuth

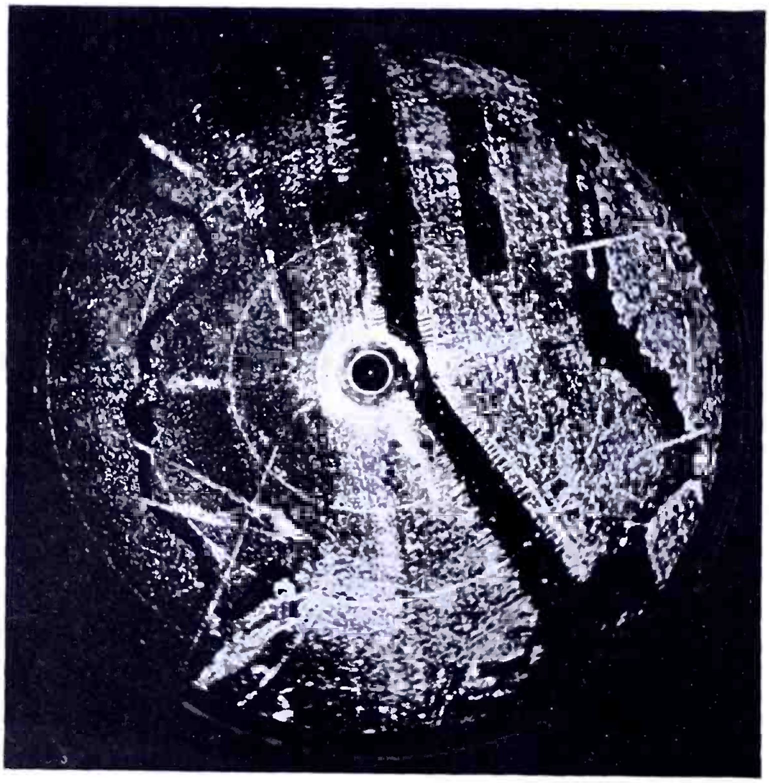


Fig. 9—High-definition PPI image of New York City (courtesy of the Radiation Laboratory, M.I.T.).

A circular *A* scan is called a *J* scan, and a *B* scan in polar coordinates is the PPI. The PPI scan is tantamount to rotating an intensity-modulated *A* scan about one end (where distance = 0) as a pivot. A photograph of a high-resolution airborne PPI image of New York City, obtained through the courtesy of the Radiation Laboratory (M.I.T.), is shown in Figure 9.

III. RADAR CATHODE RAY TUBES

Since radar information is obtained in times reckoned in microseconds and must be displayed in maps which are continuously resketched in times reckoned in seconds, CRT's (especially high-vacuum CRT's) are the only satisfactory means now available for general indicator purposes. This is so because cathode-ray beams are unique in that they may be modulated and deflected, with low power consumption, at megacycle frequencies.

Some pre-war television projection CRT's were operated at 70 kilovolts with 70 watts of cathode-ray beam power to afford about 2500 footlamberts of screen luminance.[14] Airborne radar CRT's were limited to voltages below 5 kilovolts to minimize the bulk of their power supplies and obviate electrical breakdown during non-pressurized stratosphere operation. Higher voltages could have been used in land and ship radars, but it was deemed best to standardize at 5 kilovolts or below to simplify logistics. A minor exception was made in the case of the few P10-screen CRT's which were operated at 9 kilovolts to compensate in part for the relatively inefficient cathodotenebrescence of evaporated KCl (P10 scotophor).

The 5-kilovolt "ceiling" on wartime radar CRT's limited their available cathode-ray beam power to values below about 1 watt. Even this low power was turned on only when signal-plus-noise overcame the arbitrarily-controlled grid bias. Since 5-kilovolt cathode rays penetrate less than 0.2 micron (μ) in most phosphors and scotophors, effective use could not be made of the 0.1-μ-thick aluminum film which is incorporated in some television CRT's. The aluminum film assures full utilization of the applied voltage and reflects all the luminescence in the direction of the observer or projection system.[15–18]

In radar, as in television, compromises had to be made between the incompatible demands for small indicators and large images. Large images may be viewed by a number of observers simultaneously, and

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[14] I. G. Maloff and D. W. Epstein, "Reflective Optics in Projection Television", *Electronics*, pp. 98-105, Dec., 1944.

[15] K. Schlesinger, U. S. patent 2,029,639, 2/4/36. R. R. Law, U. S. patent 2,233,786, 3/4/41; U. S. patent 2,308,563, 12/1/42; J. Kaspar, H. Katz, and E. Stendel, German patent 703,255, 1/30/41; and V. J. Schaefer, U. S. patent 2,374,311, 4/24/45.

[16] A. de Quervain, "Ein neuartiger Leuchtschirm fuer Kathodenstrahlroehren, speziell fuer Fernsehzwecke", *Hochfr. u. Elektroakustik*, Vol. 54, pp. 151-153, 1939.

[17] C. H. Bachman, "Image Contrast in Television", *Gen. Elec. Rev.*, Vol. 48, No. 9, pp. 13-19, 1945.

[18] D. W. Epstein and L. Pensak, "Improved Cathode-Ray Tubes with Metal-Backed Luminescent Screens", RCA REVIEW, Vol. VII, No. 1, pp. 5-11, March, 1946.

larger image blips (irrespective of shape) may be discerned at lower luminances.[19] The lower luminances are, unfortunately, automatically achieved on expanding the CRT image size (without increasing the cathode-ray beam power), since the power delivered to a screen element by an unmodulated cathode-ray beam is inversely proportional to the area of the image. Wartime radar CRT's had mostly 3-inch to 7-inch screen diameters, the largest being 12 inches. The largest United States radar images were produced by optically projecting a 4-inch P10 CRT (4AP10) image onto a 26-inch diameter translucent screen. Larger images were produced experimentally, but did not achieve practical significance.

IV. ENERGY IMPARTED PER BLIP

Panoramic radars usually provide considerable overlapping of cathode-ray beam pulses, from a given signal, during each scan. This increases the probability of obtaining signal-plus-noise blips which have greater intensities than average noise blips. The degree of overlapping of cathode-ray pulses may be exemplified by considering a 5-inch diameter CRT in PPI operation at 10 rpm and 925-cycle radial repetition frequency. Full range, which is usually made proportional to the full radial length, would be about

$$\frac{1080 \text{ microseconds}}{10.8 \text{ microseconds per mile}} = 100 \text{ miles.}$$

(0.8 microseconds is the approximate return time of the radial sweep.) At full range the circumferential velocity of the 100-mile point would be 67 millimeters/second. For a cathode-ray beam diameter of 0.5 millimeter, the center of the spot on the screen may be pulsed 7.5 times per scan if each signal-plus-noise pulse resultant is above the cutoff bias. At the 50-mile range the overlapping could be as much as 15 times per scan. The distinctive arc shape of PPI blips is a decided aid in signal detection, especially when the peak signal power is several decibels below the average noise power.

A useful concept of the means used for producing visible blips may be developed by speaking in terms of the total energy imparted per unit area of blips within a time shorter than the 0.1-second persistence of vision. An image blip is produced by the sum of the energies delivered by one or more pulses of cathode rays within units of time about 0.1 second long. This elementary energy sum $\sum_{t}^{t+0.1} E_t$ largely deter-

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[19] Studies by J. Fairbairn and R. G. Hopkinson, Gen. Elec. Co. Ltd.,[7-b] (cf. *Phot. Jour.*, Vol. 77, page 543).

mines the immediate intensity (flash) of a blip. The blip intensity at some later time is a complex function of the sums of many previous $\sum_{t}^{t+0.1} E_t$ each weighted by its time-displacement from the time of observation and further weighted by the variation of screen persistence with the state of excitation of the screen at the time each pulse was applied. The *approximate* cathode-ray energies $\sum_{t}^{t+0.1} E_t$ imparted per scan per unit area of blip, during "typical" PPI operation, are given in Table 3.

Table 3.

Energy Imparted per Blip During Operation of Radar CRT.

Screen	Kilovolts	ergs/square millimeter per scan
BT (P7)	5	0.5 to 100
DT (P10)	9	20 to 200

V. RADAR IMAGES (HUMAN DEMANDS)

The objective of radar is to locate distant objects expeditiously and to aid in translating the locative information into superior tactical action. In special cases this may be done by direct actuation as, for example, in robot radar control of computers and anti-aircraft batteries. Most radars, however, portray their information to observers who must exercise discrimination and judgment in translating the radar information into directed action.

The chief human demands on radar images are indicated in the following brief description of the properties of the human eye: The average human eye is a very selective receiver of radiant energy in the range from 4×10^{14} to 7.5×10^{14} cycles, as shown in Figure 10. After approximately 30 minutes of dark adaption the spectral sensitivity and luminance sensitivity of the average eye change considerably, as shown in Figure 11.[20] The completely dark-adapted (scotopic) eye is over 50,000 times more sensitive to low luminances than

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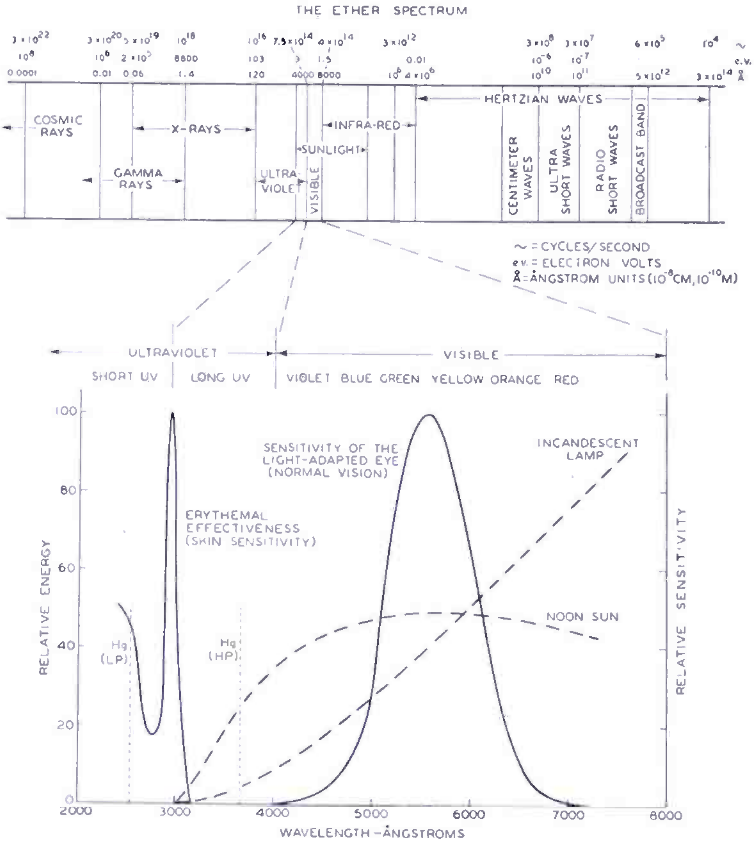
[20] C. Sheard, "Dark Adaptation: Some Physical, Physiological, Chemical, and Aeromedical Considerations", *Jour. Opt. Soc. Amer.*, Vol. 34, pp. 464-508, 1944.



Hg(LP) = 2537-Å LINE OF MERCURY DISCHARGE PREDOMINANT AT 3-4 MM PRESSURE
Hg(HP) = 3650-Å LINE OF MERCURY DISCHARGE PREDOMINANT AT HIGH PRESSURES

Fig. 10—Visible and near-visible spectra, with reference to the general electromagnetic spectrum.

the normal light-adapted (photopic) eye, but the scotopic eye is a much poorer detector of luminance differences (intensity contrasts)

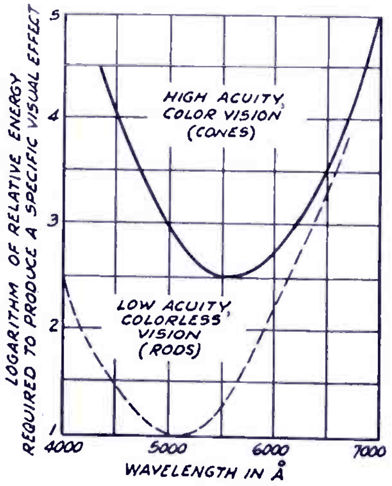


Fig. 11—Thresholds of rod (scotopic) and cone (photopic) vision as functions of wavelength and relative energy (Sheard).

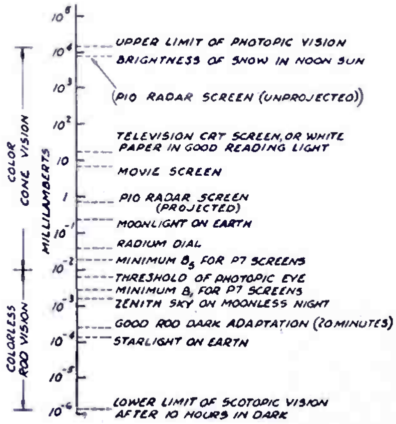


Fig. 12—Luminance chart, according to Sheard, with additional radar luminances. The mesopic region, intermediate photopic and scotopic vision, is attained gradually on going to luminances below 0.1 millilamberts.

and has much less acuity than the photopic eye. The scotopic eye is very sensitive to weak blue-green light, but it rapidly loses its sensitivity if it views strong light, other than red. A luminance scale is shown in Figure 12 to provide orientation with respect to familiar luminances. It is seen that persistent images now used for panoramic radars have very low luminances which adversely affect (1) speed of vision,[4] (2) detection of weak signals, and (3) resolution of fine details.

One beneficial effect of low luminances is the greater tolerance which the eye has for low-intensity cyclic luminances in the bothersome flicker region of image repetitions. The decrease of critical flicker frequency (CFF) with decreasing image luminance and angle of acceptance (angle subtended by the image with respect to the eye at a particular distance) is shown in Figure 13.[4] At high luminances the critical flicker frequency is lowest for blue images, but at low luminances the critical flicker frequency is lowest for red images.[21] Figure 14 shows the image repetition frequency (IRF) ranges of some present radar scans relative to (1) the tolerable flacker region, (2) the troublesome flicker region, and (3) the flickerless region of cyclic luminances. An ideal radar screen would obviate flicker or flacker by having the ideal "square-wave" persistence shown dotted in Figure 6.

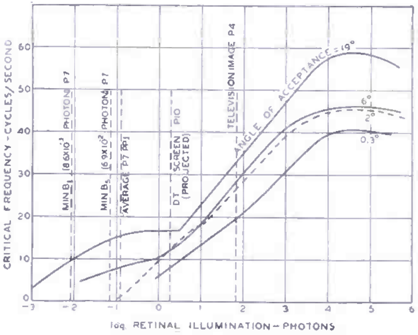


Fig. 13—Critical flicker frequency as a function of field brightness (Hecht and Smith).

An analysis by Dr. D. O. North[†-b] has shown that the best signal-to-noise discrimination in radar indicators "involves a square-law detector feeding into an adding machine (linear integrator)". Effective linear integration requires "square-wave" CRT-screen decays with persistence longer than the 0.1-second persistence of vision.

Most radar observers *desire* large (over 12-inch diameter), high-resolution (less than 0.1-mm diameter cathode-ray spot), non-flicker-

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[21] J. P. C. Southall, INTRODUCTION TO PHYSIOLOGICAL OPTICS, page 311, Oxford University Press, London, Eng., 1937. Also, Wright and Pitt, *Proc. Phys. Soc. (London)*, Vol. 46, page 459, 1943.

ing, red images with luminances greater than 20 millilamberts and image contrasts greater than 20/1. Such images would afford maximum utility with minimum tedium in extracting pertinent information. To obtain useful tactical information, however, most dark-adapted radar observers *need* only about 4-inch diameter images with 0.5-mm diameter cathode-ray spot, 0.01-millilambert image luminance, and contrasts of the order of 1.05/1, almost irrespective of color and degree of flicker or flacker. The distinction made here between need and desire is very important, especially during the transition from wartime to peacetime radars when considerations of cost and comfort enter as large desire factors additional to the need factors which already beset radar indicator designers.

From the standpoint of those who devise CRT screens, there is a noteworthy difference between research on radar and television screens. Monochrome television screens, operated at the practically-flickerless, fixed, United States-standard image repetition frequency of 60 cycles, were devised independent of changes made at the pick-up and transmission end of television. In radar, however, CRT-screen researchers became acutely aware of the design problems of panoramic radar antennae whose inertias determined the maximum image repetition frequency and corresponding image retention intervals in the ranges shown in Figure 14.

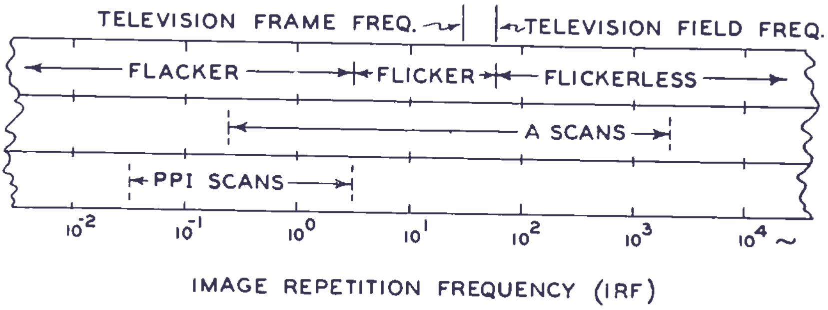

Fig. 14—The image-repetition-frequency spectrum in scans per second.

VI. Cathodosensitive Materials

The forepart of this article has stressed the human demands upon, and physical circumscriptions of, radar indicators. This section describes radar CRT screen materials which exceed the minimum subjective human needs without exceeding the objective limitations of low-voltage CRT.

General Means for Making Cathode Ray Energy Visible.

There are many proposed non-luminescence means for converting cathode ray energy into visible image traces. Among the proposals are light valves using: suspensions of opaque plate-like particles,[22] Kerr cells,[23] polarizable crystals,[24] eidephors,[25] intermediate-film techniques,[26] electrostatic repulsion of fine powers,[27] control of critical angle of reflection,[28] and scotophors.[29] Other general image-forming methods include incandescence under cathode rays[30] and electrolytic control of dyeing.[31] Thus far, however, only cathodoluminescence and catho-

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[22] a. J. S. Donal Jr., "Cathode-Ray Control of Television Light Valves", *Proc. I. R. E.*, Vol. 31, pp. 195-208, 1943.

b. J. S. Donal, Jr. and D. B. Langmuir, "A Type of Light Valve for Television Reproduction", *Proc. I. R. E.*, Vol. 31, pp. 208-214, 1943.

[23] a. D. M. Robinson, "The Supersonic Light Control and its Application to Television with Special Reference to the Scophony Television Receiver", *Proc. I. R. E.*, Vol. 27, pp. 483-496, 1939.

b. G. Otterbein, "Supersonic Light Relay in Television", *Elek. Tech. Zeit.*, Vol. 60, pp. 161-163, 1939.

[24] a. C. Schramm, "Ueber den Elektrooptischen Effekt an Zinkblende", *Ann. d. Physik*, Vol. 25, No. 4, pp. 309-337, 1936.

b. M. von Ardenne, "Practical Construction of Electron-Ray Storage Projection Tubes", *Telégr.-Fernspr.-Funk-u. Fernsehtech.*, Vol. 28, pp. 26-27, pp. 180-184, pp. 403-409, 1939.

c. D. S. Loewe A. G., Brit. patent 427,092, 4/12/35.

[25] a. F. Fischer, et al, "Theoretische Betrachtungen ueber ein neues Verfahren der Fernsehgrossprojektion", *Schweiz. Arch. Wiss. Techn.*, Vol. 6, No. 4; Vol. 7, pp. 305-318, pp. 337-334; Vol. 8, pp. 15-28, pp. 135-143, pp. 169-178, pp. 199-212, pp. 299-307, 1940-1942.

b. W. Amrein, "Fernsehgrossprojektion", *Schweizer Archiv*, Vol. 9, pp. 293-307, 1943.

[26] G. Schubert, et al, "Das Zwischenfilm-Verfahren", *Fernseh Hausmitt*, Vol. 1, No. 3, pp. 129ff, 1932; Vol. 1, No. 4, pp. 42ff, 1933; Vol. 1, No. 5, pp. 29ff, 1934; Vol. 1, No. 6, pp. 49ff, 1935; Vol. 1, No. 6, pp. 201-210, 1939.

[27] a. P. Selenyi, "Uber die Verwendung der negativen Ladung der Kathodenstrahlen als Schreibmittel in Kathodenstrahloszillographen", *Zeits. f. Physik*, Vol. 11-12, pp. 895-897, 1928.

b. M. Suzuki and T. Tsuji, "Kathode-Ray Dust Oscillogram, *Jour. Inst. Elec. Eng. Japan*, Vol. 56, pp. 898-902, 1936.

[28] G. M. Wright, British patent 467,918, 6/23/37.

[29] a. E. Goldstein, "Ueber die Einwirkung von Kathodenstrahlen auf einige Salze", *Ann. d. Physik und Chemie*, Vol. 54, pp. 371-380, 1895; Vol. 60, pp. 491-499, 1897.

b. H. Nagaoka and T. Mishima, "Coloration by Kathode Rays", *Inst. Phys. & Chem. Res., Tokyo, Sci. Papers*, No. 603, pp. 77-94, 1935.

c. A. H. Rosenthal, "A System of Large-Screen Television Reception Based on Certain Electron Phenomena in Crystals", *Proc. I. R. E.*, Vol. 28, pp. 203-212, 1940.

[30] a. R. C. Clincker and L. J. Davies, British patent 378,397, 8/4/32.

b. J. L. Baird, British patent 442,963, 2/17/36.

[31] a. V. Bausch, Jr., German patent 591,455, 1/22/34.

b. H. Cunningham, U. S. patent 2,012,270, 8/27/35.

dotenebrescence have found practical application in radar. Of these, cathodoluminescence is unique in requiring only the primary cathode-ray beam for practical operation over a wide range of image repetition frequencies from about 0.01 to 2000 or more scans per second. The phenomenal scope of phosphors in being able to convert a wide energy range of either corpuscular or undulatory excitants into the 1.5-electron-volt-wide visible region of the spectrum is depicted in Figure 15 (see opposite page.) Cathodotenebrescence is probably the least cumbersome of the other listed possibilities, requiring only a strong extraneous source of light and heat in addition to the primary cathode-ray beam. Present cathodotenebrescent radar CRT screens, however, are limited to image repetition frequencies slower than about 0.1 scan per second and are restricted to land or ship radars where additional bulk and kilowatts of power are not unduly detrimental.

Hypothetical Ideal Performances of Phosphors and Scotophors.

Assuming only cathodoluminescent or cathodotenebrescent screens, it is interesting to calculate some maximum bright-trace luminances or dark-trace contrasts obtainable in hypothetical perfect screens allowing 100 per cent efficiency and ideal square-wave decays lasting exactly one scan interval.

1. *Positively-modulated*[†-k] *cathodoluminescent (bright-trace) screens.* Since 1 erg/second $= 10^{-7}$ watts $= 10^{-7} \times (650$ lumens$)$,[32] and 1 lumen/square millimeter $(\text{mm}^2) = 10^5$ millilambert (mL), then 1 erg/mm^2 second $= 6.5$ mL at 100 per cent efficiency. This may be expressed as

$$L_m = 6.5\, Ex/t_s \text{ (mL)} \tag{1}$$

where L_m is the maximum square-wave luminance (in mL),

[†-k] The light outputs of phosphors may be modulated in the three following modes, according to their temperature dependence characteristics of light output (Fig. 15 of reference 4):

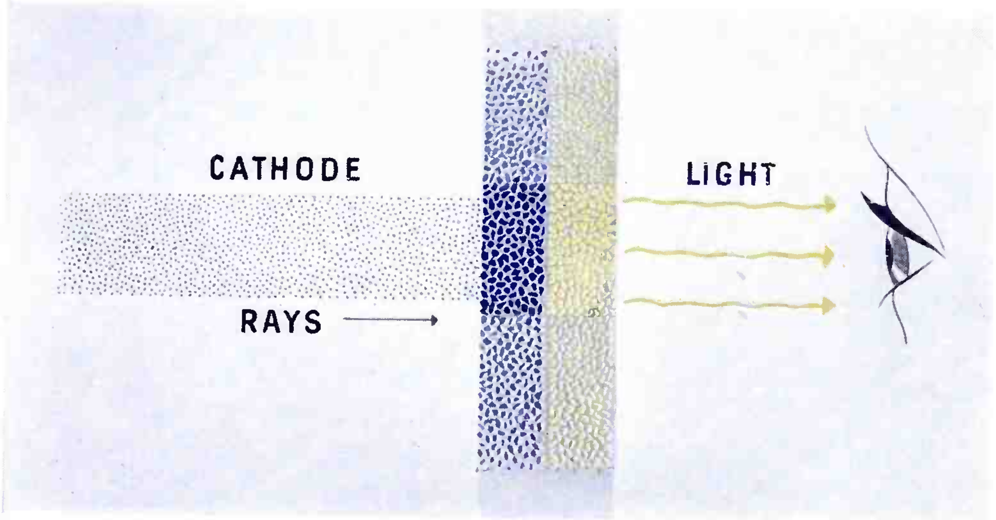
1. Positive modulation of luminescence is the normal increase of luminescence with increasing excitation density at temperatures below the fairly critical temperature (T_c) above which the efficiency of luminescence sharply decreases.

2. Negative modulation of luminescence is accomplished by increasing the temperature of an excited phosphor above T_c and thereby decreasing the luminescence.

3. Positive modulation of incandescence is accomplished by further raising the temperature of the phosphor until incandescence supplants luminescence.

Typical temperature-dependence curves of the luminescences of phosphors are shown in Figures 28-31.

[32] Committee on Colorimetry, *Jour. Opt. Soc. Amer.*, Vol. 33, pp. 534-543, 1943, Vol. 34, pp. 183-218, pp. 245-266, 1944.



	FLASH	USEFUL PERSISTENCE 0.5"	1"	2"	3"
SINGLE	50,000	8	4	2.5	2
CASCADE	2,650	26.8	15.3	8.8	6

Fig. 24—The structure and performance of a cascade screen (P7) relative to a single-layer screen (P7/2).

(See inside for Figure 15.)

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[32] Committee on Colorimetry, *Jour. Opt. Soc. Amer.*, Vol. 33, pp. 534-543, 1943, Vol. 34, pp. 183-218, pp. 245-266, 1944.

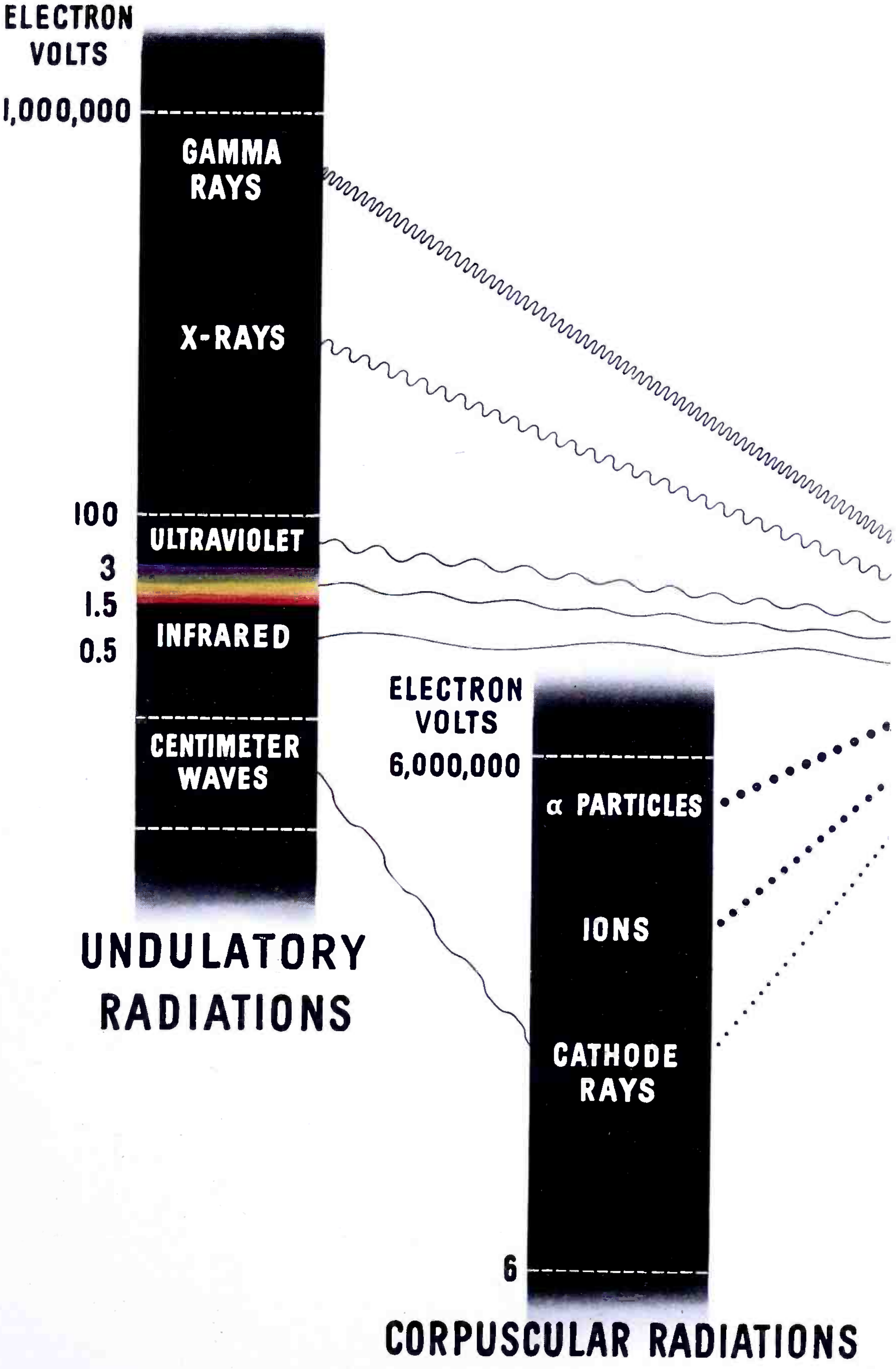
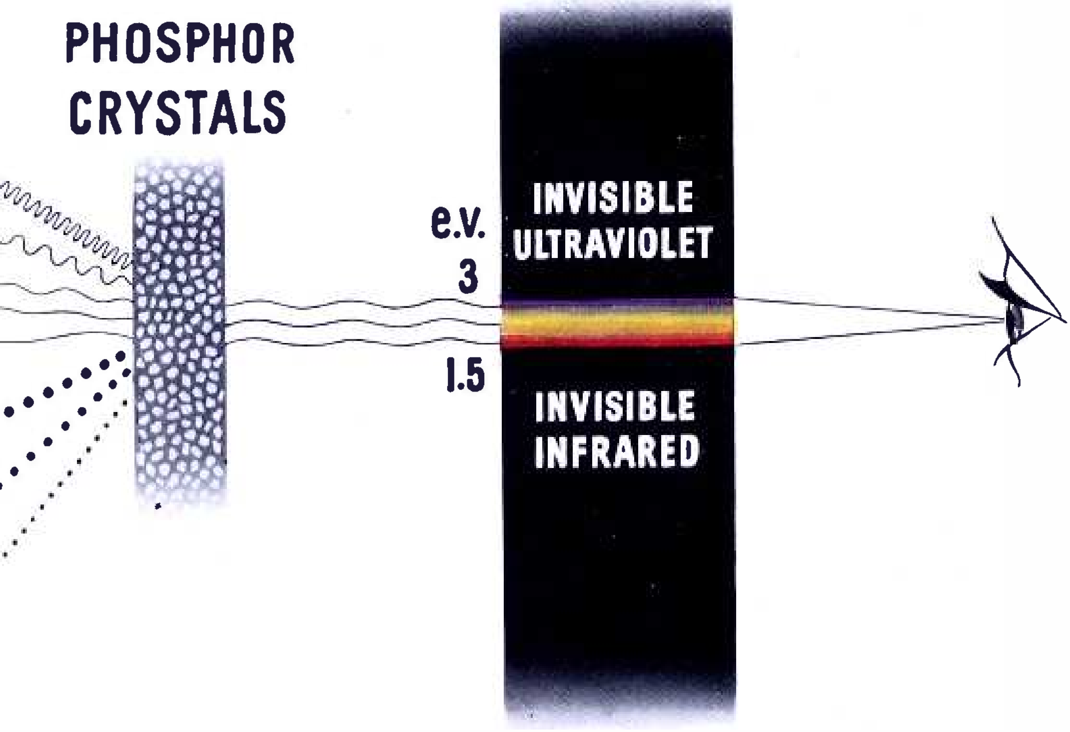


Fig. 15—A megavolt-wide range of pri
phosphors to visible or near



mary photons or particles excites
-visible luminescence.

E is the cathode-ray beam energy density (in ergs/mm^2),

x is the fraction of the total lumens emergent from the viewed side of the screen, and

t_s is the length of the scan interval (in sec.).

In conventional unmetallized CRT screens, the factor x is always less than 0.5 because most of the luminescence emerges from the screen side facing the electron gun inside the CRT. Hence Equation (1) may be rewritten to

$$L_m \leq 3.25\, E/t_s \text{ (mL)} \tag{2}$$

and used to calculate the hypothetical maximum square-wave luminances, L_m, for weak and strong radar signals (Table 3) and for several persistence (scan) intervals as shown in Table 4.

Table 4.

Ideal "Square-Wave" Bright-Trace Luminances.

Scan Interval t_s (sec)	Weak Signal	Moderate Signal	Strong Signal	Units
	$E = 0.5$	20	200	ergs/mm^2
30	0.054	2.16	21.6	mL
10	0.163	6.5	65	mL
3	0.54	21.6	216	mL
1	1.63	65	650	mL
0.1	16.3	650	6500	mL

It is evident, from Table 4, that even with 100 per cent cathodoluminescence efficiency the square-wave luminance from weak signals would be less than 10 percent of television image luminance (approximately 20 millilamberts) for scan intervals greater than one second.

2. *Cathodotenebrescent, or negatively-modulated*$^{\dagger\text{-}k}$ *luminescent, (dark-trace) screens.* If, instead of converting the cathode-ray beam energy into light, the beam be made to decrease the reflection, transmission, or emission of light from a screen, then the L_m values in Equation (1) may be converted into luminance decrements which

would afford maximum square-wave contrasts, C_m (in per cent), calculable from:

$$C_m = 100(L_o - L_d)/L_o = 100|-L_m|/L_o \tag{3}$$

where L_o is the luminance of the unbombarded screen (in mL)

L_d is the luminance of the cathode ray-bombarded screen (in mL), and

L_m is defined by equation (1).

By combining equation (1) and equation (3) and setting $x = 1$, the maximum square-wave contrast becomes

$$C_m = 650E/L_o t_s \ (\%) \tag{4}$$

Hypothetical maximum square-wave contrasts, assuming no noise in the image, are calculated from equation (4) and shown in Table 5.

Table 5.

Ideal "Square-wave" Dark-Trace Tenebrescences (Contrasts) in per cent.

Background Luminance, L_o, *mL*	Scan Interval t_s, (sec)	Weak Signal	Moderate Signal	Strong Signal
		$E = 0.5$	20	200 ergs/mm^2
10,000	30	0.001%	0.04%	0.4%
10,000	10	0.003	0.13	1.3
10,000	3	0.011	0.43	4.3
10,000	1	0.033	1.3	13
10,000	0.1	0.325	13.0	100 (0.13″)
100	30	0.11%	4.3%	43%
100	10	0.33	13.0	100 (13″)
100	3	1.1	43	—
100	1	3.25	100 (1.3″)	—
100	0.1	32.5	—	—
1	30	11%	100% (130″)	100% (1300″)
1	10	33	—	—
1	3	100 (3.3″)	—	—

Numbers in parentheses denote durations, in seconds, of 100% contrasts at the given values of L_o and E.

Tables 4 and 5 indicate the maximum possible performances of *ideal* luminescent or tenebrescent bright-trace and dark-trace radar CRT screens operated within the present ranges of radar voltages, grid swings, signal strengths, and persistence times. The data further show how image luminances and contrasts may be increased by decreasing the scan interval (increasing the image repetition frequency).

Real vs. Ideal Phosphors and Scotophors.

The actual performances of CRT screens are a far cry from the 100-per cent-efficient, linear-response, square-wave-decay *ideal* cases just examined. Real radar CRT screens have less than 10 per cent efficiency, only a fair degree of linearity of response to cathode rays, attain high initial levels of bright-trace luminance or dark-trace contrast which gradually decay to lower levels and carry-over at the ends of scan intervals sometimes to confuse subsequent images and hamper range-changes in radar operation. An approximate comparison of ideal and real panoramic-radar (3-second PPI) screen performances is given in Table 6.

Table 6.

Exemplary Comparison of Ideal and Real Radar CRT Screens.

Screen		Useful Decay Interval				Undesirable Carry-Over
		Persistence of Vision				
		$t = 0$	0.1	1	3	10 sec.
Bright-Trace*	Ideal	21.6	21.6	21.6	21.6	0 mL
	Real (P7)	500	0.6	0.06	0.02	0.006 mL
Dark-Trace**	Ideal	15	15	15	15	0% Contrast
	Real (P10)	20	18	8	4	2% Contrast

* Excitation by 20 ergs/mm²/scan.
** Excitation by 530 ergs/mm²/scan (background, L_{o}, = 8000 mL).

Despite the marked shortcomings of phosphors and scotophors, they have won a vital role in radar; having achieved useful retentivity of information far beyond the persistence of vision. A large measure of this success is, of course, attributable to the phenomenal capabilities of the human eye and brain acting as a discriminating receiver of weak and variable signals.

Real Phosphors and Scotophors.

All the efficient CRT screens comprise crystalline inorganic materials whose well-ordered structures, serve as (1) suspensions for a sparse population of special imperfections which are required to afford visible luminescence or tenebrescence, and (2) efficient means for transmitting energy to and from these imperfections. The wide range of appearances and sizes of phosphor crystals is shown in Figures 16 and 17. These micrographs show that phosphor crystals may be produced with dimensions ranging from less than 0.1 micron to over 30

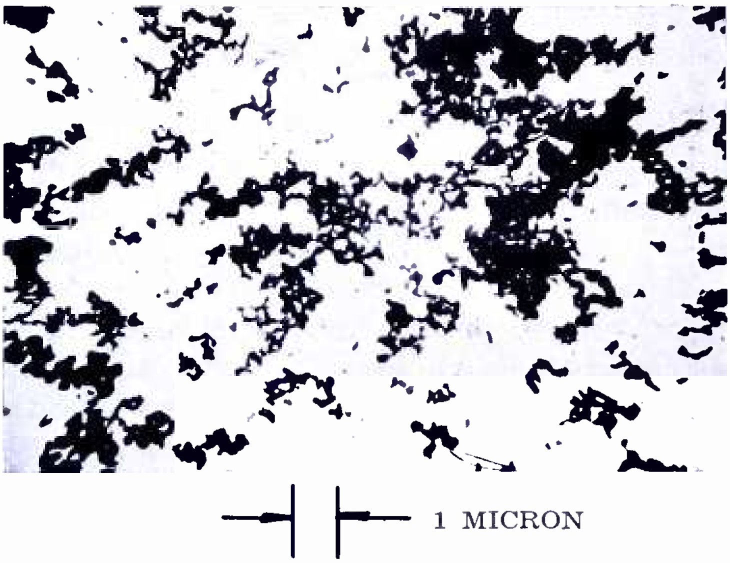


Fig. 16—Electron micrograph of very fine α-Zn_2SiO_4:Mn (Special P1).

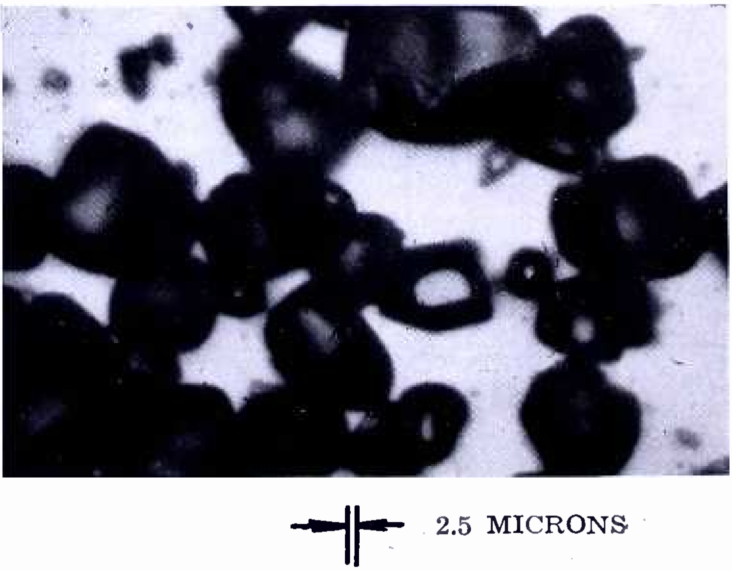


Fig. 17—Photomicrograph of β^*-ZnS:Ag(P7/1).

microns. A similar, but less extensive, range of gross crystal sizes is evident in evaporated screens of the potassium-chloride (KCl) scotophor used in radar P10 screens.

Energy Storage (Trapping).

Although the mechanisms of luminescence and tenebrescence in phosphors and scotophors are very imperfectly understood, a number of hypothetical mechanisms have been devised as heuristic aids in research. A conjectural and oversimplified mechanism of the luminescence of phosphors is shown in Figure 18. The abscissae indicate generalized distances along lattice planes in the phosphor crystals. The ordinates represent potential energies of electrons; ranging from the lowest state, B_0, wherein electrons are bound to crystal atoms or ions, up to the next-higher, continuous, normally-unoccupied state (conduction band, B_1) wherein electrons are free to wander through the phosphor crystal until they encounter a receptive activator impurity

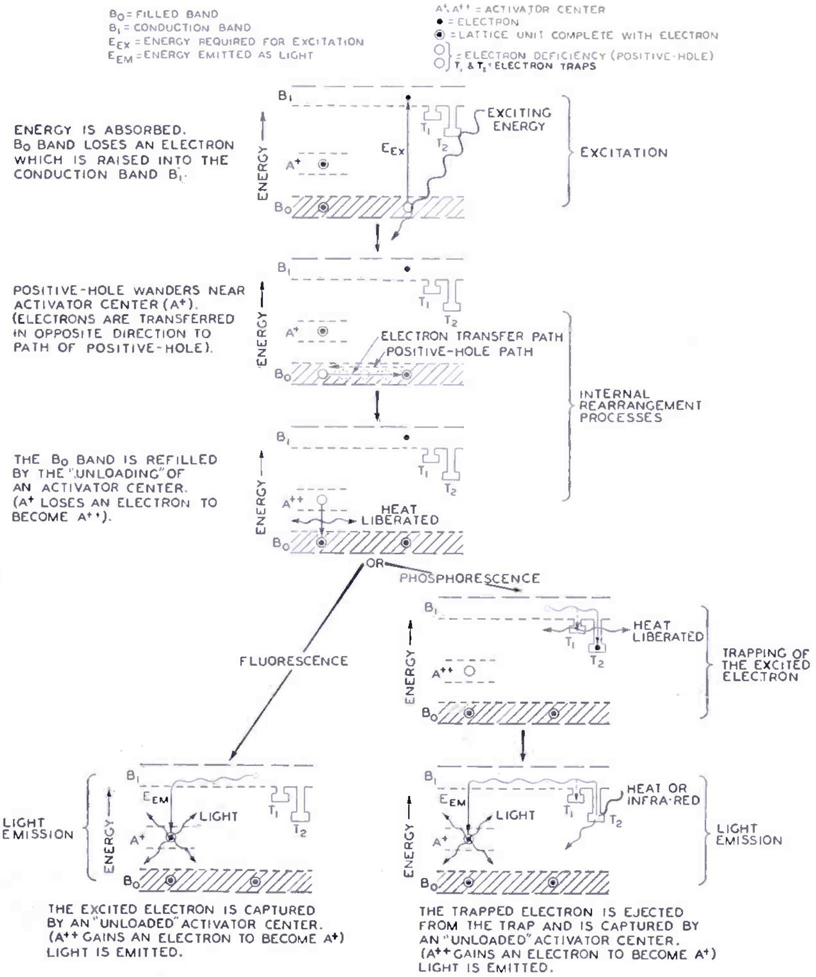


Fig. 18—A diagrammatic representation of the luminescence of phosphors.

center, (fluorescence emission), or are captured in a crystal imperfection (trap) to await later release and possible ultimate combination with an activator center (phosphorescence emission). This causative distinction between fluorescence and phosphorescence is of little utility in the case of phosphors where an arbitrary fiducial time, of the order of 10^{-8} second, is usually chosen to separate the two phenomena.[4] The action of scotophors corresponds to that shown in Figure 18 for phosphors, except that the most useful portion of the mechanism is the trapping action which produces an induced absorption band in the visible region of the spectrum. The average spectral frequency of the induced absorption band is proportional to the energy difference (trap depth) between the trap and the conduction band. Similarly, the spectral frequency of fluorescence (*and* phosphorescence) is proportional to the "depth" of the activator center below the lower edge of the conduction band. The observed broad bands of excitation and emission may be interpreted as representing the statistical deviation of the actual energy levels of particular phosphor centers from the most probable level given by the peak of the spectral distribution curve. This is particularly applicable to the sparsely-distributed activator centers which are foreign to the bulk lattice and are not to be expected to assume uniform energy situations during the thermally violent crystallizations of phosphor crystals. Similar considerations apply to energy distributions of phosphor traps and to the stimulation spectra of the infra-red-sensitive phosphors which are mentioned later in this article.

Intermediate trapping of electrons in phosphors or scotophors is essential for CRT screens having appreciable persistence, as in panoramic radar indicators. Many empirical chemical and physical means are known for influencing greatly electron trapping (which is here understood to include metastable states in the cases of non-photoconducting materials), but the exact compositions, constitutions and locations of traps are still major problems.

Scotophor Traps. In the case of scotophors, such as KCl, traps may be identified with so-called F-centers which are presumed to be electrons occupying the sites of absent halogen ions (Cl^-).[33] The omission of occasional crystal units occurs when atoms or ions scramble for lattice sites during crystal growth; the fraction, f, of omission defects being a function of equilibrium temperature according to:[34]

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[33] J. H. DeBoer, ELECTRON EMISSION AND ABSORPTION PHENOMENA, Cambridge University Press, London, Eng., 1935.

[34] N. F. Mott and R. W. Gurney, ELECTRONIC PROCESSES IN IONIC CRYSTALS, Oxford University Press, London, Eng., 1940.

$$f = A\epsilon^{-W_o/kT} \tag{5}$$

where A is a constant ($\approx 10^4$ for KCl),

W_o is the work required to form a vacant lattice site at $T = 0$ (in ergs),

($W_0 \approx 1.6 \times 10^{-12}$ erg for KCl)

$k = 1.38 \times 10^{-16}$ erg/degree, and
T is the equilibrium temperature, in degrees Kelvin.

At temperatures near the melting point of KCl (melting point = 1074°K), f becomes about 0.2 and it is reasonable to assume that many of the omission defects are frozen-in when KCl is evaporated and condensed on a cool glass surface as is done in making P10 screens. Hence, one might expect a large number of the 3.2×10^{22} lattice sites/cm^3 in P10-screen crystals to be empty, and half of these omission defects are potential F-centers. Calculations from experimental data on the intensity of cathodotenebrescence show that the number of F-centers/cubic centimeter may be of the order of 10^{18} in P10-screens operated near room temperature.[†-b] This corresponds to an F-center concentration of about 0.01 per cent which is comparable with the normal activator concentrations in sulphide-type phosphors, but is only about one one-hundredth of the normal activator concentration in silicate- (fluoride-) type phosphors.

The decay of tenebrescence, C, of KCl is a power-law relation of the type:

$$C = C_o t^{-n} \tag{6}$$

where C_0 is the tenebrescence or contrast [Equation (3)] at time $t = 0$ and n decreases from about 1.5 to less than 0.1 with decreasing temperature or intensity of illumination and with increasing degree of tenebrescence (contrast).[†-1]

Phosphor Traps. Phosphors may be broadly classified, according to phosphorescence, as (1) sulphide- (selenide-) type (usually t^{-n}-decay), and (2) silicate- (fluoride-) type (usually ϵ^{-t}-decay).[7]

1. The crystalline state of *sulphide-type phosphors* markedly affects phosphorescence, as evidenced by the longer and brighter phosphorescence of β^*-ZnS:Cu (above 1020°C)[35] contrasted with α^*-ZnS:Cu

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[†-1] Measurements by Drs. R. W. Hull, H. J. Kelly, and W. D. Hope of the Radiation Laboratory (M.I.T.), as reported in †-b.

[35] E. T. Allen & J. L. Crenshaw, "The Sulphides of Zinc, Cadmium, and Mercury; their Crystalline Forms and Genetic Conditions", *Amer. Jour. of Sci.*, Vol. 34, pp. 341-361, 1912.

(below 1020°C) in Figure 19.[†-m] Increasing partial substitution of cadmium for zinc in ZnS:Cu decreases the duration and intensity of persistence as shown in Figure 20. Apart from major changes in the bulk material of phosphor crystals, as little as 10^{-8} of copper produces a pronounced phosphorescence in zinc sulphide phosphors while 10^{-6} of nickel decreases both phosphorescence and efficiency. The phosphorescences of sulphide-type phosphors are generally represented as so-called

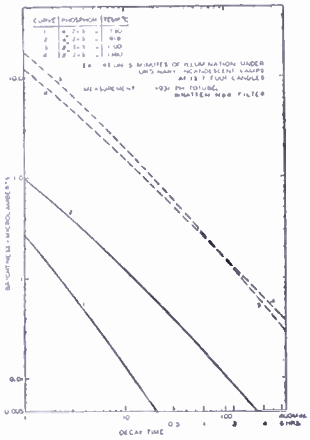

Fig. 19—The relative phosphorescences of cubic (α *) and hexagonal (β *) ZnS:Cu(0.003%).

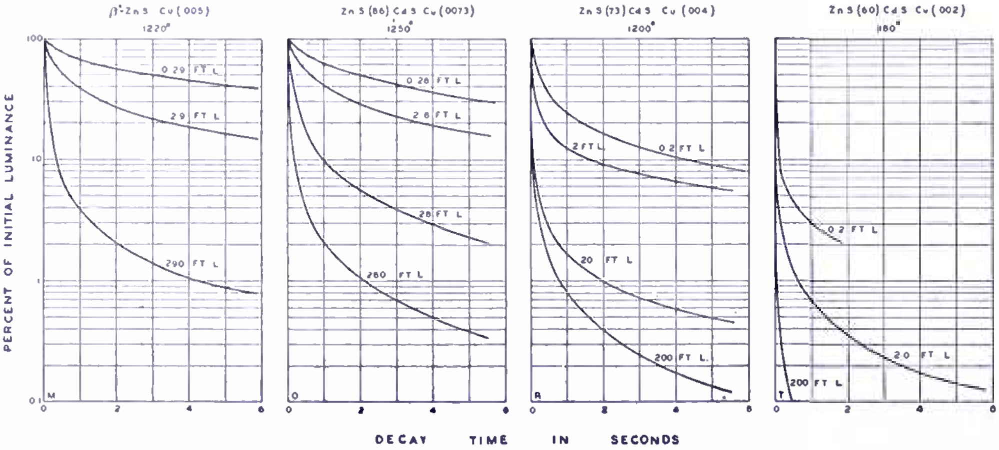

Fig. 20—Relative phosphorescences of selected members of a series of high-temperature ZnS:CdS:Cu phosphors after ultraviolet (3650 Å) excitation to the various initial luminances (L_o, in footlamberts) marked on each curve.

[†-m] The phosphors shown in Figure 19 were prepared by Mr. J. A. Dugan under the supervision of Dr. D. R. Hale. The measurements were made with an electronic phosphoroscope which was designed and constructed by Dr. R. E. Shrader.

power-law decays, decaying with time, t, according to:[36]

$$L = L_0 \left(\frac{b}{b+t} \right)^n \tag{7}$$

where the "constants" b and n are not constants at all, but vary considerably with: (1) initial luminance, L_0 (see Figure 20), (2) duration and type of excitation (Figure 3), and (3) time after cessation of excitation.[6] For practical purposes, b is smaller than about 10^{-3} second and n varies from about 0.2 to 2, being near unity for long-persistence sulphides.

Sulphide-type phosphors are generally good photoconductors and the strong correlation between their photoconductivities and phosphorescences[37] leads to the hypothesis that the scheme of Figure 18 applies in their general case. Theoretical considerations have led to the hypothesis that the activator centers are located interstitially (e.g., Cu between Zn's and S's) in phosphor crystals exhibiting power-law decays, especially when the crystal anions are predominantly sulphur or selenium.[7, 38] Whether similar considerations may be applied to traps, is yet unresolved.

2. Changes in the crystalline state of *silicate-type phosphors* do not greatly affect their exponential decays, as shown for the allotropic transition from α- to β-Zn_2SiO_4:Mn in Figure 21.[39, 40, †-n] The decay constant, a, of a specific silicate-(fluoride-) type phosphor is largely determined by its chemical composition, but the initial exponential decay:

$$L = L_0 \epsilon^{-at} \tag{8}$$

usually goes over into a power-law decay at room temperature and low

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[36] R. P. Johnson and W. L. Davis, "Luminescence During Intermittent Optical Excitation", *Jour. Opt. Soc. Amer.*, Vol. 29, pp. 283-290, 1939.

R. B. Nelson, R. P. Johnson, and W. B. Nottingham, "Luminescence During Intermittent Electron Bombardment", *Jour. Appl. Phys.*, Vol. 10, pp. 335-342, 1939.

[37] A. E. Hardy, "The Photoconductivity of Zinc-Cadmium Sulphide as Measured with the Cathode-Ray Oscillograph", *Trans. Electrochem. Soc.*, Vol. 87, pp. 353-364, 1945.

[38] F. Seitz, "Interpretation of the Properties of Zinc Sulphide Phosphors", *Jour. Chem. Phys.*, Vol. 6, pp. 454-461, 1938.

[39] H. W. Leverenz and F. Seitz, "Luminescent Materials", *Jour. Appl. Phys.*, Vol. 10, pp. 479-493, 1939.

[40] H. P. Rooksby and A. H. McKeag, "The Yellow Fluorescent Form of Zinc Silicate", *Trans. Faraday Soc.*, Vol. XXXVII, No. 242, Part 6, pp. 1-4, 1941.

[†-n] The measurements in Figure 21 were made by Mr. T. B. Perkins.

luminances.[41] The later power-law portion of the decay may be greatly intensified in the case of α-Zn_2SiO_4:Mn by co-crystallizing BeO and SnO_2 with the material to produce t^{n}-persistences comparable with those of the better sulphide phosphors (Figure 22).[42] The constant, a, for the practically-exponential initial decays of phosphors, in which oxygen or fluorine dominate the anion structures of the crystals, has known values ranging from about 10^6 for ZnO:(Zn)[43] down to 10 for ZnF_2:Mn.[†-o]

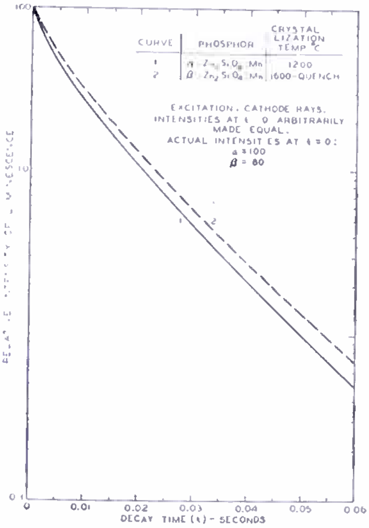

Fig. 21—Relative cathodophosphorescences of α- and β-Zn_2SiO_4:Mn.

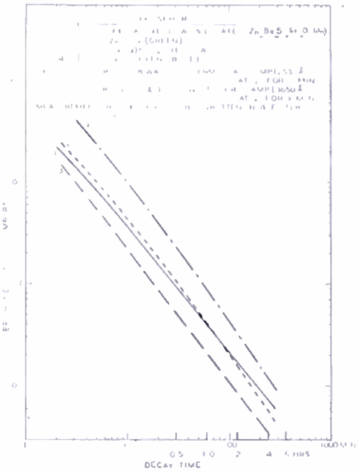

Fig. 22—Phosphorescences of some long-persistence sulphide and silicate phosphors.

Silicate-(fluoride-) type phosphors are rather poor photoconductors relative to the sulphide-type materials,[44, 45] and it is likely that this

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[41] G. R. Fonda, "Phosphorescence of Zinc Silicate Phosphors", *Jour. Appl. Phys.*, Vol. 10, pp. 408-420, 1939.

[42] A similar effect is obtained by using arsenic oxide; cf., H. C. Froehlich and G. R. Fonda, "Exaggerated Phosphorescence of Zinc Silicate Phosphors", *Jour. Phys. Chem.*, Vol. 46, No. 8, pp. 1-8, 1942.

[43] F. Schröter, "Ueber Grenzgebiete der Fernsehforschung", *Telefunken Mitt.*, Vol. 21, No. 85, pp. 7-23, 1940.

[†-o] The manganese-activated zinc-, and/or magnesium-, fluoride phosphors were devised by M. C. Banca in 1931. Our measurements show that the useful decays of these materials approximate the relation $L = L_o\epsilon^{-10t}$ (t in sec).

[44] R. C. Herman and R. Hofstadter, "Photoconductivity of a Natural Willemite Crystal", *Phys. Rev.*, Vol. 59, pp. 78-84, 1941.

[45] a. R. P. Johnson, "Luminescence of Sulphide and Silicate Phosphors", *Jour. Opt. Soc. Amer.*, Vol. 29, pp. 387-391, 1939.

b. J. T. Randall and M. H. F. Wilkins, "The Phosphorescence of Various Solids", *Proc. Roy. Soc.*, Part A, Vol. 184, No. 999, pp. 347-408, 1945.

c. G. F. J. Garlick and M. H. F. Wilkins, "Short Period Phosphorescence and Electron Traps", *Proc. Roy. Soc.*, Part A, Vol. 184, No. 999, pp. 408-434, 1945.

d. F. Urbach "Zur Lumineszenz der Alkalihalogenide II", *Akad. Wiss. Wien, Math-Naturw. Kl., IIa*, Vol. 139, No's. 7 and 8, page 363, 1930.

weak photoconductivity is mainly associated with the later-stage power-law decay, while the initial exponential decay is localized as a type of metastable-state phenomenon independent of long-range conduction. Experimental evidence indicates that the activator centers in silicate and fluoride phosphors are mainly in substitutional sites (e.g., Mn in place of Zn, Cd, or Mg).[4, 46] Exponential decays are much less affected than power-law decays by changes in temperature, crystal structure, impurity concentration, or excitation, because substitutional impurities are in regions of lower potential energy and are buffered by closer coupling with the lattice forces.[7]

Glow Curves. A useful method for statistical studies of the trapping depths and distributions in phosphors is based on measuring the "glow curves" of phosphors which are first excited and then warmed from very low temperatures.[45] Some typical glow curves, determined by A. F. Wells of the University of Birmingham, are shown in Figure 23 for ZnS:Cu phosphors crystallized at various temperatures. Comparison of Figures 19 and 23 shows the correlation between glow curves and the intensity and decay of phosphorescence. The shallowest (weakest) traps are the first to release stored electrons during phosphorescence, and glow curves taken at various times after cessation of excitation show a steady shift toward higher temperatures.[45b]

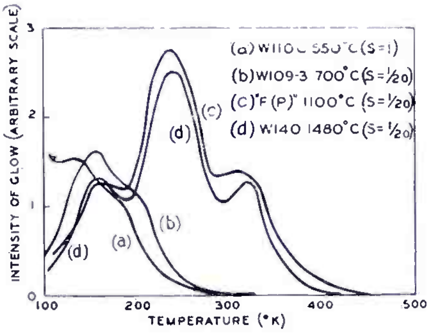

Fig. 23—Glow curves of ZnS:Cu phosphors crystallized at various temperatures (A. F. Wells).

Infra-red-Sensitive Phosphors. In recent years, efficient infra-red-stimulable phosphors have been developed which are capable of storing most of their phosphorescence energy for several days, even at room temperature.[47] The best of these phosphors comprise sulphides or sul-

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[46] H. G. Jenkins, A. H. McKeag, and H. P. Rooksby, "Position Occupied by the Activator in Impurity-activated Phosphors", *Nature*, Vol. 143, pp. 978, June 10, 1939.

[47] Session on Infrared-sensitive Phosphors, Optical Society of America, Papers 9-15, Cleveland meeting, March 7, 1946.

W. Primak and R. Ward, Paper 56, Amer. Chem. Soc., Atlantic City Meeting, April 10, 1946.

phoselenides of the alkaline-earth elements (Ca,Sr,Ba), activated with samarium (or terbium) and europium (or cerium), and are crystallized with fluxes such as lithium fluoride, calcium fluoride, and alkaline-earth sulphates. This class of materials had its beginnings in the work of Tomaschek,[48] Travnicek,[49] and Rothschild,[50] who demonstrated (1) the enhancement of phosphorescence obtainable by the action of two activators, e.g., the phosphorescence of SrS:Sm is enhanced by addition of Gd or Bi, and (2) the feasibility of using oxysulphides and mixed-cation phosphor bases, e.g., CaO:CaS:Sm and CaS:SrS:(+ activator) in the so-called Lenard phosphors. Subsequent work by Kunz and Urbach brought these phosphors into focus as having possible applicability in infra-red detectors,[51] and recent OSRD*-sponsored work by Urbach resulted in the development of two practical materials, which may be denoted in the usual notation as SrS:Sm:Eu and SrS:Sm:Ce.[47] These laboratories were apprised of the status of Dr. Urbach's work after the development of SrS:Sm:Eu and then carried out concurrent investigations which showed: (1) partial substitution of S by Se in SrS:Sm:Eu increases the visual efficiency of the material by displacing the emission spectrum nearer the maximum sensitivity of the photopic or scotopic eye, (2) terbium is useful as a "storage agent" in addition to, or in place of, samarium in SrS:Sm:Eu, and (3) these infra-red-stimulable phosphors are excellent phosphorescent materials at temperatures between 200° and 500°C.[47,†-p] The strong high-temperature phosphorescences of these materials indicates the presence of only deep-lying traps with large (approximately 1-electron-volt) electron binding energies relative to room-temperature kT (see Equation 5). The emission-spectrum shift on partially substituting Se for S in SrS:Sm:Eu may be as much as 600Å toward the blue (starting at about 6300Å peak emission for SrS:Sm:Eu). This spectral shift toward the blue is anomalous in the sense that partial substitution of Se for S in ZnS phosphors causes the emission spectrum to shift toward the red.[52]

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[48] R. Tomaschek, "Phosphorescent Properties of Rare Earths in Alkaline Earth Phosphors", *Ann. d. Physik*, Vol. 75, pp. 109-142, 1924.

[49] M. Travnicek, "Phosphorescence of Samarium in Mixed Sulphides and Oxides", *Ann. d. Physik*, Vol. 79, pp. 237-260, 1926.

[50] S. Rothschild, "Sensitized Phosphorescence", *Die Naturwiss.*, Vol. 20, pp. 850-851, 1932; *Physik. Zeits.*, Vol. 35, pp. 557-560, 1934.

[51] J. Kunz and F. Urbach, U. S. patent 2,074,226, 3/16/37.

[*] Office of Scientific Research and Development.

[†-p] These particular investigations were carried out under contract OEMsr-440 between the Office of Scientific Research and Development and the Radio Corporation of America.

[52] H. W. Leverenz, "Phosphors Versus the Periodic System of the Elements", *Proc. I. R. E.*, Vol. 32, pp. 256-263, 1944.

Recently-announced measurements by Ellickson[53] may be interpreted as showing that the maximum number of traps in an optimally excited and stimulated SrS:Sm:Ce phosphor is about 10^{17} traps/cubic centimeter. This figure approximates the Sm-activator concentration in the phosphor and is the same magnitude as the maximum concentration of F-centers (traps) previously indicated for scotophors. An independent check on these general trapping concentrations is provided by integrating over the phosphorescence curve of a well-excited conventional phosphor such as the "optimum" β*-ZnS:O:Cu phosphorescence reported by Schilling[1] or the continuations of decay curves shown in Figure 20. Using 2.5 electron volts as the average energy for quanta emitted by β*-ZnS:Cu, then 1 lumerg/square centimeter/second $\sim 6.25 \times 10^{11}/2.5 = 2.5 \times 10^{11}$ quanta/square centimeter/second $= 0.067$ mL $= 2.14 \times 10^{-5}$ candle/square centimeter. Dr. L. S. Nergaard has shown that the decay of β*-ZnS:Cu may be approximated by an expression of the general type:

$$L = A\left(\frac{t}{t_o}\right)^{-n} \epsilon^{-\left(a \log_\epsilon \frac{t}{t_o}\right)^2} \qquad (9)$$

Specifically, when t_o is arbitrarily set equal to 1 second, Schilling's curve for "optimum" phosphorescence of β*-ZnS:O:Cu is empirically fitted from 0.1 to 10^5 second by

$$L = 1.26 \times 10^{13}\, t^{-0.286}\, \epsilon^{-(0.234 \log_\epsilon t)^2} \text{ quanta/square centimeter/second.} \qquad (10)$$

Integration of Equation (10) indicates that about 10^{15} quanta/square centimeter may be emitted by a good β*-ZnS:Cu phosphor as phosphorescence. Since the effective excited depth of phosphor is usually less than 0.1 mm (100μ), the total volume emission is over 10^{17} quanta/cubic centimeter which is reasonably near the general maximum trapping concentration of 10^{18} traps/cubic centimeter. Silicate-, or fluoride-, type phosphors may have "trapping" (metastable-state) concentrations as high as 10^{19} traps/cubic centimeter because their activator concentrations are about 100 times larger than those of sulphide-type phosphors.

Cascade Screens. Returning to the radar-screen problem with real phosphors and scotophors, it is apparent that real materials may be excited to store a maximum of about 10^{18} quanta of absorption or

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[53] R. T. Ellickson, "Some Properties of Infra-red-sensitive Phosphors", paper F7, *Bulletin of the American Physical Society* (Cambridge meeting), Vol. 21, No. 2, 4/26/46.

emission per cubic centimeter. The number of quanta stored per square centimeter of exposed screen surface determines the total tenebrescence or phosphorescence and this number in practice depends on (1) the depth of penetration of the excitant, (2) the energy density of the excitant and the duration of excitation, (3) the trapping efficiency of the phosphor or scotophor at the particular operating temperatures and with the particular excitant. Approximate maximum values of phosphorescence are readily calculable for a given decay and given depth of excitation, using generally-known expressions for the variation of power losses of various excitants in matter.[†-b]

Earlier in this article it was mentioned that the cascade principle could be used to transform cathode-ray energy into ultraviolet or violet light by an intermediate phosphor whose luminescence excited longer-wave luminescence in another phosphor. By this means, the disadvantageous shallow penetration of low-voltage cathode rays and the intense local heating caused by such cathode rays are obviated through the cascade transformation into deeper-penetrating violet quanta which leave relatively little residual heat (small quantum deficit) in the final phosphor.

Practical obtention of cascade screens for radar CRT was accomplished by using stratified layers[54, 55] of phosphors as shown in Figure 24 (facing page 216). The data at the bottom of Figure 24 were excerpted from Table 7 which shows the relative performances of cascade and non-cascade screens under excitation by cathode rays.

Comparison of lines 1 and 2 in Table 7 shows that, under the given cathode ray excitation, a simple stratified sulphide-phosphor (P7) screen (No. 2) has about 1/6 the flash (luminescence during excitation) and over 3 times as much phosphorescence intensity as the single-layer ZnS(86):CdS:Cu-phosphor (P7/2) screen (No. 1). Line No. 3 shows that a selective barrier layer further reduces the flash without decreasing phosphorescence. In lines 5 and 6 the barrier layer is seen to decrease flash and increase phosphorescence.

For two-layer cascade screens, using phosphors having decays according to Equations 7 or 8, the light output, L, of the final layer may be expressed as a function of time, t, after the inception of a cathode ray pulse according to the following relations derived by D. O. North:[†-b]

Case A:

$$CR \rightarrow \epsilon^{-a_1 t} \rightarrow \epsilon^{-a_2 t} \tag{11}$$

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[54] H. W. Leverenz, U. S. patent 2,243,828, 5/27/41.

[55] H. W. Leverenz, "Optimum Efficiency Conditions for White Luminescent Screens in Kinescopes", *Jour. Opt. Soc. Amer.*, Vol. 30, pp. 309-315, 1940.

that is, when both layers have exponential decays,

$$L_{\epsilon_1\epsilon_2}(t) = K_{\epsilon_1\epsilon_2} \frac{\epsilon^{-a_1 t} - \epsilon^{-a_2 t}}{a_2 - a_1} \tag{12}$$

where $K_{\epsilon_1\epsilon_2}$ is proportional to the cathode-ray energy input and the efficiencies of the cascaded phosphors.

Table 7.

Cathodoluminescence of Single-layer (1) versus Cascade Screens (2 to 9).

(Luminances in arbitrary units as determined with a 1P21 photo-multiplier, plus a No. 15 Wratten filter, after *one* 1/720-second cathode ray pulse at 6 kilovolts, and 220 microamperes per square centimeter.)

				Luminescence		Phosphorescence						
				"Knee" $\tau = 1/6000''$	Peak 1/720"							
No.	B	I	Y		$t = 0$	.25	.5	1	1.5	2	2.5	3 sec.
1.	—	—	10	50000	56100	—	8	4	3	2.5	2.3	2
2.	8	—	12	8530	13000	44	26.8	15.3	10.7	8.8	7.6	—
3.	8	gl	12	2650	6600	—	25	15	10.8	8.5	7	5.8
4.	10	—	14	6260	10450	—	25	17.3	13	10.3	8.8	7.8
5.	12	—	8	4850	7700	—	14.5	8.5	6	4.8	3.8	3.3
6.	12	gl	8	2250	4950	—	17	9.8	7	6	4.8	4.3
7.	12	—	10	2470	5280	34.4	17.2	10.7	7.6	5.7	—	—
8.	12	—	12	3800	6050	38.2	22.9	13.4	9.5	7.6	—	—
9.	14	—	12	2970	5250	44	26.8	15.3	11.5	9.5	7.6	—

B = milligrams per square centimeter of β^*-ZnS:Ag (.015%),

I = barrier, gl = glass

Y = milligrams per square centimeter of ZnS(86):CdS:Cu(.0073%)

Case B:

$$CR \rightarrow \left(\frac{b_1}{b_1 + t}\right)^{n_1} \rightarrow \left(\frac{b_2}{b_2 + t}\right)^{n_2} \tag{13}$$

that is, when both layers have power-law decays with b_1 and $b_2 > 0$, and t finite. Assume $n_1 = n_2 = 1$ (hyperbolic decay), which is approximately representative of the useful portion of suphide-phosphor decays, then

$$L_{h_1h_2}(t) = K_{h_1h_2} \frac{b_1 b_2 \log_\epsilon \dfrac{(b_1+t)\,(b_2+t)}{b_1\,b_2}}{b_1+b_2+t} \tag{14}$$

In both cases, the shorter-persistence phosphor dominates the final result and the relative order of the layers is immaterial (assuming each excites the other) as evidenced by the symmetry of the constants in Equations (12) and (14).

Several cascade-decay curves, calculated from Equations (12) and (14), and assuming an excitation pulse lasting less than 10^{-7} second, are shown in Figure 25. Concave-downwardness, at times longer than the 0.1-second persistence of vision, is possible if the constants a_1 and a_2 are both less than 10, or if the constants b_1 and b_2 are both greater than 0.05. Only one exponential-decay phosphor, (Zn,Mg)F_2:Mn, is known with the constant a as low as 10 and no comparable material is available whose cathodoluminescence will excite (Zn,Mg)F_2:Mn (which requires wavelengths below 2500Å for excitation[t-q]). Of the

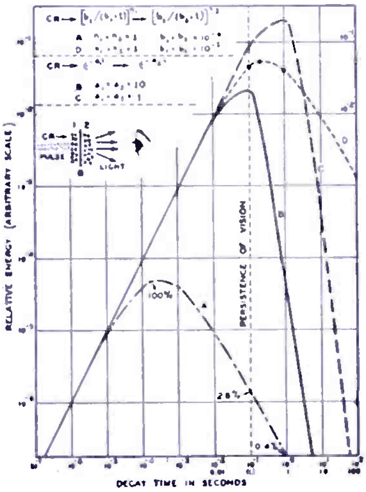

Fig. 25—Calculated cascade decays after an excitation pulse (assumed less than 10^{-7} second).

[t-q] The long-wave limits of the excitation bands of silicate (fluoride)-type phosphors are usually about 1500Å less than the short-wave limits of their emission bands. These ϵ^{-t}-decay phosphors, therefore, generally require excitations below 3000Å. In the case of the sulphide (selenide)-type phosphors the excitation and emission bands usually overlap to a considerable extent (Figure 26).

power-law-decay sulphide-type phosphors, the "constant" b, under practical conditions of excitation, is less than 10^{-3} for the known phosphors. Hence, for the present at least, visible concave-downward decays are unobtainable unless one resorts to the complicated expedient of cascade excitation of an infrared-stimulable phosphor which is then irradiated with an increasing intensity of infrared to compensate for its natural power-law decay.

Despite the non-achievement of visible concave-downward decays, which were hoped for in the early work on radar CRT screens, cascade screens achieved great practical importance in making possible panoramic radars with scan intervals up to 300 times as long as the persistence of vision. About 350,000 all-sulphide cascade-screen CRT (**P7** and P14) and about 6 tons of sulphide phosphors were manufactured by this company alone during the war.

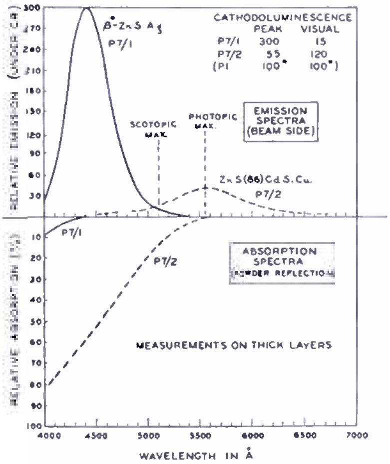

Fig. 26—Absorption (excitation) and emission spectra of sulphide phosphors used in P7 cascade screens.

The choice of sulphide phosphors for cascade-screen CRT is complicated and requires a number of compromises to assure (1) reduction in distraction and loss of dark adaptation caused by flash, (2) increase in useful phosphorescence during the particular scan interval used, and (3) decrease in phosphorescence beyond the scan interval to minimize cluttering of new information. In both P7 and P14-screens, layer 1 (the layer struck by the cathode-ray beam) is a β^*-ZnS:Ag phosphor having maximum cathodoluminescence output in the violet region of the spectrum, and layer 2 is chosen from the ZnS:CdS:Cu family whose decays are changed by varying the ratio ZnS/CdS (see Figure 20). The relations of the absorption and emission spectra of the P7-screen components are shown in Figure 26. The P14-screen comprises the same P7/1, β^*-ZnS:Ag, first layer with a ZnS(73-77):

$CdS{:}Cu$ phosphor in the second layer instead of the $ZnS(85\text{-}88){:}CdS{:}Cu$ phosphor used in P7 screens. Some CRT manufacturers used α^*-$ZnS{:}Ag$ instead of β^*-$ZnS{:}Ag$ for layer 1, particularly those whose sulphide-phosphors were purified in alkaline media. It is quite difficult to synthesize an efficient β^*-$ZnS{:}Ag$ phosphor from ZnS which has acquired oxygen-containing contaminants such as are dissolved off glass and ceramic ware by alkaline solutions. Some of the purity precautions taken in these laboratories have been outlined in other articles.[4, 56]

Effective barrier layers have not yet been achieved in practical cascade screens, although efforts have been made to coat the $ZnS{:}CdS{:}Cu$ particles with silica[57] or silicates.[58] The most promising practical technique appears to be that of applying an intermediate transparent evaporated layer of GeO_2, ZnF_2, ZnS, or the like, by a method similar to that used to apply electron-pervious light-reflecting coatings on present CRT screens.[15-18]

VIII. Summarized Data on Practical CRT Screens

Some *approximate* general properties of the more useful or potentially-useful, CRT screens are given in Table 8. The P8 and P9 screens were United Kingdom (British, Gen. Elec. Co., Ltd.) radar screens which were RMA*-coded for Canadian stand-by during the war. The missing RMA screen, P13, was not included because it has very inefficient cathodoluminescence.[4, 52] Before and during the war there was a tendency to call sulphide-plus-silicate screens P4, and all-sulphide screens P6. Recently, the RMA committee on screen nomenclature has designated monochrome-television screens P4, and color-television screens P6, regardless of composition.

The screens in Table 8 are listed in the order of their approximate persistences after low-voltage cathode-ray excitation. It is worth noting that the two dark-trace screens at the right of Table 8 both exhibit decelerated decays as the cathode-ray excitation energy input is increased, while bright-trace phosphor screens generally exhibit accelerated decays with increasing degree of excitation (Figure 20). The persistences of "strong" (contrast $> 1.5{:}1$) blips on P10 (KCl)

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[56] H. W. Leverenz, "Phosphors Brighten Radio Future", *Radio Age*, Vol. 3, No. 1, pp. 7-11, 1943.

[57] R. Puleston and S. T. Henderson, British patent 511,038, 8/8/39; U. S. patent 2,274,163, 2/24/42; (cf. A. Schleede and B. Bartels, U. S. patent 2,117,858, 5/17/38).

[58] F. Michelssen, "Einige Gesichtspunkte ueber den Aufbau und Betrieb gasgefuellter Braunscher Roehren fuer Fernsehzwecke", *Hochfr. u. Elektroak.*, Vol. 44, pp. 95-101, 1934.

* Radio Manufacturers Association.

	Screens with Retentivities *Shorter* Than Persistence of Vision							"Memory" Screens; Retentivities *Longer* Than Persistence of Vision							
RMA no.	—	P5	P11	P4, P6	P4	P1	P3	P12	P2	—	P14	(P9)	P7, (P8)	P10	—
RMA code	—	BBK	BBB	WWK	WWW	GGB	YYB	OOB	GGB	GGM	BOM	WWK	BYL	DTL	DTL
Composition	ZnO(Zn)	$CaWO_4$:W	α^P-ZnS:Ag	ZnS:Ag + ZnS:CdS:Ag	α^P-ZnS:Ag + $Zn_8BeSi_5O_{19}$:Mn	Zn_2SiO_4:Mn (α)	$Zn_8BeSi_5O_{19}$:Mn	Zn(Mg)F_2:Mn	ZnS:Cu(Ag) (β^*)	ZnS:CdS:Ag:Cu (EM1)	β^*-ZnS:Ag on ZnS(75):CdS:Cu	$Ca_2P_2O_7$:Dy (GEC Ltd.)	β^*-ZnS:Ag on ZnS(86):CdS:Cu	KCl	Stable phosphor
Bright or Dark Trace	BT	BT	BT	BT	BT	BT	BT	BT	BT	BT	BT	BT	BT	DT	DT
Table [illegible] no.	2	5	13	56	67	19	21	58, 61	57, 60	62-64	68	65	70	71	11, 19, 46, 68
Color	Green-white	Blue	Blue	White	White	Green	Yellow	Orange	Green	Yellow-Green	White + Orange	white	white + yellow	magenta on white	(any phosphor color)
Contrast	20:1	10:1	10:1	30:1	30:1	20:1	20:1	20:1	20:1	20:1	20:1	30:1	20:1	1.2:1	≈ 100:1
Candles/watt (6kv, 1μA/cm²)	1.6	0.2	2.1	4.5	2.4	3	2.5	2	4	3	2.1	0.5	2.4	—	1 - 6 (ZnS(50)CdS:Ag)
Min. Coulomb/cm² per raster, for visible trace (6kv)	10^{-10}	10^{-10}	10^{-10}	10^{-10}	10^{-10}	10^{-10}	10^{-10}	10^{-10}	10^{-10}	10^{-10}	10^{-9}	10^{-6}	10^{-9}	10^{-7}	10^{-5}
Operating (6kv) luminance (millilamberts)	12	1.3	14	30	16	20	17	0.2 (.2*)	0.1 (.5*)	0.07 (.5*)	0.003 (2*)	0.003 (2*)	0.03 (1*)	8000	3000
Source of light	CRT screen	CRT screen	CRT screen	CRT screen	CRT screen	CRT screen	CRT screen	CRT screen	CRT screen	CRT screen	CRT screen	CRT screen	CRT screen	external lamps	CRT screen
Decay form	ϵ^{-t}	ϵ^{-t}	t^{-n}	t^{-n}	$t^{-n} + \epsilon^{-t}$	ϵ^{-t}	ϵ^{-t}	ϵ^{-t}	t^{-n}	t^{-n}	t^{-n}	t^{-n}	t^{-n}	t^{-n}	t^{-n}
Decay time to 1% (sec.)	10^{-6}	10^{-5}	.005	.001 + .005 (Y) (B)	.005 + .06 (B) (Y)	.05	.06	.4	.3	1	1	2	3	5	1 to 10
Mechanism	electronic	electronic	electronic	electronic	electronic	electronic	electronic	electronic	electronic	electronic	electronic	electronic	electronic	electronic and ionic	electronic and thermal
Application index (10 = best)	7	10	3	3	5	10	10	1	6	6	5	2	5	2	4?
Range of scans/sec.	$60-10^6$	$60-10^5$	$60-10^4$	$60-10^4$	$30-10^3$	$20-10^3$	$20-10^3$	3-30	1-10	0.7-8	0.5-6	0.2-4	0.1-5	0.01-5	0.1-5
Power required (watts)	5	5	5	5	5	5	5	5	5	5	5	5	5	1000	200
Chief Use	Photography of very rapid transients. (to 500sc/sec.)	Photography of rapid transients (to 60sc/sec.)	Photography of transients (to 5sc/sec.) 60 70cm/μsec	Television (especially color)	Television	Most CR oscilloscopes. Rapid-scan radar CRT	Same as P1	Fire-control radars operating at 4-10 scans/sec.	Pre-war long-persistence oscilloscopes	H2S radar operating at one scan/sec	Eagle and H2K radars operating at about 1 scan/sec.	Some UK radars requiring high definition and long persistence	Most radars operating slower than one scan per second	Radars operating in high ambient light and slower than 0.2 scan/sec	None developed
Remarks	Efficient at low voltage (≤4kv) and high cd (>5μa/cm²)	Low visual efficiency see Fig. 27	Highest energy output of all known phosphors see Fig. 27	The yellow component, ZnS(46)CdS:Ag has the highest cathodolum. efficiency known (>5cP/watt)	Easier to manufacture than P6	The "old reliable" of the CRT industry	Same as P1 except for yellow color. 33-Z-11A (Table 24, 25) is also useful	Difficult to apply. Loses efficiency and changes decay during operation	Largely superseded by cascade screens (P14, P7)	Single layer screen, intermediate P2 and P14 in performance	Cascade screen (2 layer)	Deteriorates rapidly under strong CR bombardment	Cascade screen (2 layer)	Low contrast, high power consumption, excessively long decay. Brightest image	Highest contrast and second brightest image

Table 8

Compilation of Data for Some CRT Screens

screens are so unduly long, even for slow-scan panoramic radars, that the proposed application of this screen in television is palpably improbable.[29c] It was found that evaporated KCl screens co-crystallized with traces of certain elements having valencies greater than unity (notably thorium, magnesium, and aluminum) had their pristine decays remarkably accelerated, but the effect was too temporary to be used in practice. The P12, $Zn(Mg)F_2:Mn$, screen also changes its decay during use; the time taken to decay from 10 footlamberts to 1 footlambert decreasing from (1) 0.13 second to 0.08 second for $ZnF_2:Mn$, and (2) 0.24 second to 0.08 second for $ZnF_2(50):MgF_2:Mn$ (both end-results after 50 hours of life-test operation).[†-r]

In general, it was found that (1) cascade-sulphide-screen (P7 and P14) CRT's were the most stable and useful for panoramic-radar indicators, (2) P12 screens were useful in radars operated in the flicker region at scan intervals shorter than about 0.3 second, and (3) P1 screens were usually adequate for searchlighting radars with scan intervals shorter than 1/60 second. None of the screens can be said to be completely satisfactory, but the newer P7, P10, P12, and P14 were vital in enabling the devisal of panoramic Allied radars superior to the enemy's.

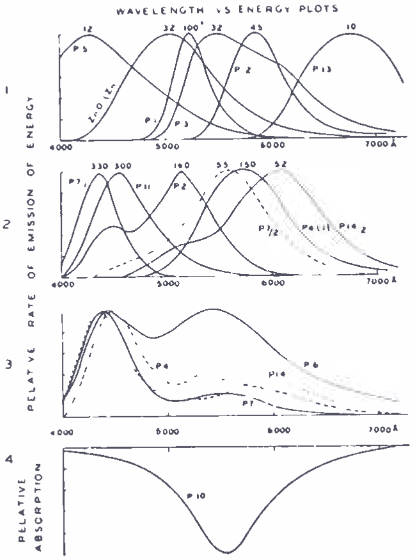

Fig. 27—Spectra of cathode-ray excited RMA-coded CRT screens.

Spectral distribution curves of practically all the United States-produced RMA CRT screens and screen components are shown in Figure 27. The numbers near the peaks of the emission bands of individual phosphors are the heights of the bands relative to the

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[†-r] Measurements made by H. P. Steier.

peak of the cathodoluminescence band of P1 which is arbitrarily set equal to 100. Screens with complex spectra, such as the P2, P7, and P14 screens, have phosphorescence colors corresponding to their long-wave bands only, e.g., luminescence of P7→phosphorescence given by P7/2. The measurements were made at 6 kilovolts and about 1 microampere per square centimeter of steady cathode ray, using the automatic recording spectroradiometer[59] or a quartz-optics spectrograph and densitometer.

Temperature-dependence curves of the photoluminescence efficiencies of some of the more useful phosphors are shown in Figures 28-31. In the case of cathodoluminescence, these curves should probably be shifted about 150°C to the right to check with tentative measurements made on several of the phosphors in a demountable CRT. Quantitative temperature-dependence curves are of practical importance in determining the optimum operating temperatures of phosphors as well as their behaviors in negative-modulation ("CR-burn") operation. In "CR-burn" operation, one cathode ray source may be used to uniformly excite and elevate the temperature of a phosphor screen while a second cathode ray source produces a modulated scanning beam effectively to "push the phosphor over the brink" of its temperature break-point. Decay of the dark-traces thus formed is a function of the rate of thermal dissipation of the excess heat supplied by the modulated scanning beam. Several experimental two-gun "CR-burn" CRT were made and found to have exceptional luminances and contrasts, but their low sensitivities to weak signals prevented practical application in wartime radars.

The fastest-decay phosphor, ZnO:(Zn), listed in Table 8 is especially useful for (1) recording very rapid transients,[60] (2) operation under very low-voltage cathode rays (≈ 5 volts), and (3) for transforming instantaneous gamma radiation into light suitable for actuating a 1P21(S4) or 1P22(S8) photomultiplier. In this connection, the β^*-ZnS:Ag phosphor has been found quite useful in transforming corpuscular radiations from radioactive materials into light which actuates blue-sensitive photomultipliers.

The data given in this article and in the Final Report[†-b] catalogue

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[59] V. K. Zworykin, "An Automatic Recording Spectroradiometer for Cathodoluminescent Materials", *Jour. Opt. Soc. Amer.*, Vol. 29, pp. 84-91, 1939.

[60] H. Goldstein and P. D. Bales, "High Speed Photography of the Cathode Ray Tube", *Rev. Sci. Instr.*, Vol. 17, pp. 89-96, 1946. R. Feldt, "Photographing Patterns on CRT", *Electronics*, pp. 130ff, Feb., 1944. D. F. Winter, "Fast Sweep Synchroscope", Paper L1, American Physical Soc., Cambridge meeting, April 26, 1946.

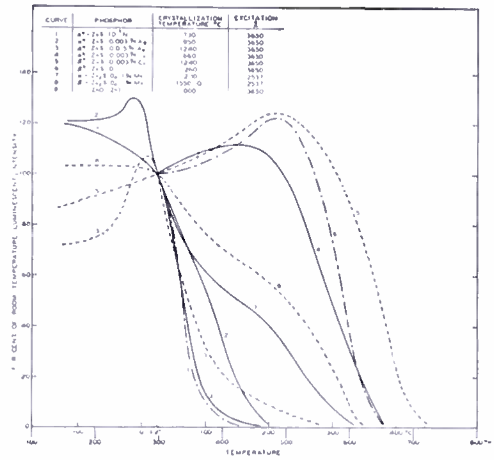

Fig. 28—Photoluminescences of phosphors as a function of temperature.

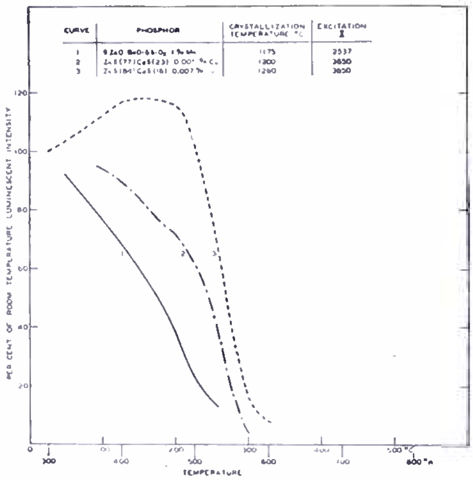

Fig. 29—Photoluminescences of phosphors as a function of temperature.

the present CRT screens. Radar indicator designers may find these data useful in designing indicators to be operated with present screens, but should keep in close contact with CRT screen researchers to profit from new developments. As long as research on cathodosensitive materials continues to be mostly empirical, large and unforeseeable improvements may be expected. This statement is emphasized by noting that of all the "memory" screens to the right of Table 8, only the almost passé P2 was in practical use before the war.

If all radars could be made to scan faster than 30 "looks" per second, then the development of radar CRT screens might coincide with the development of television CRT screens. As long as the scan intervals of vital radars remain longer than the persistence of vision,

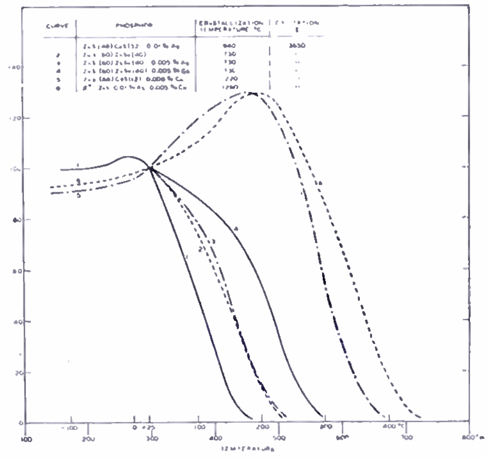

Fig. 30—Photoluminescences of phosphors as a function of temperature.

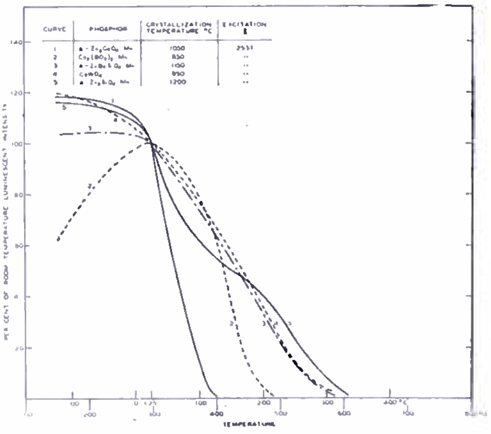

Fig. 31—Photoluminescences of phosphors as a function of temperature.

however, research on new and improved radar indicators should be separately fostered to ensure adequate progress for our changing tactical requirements.

IX. ACKNOWLEDGMENTS

During the course of the NDRC-sponsored research on radar CRT screens we were aided greatly by Drs. L. A. DuBridge, R. F. Bacher, D. H. Ewing, L. J. Haworth, and T. Soller of the Radiation Laboratory, Massachusetts Institute of Technology, who indicated to us the directions in which the work might proceed for maximum tactical benefit. These and many other members of the Radiation Laboratory and of a number of other laboratories, both in this country and in England, cooperated in expediting the attainment of superior radar indicators for Allied use. The British are to be commended particularly for being the first to apply cascade-sulphide and scotophor CRT screens in radar.

Within our research group, S. Lasof, Dr. R. E. Snrader, F. E. Williams, and E. J. Wood made substantial contributions to the research results herein reported. Further development and practical application of the research findings was done by the phosphor-development group (B. E. Artau, supervisor) and CRT-development group (Dr. L. B. Headrick, supervisor) of the Harrison, N. J. and Lancaster, Pa. plants.[†-b]

Our appreciations are expressed for the helpful administrative aid and encouragement received from Drs. G. R. Shaw and E. A. Lederer during the early research work at Harrison, N. J. (1941-42), and from Mr. E. W. Engstrom and Dr. V. K. Zworykin during the later work at Princeton, N. J. (1943-1945).

FREQUENCY MODULATION MOBILE RADIOTELEPHONE SERVICES*

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Summary—*The proposed use of frequencies in the Very High Frequency ranges of 30-44 and 152-162 megacycles for Common-carrier General Mobile Radiotelephone Communication is discussed with reference to propagational and equipment advantages. Consideration is limited to the radio link for vehicular and marine mobile service. Frequency modulation and its advantages for mobile communication are discussed briefly. The use of separate transmitting and receiving frequencies is the basis for all recommendations and allocation plans which are traced from their origin by the Radio Technical Planning Board to the most recent Industry suggestions to the Federal Communications Commission. Geographical considerations for service areas of fixed stations are based on Radio Manufacturers Association recommendations for transmitter powers, antenna heights, desired and undesired signal levels, etc. The Urban and Highway proposed services, including Marine, are compared on an operational and equipment basis and the most important mobile unit performance requirements are given. References from Radio Technical Planning Board (RTPB), Radio Manufacturers Association (RMA), Federal Communications Commission (FCC) and technical publications are provided.*

THE use of very high frequencies for relatively short range communication and broadcast systems was beginning to grow by leaps and bounds during the short period before World War II. The entry of the United States into the war necessitated the postponement of development work necessary for the commercial utilization of frequencies in this section of the radio spectrum. However, wartime developments for two-way communication by planes, tanks and motor vehicles as well as by surface vessels have greatly aided the design and application engineers in the problems encountered for commercial radiotelephone services. A consideration of all types of services (including sound broadcasting, television, facsimile and radio relay systems) now using and intending to use frequencies in the very high frequency range (30-300 megacycles) is considerably beyond the scope of this paper. Only the proposed use of frequencies for Common-carrier General Mobile Radiotelephone Communication in the 30-44 and 152-162 megacycle bands by motor vehicles and surface vessels will be considered. This type of service is an arrangement permitting ordinary

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* Decimal Classification: R540.

telephone subscribers to communicate, by means of a radio link, with mobile units. Communication of this type is considered to be useful for trucks, taxicabs, ambulances, doctors' cars and public service vehicles as well as surface vessels of various descriptions, including tugboats, ferryboats, lighters, barges, fishing vessels and all kinds of pleasure craft. Public telephone communication with passenger trains and passenger aircraft may eventually fall in the same category.

The use of frequencies in this section of the radio spectrum has many attractive and advantageous features[1] such as (1) small and efficient antenna systems which also are more easily made directive, if desired (with a resultant which is equivalent to a gain in transmitter power); (2) compact and lightweight transmitters and receivers; (3) reduced levels of natural and man-made interference, permitting comparatively low transmitter powers to be used for effective reception with low noise levels; (4) a relatively high degree of constancy of the received signal irrespective of secular, diurnal and atmospheric changes and; (5) a fairly definite limitation of both the service range and the usual interference area due to the absence of sky-wave (as compared to lower frequencies).

In addition to physical, electrical and propagational advantages as outlined above, it is generally agreed[2] that frequency modulation offers numerous advantages over amplitude modulation. Frequency modulation offers the outstanding advantage of being relatively noise free and lends itself to amplitude limiting, which tends to insure a more uniform volume. Obviously, for "high-fidelity" circuits frequency modulation requires considerably more space in the radio spectrum. However, for voice communication, audio frequencies between about 300 and 3000 cycles are adequate. Therefore, the "more-spectrum" disadvantage is considered to be justifiable due to the many advantages of frequency modulation since, for good voice transmission and allowing for the same carrier instability, the band occupied is only 3 or 4 times wider than for amplitude modulation.

Field tests[3] conducted in 1939-1940 on 42.6 megacycles conclusively show that the theoretical advantages[4] of frequency modulation over

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[1] "Radio at Ultra-High Frequencies," RCA Institutes Technical Press, April, 1940.

[2] "Use of Radio Channels in the Independent Telephone Field," Radio Technical Planning Board, Panel 8 Committee 1, Document P8C1-391-A, pp. 5-8, June 23, 1944.

[3] Raymond F. Guy and Robert M. Morris, "NBC Frequency-Modulation Field Test," RCA REVIEW, Vol. V, No. 2, pp. 190-225, October, 1940.

[4] S. W. Seeley, "Frequency Modulation—Bibliography," RCA REVIEW, Vol. V, No. 4, pp. 468-480, April 1941.

amplitude modulation for noise suppression are not a dream of the mathematician.

To provide two-way communication between land telephone and mobile units, it is considered essential to use different frequencies for transmission from the fixed station and the mobile unit. The use of separate frequencies permits simplification of the fixed station terminal equipment and improves the service which can be rendered. Such a system is known as "duplex" as contrasted to a single frequency or "simplex" system.

A "full-duplex" system[5] would mean one in which the transmission may proceed in either direction without the use of switching to determine the direction of transmission at any given moment. This is the condition obtained when two parties are conversing over a regular land-telephone circuit, since each may "interrupt" the other at will. A system providing full-duplex operation is, at present, not feasible, however, due to space limitations on the mobile unit. Obviously, two frequencies and two antennas are the fundamental requirements; but the selectivity of the mobile unit receiver is the stumbling block (assuming that the fixed station transmitter and receiver antennas could be geographically separated) since the mobile receiver would have to be capable of receiving a relatively weak signal from the fixed station in the presence of the comparatively strong signal from mobile unit transmitter.

In the present state of the art, it is necessary to use a "push-to-talk" switch (or voice operated relay) at the mobile unit and let the presence of transmission from the mobile unit switch (by means of relays) the fixed station terminal facilities. Thus, the fixed station transmitter is prevented from being turned on by the voice of the land-line subscriber when the mobile unit is talking and the fixed station receiver output is fed into the land-line. In effect, the mobile unit can "interrupt" the land-telephone.

An alternate method, which has been used to some extent and is being considered for these new common-carrier general mobile services, allows the fixed station transmitter to "re-radiate" the incoming signal from the mobile unit. This system requires that the fixed station receiver be unaffected by radiation from the fixed station transmitter. This may be accomplished by either adequate separation of the frequencies in the duplex system (with required receiver selectivity) or physical separation of the fixed station transmitting and receiving

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[5] W. R. Young, "Committee on Emergency Services, Transmitter Section, RMA Engineering Department—Appendices 1, 2 and 3," February 3, 1946.

antennas or a combination of both. Such a system is subject to the criticism that it reduces privacy to the extent that an eavesdropper may hear both sides of the conversation by listening to the fixed station transmitter.

For either of the fixed station systems as discussed above (landline switching by mobile transmitter or re-radiation of mobile unit transmission) it is obviously desirable to have as much separation as possible between the two frequencies of the duplex channel. This matter has had the cognizance of all reports and recommendations of the Radio Technical Planning Board[2, 6, 7] and Radio Manufacturers Association[5, 8, 9] in their attempts to aid the Federal Communications Commission in the matter of frequency allocations for the new communication bands.

The original Bell Telephone System Plan[2] for Highway and Urban services recommended a total of 110 duplex channels, 16 of which were for Highway and the remainder (94) for Urban services. All of the frequency blocks specified were in the range of 108-129 megacycles which was considered necessary for integration with other services, either existing or proposed, but which was at variance with the ultimate decision to place the Highway and Urban services in the ranges 30-44 and 152-162 megacycles, respectively.

The above proposal contemplated two types of service, namely: Highway two-way service on a message basis to and from vehicles on or near main trunk highways and Urban two-way service to and from vehicles operating in or close to cities or towns. Either type of service could, it was planned, be operated on a one-way or paging basis only. This would eliminate the need for a transmitter in the vehicle and, for certain purposes, would be adequate.

Contrasting the two systems, the Highway service would be chiefly of value to salesmen, heavy trucks, buses, construction crews, etc., and the Urban service would be useful to doctors, delivery trucks, taxicabs, ambulances, etc.

The Highway proposal contemplated the assignment of 8 frequencies for fixed-mobile communication within a radius of 10 miles so that

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[6] Austin Bailey, "Report of the Subcommittee on Common Carrier General Mobile Radiotelephone Service," RTPB Document P13C8-488-A.

[7] "Common-carrier General Mobile Radiotelephone Service," Brief in Behalf of RTPB Panel 13 Committee 8, P13C8-677-A, FCC Docket 6651.

[8] "Minimum Number of Channels—Part II, Radiotelephone," RTPB Document P8C2-500-A, July 26, 1944 and Supplement Document P8-498-A, September 19, 1944.

[9] "Summary of Existing and Proposed Allocations in Range 30-40 MC," RMA Engineering Department, March 12, 1946.

4 conversations could be carried on simultaneously. Three other sets of 8 frequencies would be used in adjacent areas and the pattern would be repetitive to cover the main highways of the nation.

The Urban proposal was considerably more ambitious in estimating that a total of 188 frequencies (94 pairs or duplex channels) would be required to serve a large city such as New York. These same frequencies were, of course, to be used all over the nation and in smaller cities could be shared with other services.

A part of the Bell Telephone System Proposal[2] was reflected in the Radio Technical Planning Board Report[8] of July 26, 1944 (Document P8C2-500-A) which suggested that for Radiotelephone Services in the very high frequency region it would be logical, as an aid to the development of both vehicular and maritime use of the bands, that both of these services share the fixed station facilities, particularly in port cities. It was estimated, however, that ultimately 3 duplex channels would be required in the most active port cities for marine communication to harbor craft and pleasure craft normally staying within the local area. On the basis that large passenger ships would use this type of short range service when entering and leaving a port it was estimated that a total of 20 duplex channels in the Urban band would serve the vehicular as well as marine requirements.

After the complete and exhaustive hearings held by the Federal Communications Commission from September 28th through November 2nd, 1944 a report[10] was issued designating certain frequency bands for Highway, Urban and Marine Communication; but the Commission stated that before assigning specific frequencies for these new services, a study would be made to determine the most efficient plan.

Excerpts from the Table of Allocations of this Document[10] for the bands 30-44 and 152-162 megacycles show minimum provisions as follows:

Band (megacycles)	Class of Station	Channel	Width (kilocycles)
30.5– 40	Maritime Mobile, Geophysical	9	40
30.5– 40	General Highway Mobile (Experimental), Marine (for mobile units of duplex system)	12	40
42– 44	General Highway Mobile (Experimental), Marine (for land stations of duplex system)	12	40
156–162	Forestry and Conservation, Marine, Urban, Mobile Experimental	7	60

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[10] "Proposed Allocations from 25,000 Kilocycles to 30,000,000 Kilocycles," FCC Docket No. 6651, pp. 22-24 and 171-183, January 16, 1945.

In a further and final Federal Communications Commission Release[11] dated May 17, 1945 provision was made for 20 duplex channels in the band 30-44 megacycles to be classed as General Highway Mobile (12 each for common carrier vehicles and fixed stations and 4 each for trucks and buses). The 12 duplex channels are also to serve marine needs, although 10 frequencies (shared) for Maritime Mobile in the band 30-40 megacycles and 5 frequencies (shared) in the band 42-44 megacycles are indicated. In the band 152-162 megacycles, 8 channels are specified for Maritime Mobile and 24 for Urban Mobile (which will include marine as well as vehicular units).

At the request of the Federal Communications Commission, Industry (represented by the Radio Manufacturers Association and Radio Technical Planning Board bodies) has formulated new recommendations for specific assignment patterns in the subject very high frequency band. An assignment pattern for the 152-162 megacycle band was much easier to produce than one for the 30-42 megacycle band since the use of the higher band, to date, has been only experimental and since the Railroads have already received their allocation of 60 channels in the top section of the 152-162 megacycle band, as shown in a later tabulation.

Considerable study[5] was made by the Engineering Department of the Radio Manufacturers Association which assumed the following:

(1) Frequencies near 150 megacycles, using frequency modulation.

(2) Three types of stations:

  (a) motor vehicle equipment, using a quarter-wave whip antenna with an effective height of 6 feet and with 50 watts antenna power.

  (b) fixed stations for small communities (10,000 population or less) using half-wave dipoles 100 feet above ground and with 50 watts antenna power.

  (c) fixed stations for large communities using half-wave dipoles 300 feet above the ground and with 250 watts antenna power.

(3) Service area based on minimum signal of 20 microvolts.

(4) Undesired signal for small and large communities 2 and 5 microvolts, respectively (when desired signal is 20 microvolts).

(5) The use of alternate channels[12] i.e., with the center frequencies 120 kilocycles apart and, for systems in the same area (such as New York City and Newark, N. J.) the use of double-alternate channels (center frequencies 240 kilocycles apart).

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[11] "FCC NEWS RELEASE NO. 80302" dated May 17, 1945.

[12] "Committee on Emergency Services, RMA Engineering Department," October 12, 1945.

Based on the above assumptions the service radius for small and large communities was computed to be 9 and 17 miles respectively. In the case of larger communities (where the power of the mobile transmitter is considerably less than the station transmitter), it was assumed that transmission would be made equal in both directions by the use of either a fixed station receiver antenna with more gain than a simple dipole or "satellite" receiver(s) serving the fixed station (as is common practice in the 2-3 megacycle telephone band).

For two-frequency or duplex systems, as already described, the controlling interference is that which occurs between the fixed station of one area with a mobile unit in another area, or vice versa. From simple geometry, it is apparent that the proper layout for the location of fixed stations repeating the same transmitter and receiver frequencies over and over again, and covering a large area, would be to place the fixed stations on the apexes of equilateral triangles, thus maintaining the same distance between any pair of fixed stations.

From the required signal level, desired to undesired signal ratios, antenna heights and transmitter power assumptions as already mentioned, calculations indicated that the spacing between fixed stations using the same duplex frequencies should be 32 and 45 miles for small and large communities, respectively. It is, therefore, possible to obtain national coverage with no more than 4 duplex channels. For congested metropolitan areas (which will use the Urban band 152-162 megacycles) only 3 pairs of duplex frequencies are required to allow for an area larger than the circle of radius 17 miles (the service radius of one station). Visualizing a total of 4 simultaneous conversations in one area, then 12 duplex channels are required as shown below in the complete 152-162 megacycle Allocation Table prepared by RMA-RTPB representatives and presented to the Federal Communications Commission on February 6, 1946.

RECOMMENDED ALLOCATIONS AND CHANNELS FOR
152-162 MEGACYCLE BAND

Center Frequency of Channels —Megacycles	No. of Channels	Service
152.03–152.69	12	Urban Mobile (Land Stations) (Note 1)
152.75–152.87	3	Maritime Mobile (Land Stations)
152.93–152.99	2	Relay Press (Note 2)
153.05	1	Power, Petroleum, etc.
153.11–153.17	2	Relay Broadcasting (Note 3)
153.23	1	Power, Petroleum, etc.

153.29–153.35	2	Relay Broadcasting (Note 3)
153.41	1	Power, Petroleum, etc.
153.47–153.53	2	Relay Press (Note 2)
153.59–153.65	2	Relay Broadcasting (Note 3)
153.71	1	Power, Petroleum, etc.
153.77–154.43	12	Fire
154.49	1	Provisional and Experimental
154.57	1	Provisional and Experimental (100 KC band)
154.65–156.75	36	Police
156.81–156.87	2	Relay Broadcasting (Note 3)
156.93	1	Power, Petroleum, etc.
156.99–157.05	2	Relay Broadcasting (Note 3)
157.11	1	Power, Petroleum, etc.
157.17–157.23	2	Relay Broadcasting (Note 3)
157.29–157.95	12	Urban Mobile (Mobile Stations) (Note 1)
158.01–158.13	3	Maritime Mobile (Mobile Stations)
158.19	1	Provisional and Experimental
158.25	1	Maritime Mobile (Ship-to-Ship)
158.31	1	Provisional and Experimental
157.37	1	Maritime Mobile (Ship-to-Ship)
158.43–161.97	60	Railroads

Note 1. May provide radio communication service to all types of mobile units such as marine, land vehicles, aircraft, etc. Shared with Rural Subscriber Telephone and Short Distance Toll Telephone.

Note 2. Shared with Forestry-Conservation, Geophysical.

Note 3. Shared with Motion Picture, Geophysical, Forestry-Conservation.

The above allocation table recognizes that only alternate channels are useable in the present state of the art. This reduces the amount of service obtainable by the Common-carriers (as well as Fire, Police and Railroads) by a factor of two, since it is contemplated that communication nets would be set up to cover wide areas in thickly populated sections. For a mobile unit to move over a wide area (greater than that served by one fixed station) and always maintain communication, it is obviously necessary to have multi-frequency equipment which not only would be complicated from an equipment standpoint but also would have certain operational differences from single frequency equipment (e.g. manual selection by the mobile unit of the frequency of the closest fixed station; the central telephone office originating a call to a mobile unit not knowing in which fixed station service area the mobile unit was located; etc.).

With the above factors in mind, it is logical to consider the development of this new service using only one duplex channel in any metropolitan section and operating one or more fixed stations simultaneously with the same conversation, regardless of the service area in which the mobile units might be at any one time.

Since the short-range Very High Frequency service is equally attractive to the local harbor craft of an area, the marine transmitting channels (3) were placed adjacent to the Urban vehicular channels (12) in order to facilitate the intermingling of both services and to aid the eventual development of simplified multi-frequency mobile equipment. Provision has also been made for two intership channels to handle that type of communication normally desired by fishing and pleasure craft.

Allocation of frequencies for new Highway and Marine Services in the band 30-44 megacycles is a considerable problem due to the already recognized congestion in the 30-40 megacycle section. It is estimated that there are approximately 30,000 United States land stations and mobile units now utilizing the 250 channels (40 kilocycles wide) in this band at the present time. A proposal[9] has been worked out suggesting that the transition from existing assignments to a more desirable plan be effected by a "temporary change effective on or before January 1, 1947 which would gradually work into the final allocation plan to be effective on or before July 1, 1951."

Excerpts from this suggested arrangement which concern Highway and Marine services follow:

Center Freq. (Mega-cycles)	Present Allocation	Temporary (by 1/1/47)	Final (by 7/1/51)
30.54	Coastal-harbor & Ship Phone	Special Emergency	Special Emergency
31.06	Geophysical & Motion Picture	Maritime Mobile & Geophysical	Maritime Mobile & Geophysical
31.26	Coastal-harbor & Ship Phone	Maritime Mobile & Geophysical	Maritime Mobile & Geophysical
31.66	Coastal-harbor & Ship Phone	Special Emergency	Special Emergency
33.62	Special Services & Experimental	Forestry-conservation & Maritime Mobile	Forestry-conservation & Maritime Mobile
33.82	Special Emergency	Forestry-conservation & Maritime Mobile	Forestry-conservation & Maritime Mobile
33.90	Fixed	Forestry-conservation & Maritime Mobile	Forestry-conservation & Maritime Mobile
33.94	Police	Police	Forestry-conservation & Maritime Mobile
35.10	Police	Police	Forestry-conservation & Maritime Mobile
35.14	Special Emergency	Forestry-conservation & Maritime Mobile	Forestry-conservation & Maritime Mobile
35.18	Relay Press	Maritime Mobile & Geophysical	Maritime Mobile & Geophysical

35.22	Police	Police	General Highway Mobile (land stations) for Common-carriers
35.26	Relay Broadcasting	Highway (Common-carrier)	
35.30	Government	Highway (Common-carrier)	
35.34	Coastal-harbor & Ship Phone	Highway (Common-carrier)	
35.38	Fixed	Highway (Common-carrier)	
35.42	Fixed	Highway (Common-carrier)	
35.46	Special Services & Experimental	Highway (Common-carrier)	
35.50	Police	Police	
35.54	Geophysical & Motion Picture	Highway (Common-carrier)	
35.58	Marine Fire—Municipal	Fire	
35.62	Relay Broadcasting	Highway (Common-carrier)	
35.66	Coastal-harbor & Ship Phone	Highway (Common-carrier)	
35.70	Government	Highway (trucks)	General Highway Mobile (land stations) for Trucks
35.74	Forestry	Forestry-conservation	
35.78	Police	Police	
35.82	Relay Broadcasting	Highway (trucks)	
35.86	Intership	Highway (buses)	General Highway Mobile for Buses
35.90	Police	Police	
35.94	Forestry	Forestry-conservation	
35.98	Relay Press	Highway (buses)	
37.26	Coastal-harbor & Ship Phone	Police	Police
37.58	Coastal-harbor & Ship Phone	Fire	Fire
37.66	Intership & Forestry	Fire & Forestry	Fire
37.94	Coastal-harbor & Ship Phone	Police	Police
39.22	Coastal-harbor & Ship Phone	Police	Police
39.58	Coastal-harbor & Ship Phone	Forestry-conservation & Urban Transit	Forestry-conservation & Urban Transit
43.02-43.18 (5 channels)	Broadcast	Maritime Mobile & Geophysical	
43.22-43.98 (20 channels)	Broadcast	General Highway Mobile (Mobile Units)	

Recommended "Final" allocations in accordance with the above table conform, in general, to the minimum provisions[10] of the Federal Communications Commission in that (lumping Marine and General Highway Mobile—including the fixed stations) provisions are made for a total of 14 Maritime Mobile frequencies (however they are to be shared with Geophysical and Forestry-conservation) whereas the Federal Communications Commission allotted nine.[10] Forty Highway Mobile frequencies are recommended (including fixed stations for Common-carrier, buses, trucks and all types of mobile units (whereas the Federal Communications Commission allotted only twenty-four.[10]

As in the case in the 152-162 megacycle band, it is intended that in port cities, the marine traffic be handled by the same shore (fixed) station used for the vehicular trade. Also, in common with the 152-162 megacycle band, to provide continuous communication along highways, it is necessary, according to the studies made,[5, 6] to stagger fixed stations in an equilateral triangle arrangement requiring 4 different duplex channels which can be repeated over and over again. Thus, for highway coverage, the 12 duplex channels will provide for 3 separate and simultaneous conversations in any one area.

This raises the questions of equipment and operational complications similar to those discussed for the Urban (152-162 megacycle) service. However, for highway service, no compromise can be made if communication is to be accomplished from any point along a highway. This means that 30-44 megacycle vehicular equipment *must* be multi-channel and arrangement must be made for the moving vehicle to shift transmitting and receiving frequencies as it moves from the service area of one fixed station to another and also to advise the closest fixed station of its *arrival* in the area. Presumably, fixed stations would advise central offices concerned so that a call originating at a central office could be routed to the correct fixed station. Communication originating from the vehicle would not be as involved, however, since by shifting to the correct duplex channel for the local area (a choice of 1 of 4) the vehicle could originate a call immediately—if the channel was not already in use.

It is understood that plans are being made for 30-44 megacycle networks to include New York-Buffalo (via Albany), Cleveland-Cincinnati, Chicago-St. Louis and Boston-New York. Experimental vehicular equipment will, no doubt, be capable of operation on only one duplex channel and coverage will not be complete from any highway point but the initial application of radio for this service will, most certainly, prove to be (in the phraseology of the Federal Communications Commission) in the category of "interest, convenience and necessity" for the public.

Applications are now on file[13] for Urban service for a number of cities and this service is expected to develop rapidly during the coming year. Three types of services are planned[13], namely: (1) a general 2-way telephone service between any telephone and any mobile unit,

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[13] "Mobile Radio Service," *Electronic Industries*, pp. 84-85, April, 1946.

with a 3 minute initial period; (2) a special 2-way dispatch service between a particular telephone and specified mobile units including a direct line from the dispatcher to the telephone central, with an initial period of 1 minute; and (3) a 1-way signalling service to mobile units to notify the operator of the vehicle that he is to comply with certain prearranged instructions.

A summary of the most important performance specifications for equipment to fit into these proposed services (highway-marine-urban) in accordance with suggested allocations follows. These specifications conform, in general, to proposed Bell System Recommendations[14] for equipment capable of giving satisfactory radio-link service to the overall system.

Characteristics	Highway-Marine	Urban-Marine
(a) Frequency (tuning) Range		
Transmitter	42-44 megacycles	157-159 megacycles
Receiver	30-40 megacycles	152-159 megacycles
(b) Frequency Tolerance		
Installation adjustment	0.005%	0.0025%
Maximum variation (Ambient — 30° to + 60° C)	0.01%	0.005%
(c) Modulation	Phase	
(d) Transmitter pre-distortion & Receiver de-emphasis	6 decibels/octave	
(e) Deviation (equivalent to 100% modulation)	± 15 kilocycles	± 20 kilocycles
(f) Maximum Band Width (tolerance plus deviation)	40 kilocycles	60 kilocycles
(g) Output Power	30 to 60 watts	20 to 40 watts
(h) Maximum Transmitter Spurious Radiation	70 decibels below carrier	
(i) Transmitter Residual Noise Modulation	47 decibels below equivalent 100% modulation by 1000 cycle sine wave.	
(j) Transmitter AF Limiter	20 decibels	
(k) Receiver Acceptance Band (6 decibels down)	± 20 kilocycles	± 30 kilocycles
(l) Receiver Suppression		
Adjacent mid-channel	20 decibels	
Alternate mid-channel	60 decibels	
(m) Receiver Spurious Responses	— 70 decibels	
(n) Receiver Signal Input for complete Limiting	5 Microvolts	
(o) Squelch Sensitivity Range	1 to 20 microvolts	
(p) Maximum Receiver Residual Noise (car or motor-boat engine operating	34 decibels below level of 1000 cycle sine wave which modulates test signal equivalent of 100%.	
(q) Transmitter and Receiver Fidelity (with 100% modulation and referred to 6 decibels/octave "pre-distortion" or "de-emphasis" characteristics)	1000 cycle reference	
	250 cycles	0 to — 4 decibels
	500-2000 cycles	+ 1 to — 3 decibels
	2000-3200 cycles	0 to — 4 decibels

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[14] "Technical Characteristics of Mobile Equipment Recommended for Bell System General Mobile Radiotelephone Service," March 25, 1946.

In addition to the above, in order to agree with fixed station plans, mobile equipment should be designed to use the two-tone audio frequency selective system[15], instead of a loudspeaker, for the indication of incoming calls. This system has been used for several years to call individual mobile units on Harbor, Inland Waterways and Great Lakes vessels.[16]

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[15] C. N. Anderson and H. M. Pruden, "Radiotelephone System for Harbor and Coastal Services," *Proc. I.R.E.*, Vol. 27, No. 4, pp. 245-253, April, 1939.

[16] H. B. Martin, "Great Lakes Radiotelephone Service," RCA REVIEW, Vol. III, No. 3, July, 1939.

DEVELOPMENT OF PULSE TRIODES AND CIRCUIT TO GIVE ONE MEGAWATT AT 600 MEGACYCLES*

By

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***Summary**—The work here described was done for the Army[1] and Navy[2] to develop high-power air-cooled pulse triode transmitting tubes and circuits. The A-2231 tube developed during the course of this project readily provides 500 kilowatts peak power at 600 megacycles with a duty cycle of 0.1 per cent. In the push-pull oscillator described herein, two of the tubes easily give a peak power of one megawatt. At this power level the operation is stable and the frequency may be varied throughout the 560-640 megacycle tuning range with no tendency toward sparkover. By ganging together the cathode and anode tuning controls, it has been possible to accomplish tuning with a single electric motor which may be remote controlled. These same principles of tuning might be employed to cover a much wider range.*

I. Introduction

ABOUT Pearl Harbor time the need arose for pulse radar apparatus of the greatest possible power to operate at the higher frequencies. As part of their general program to stimulate work along many frontiers, the Army and Navy encouraged the development of tubes and circuits to make possible a one megawatt 1200 megacycle pulse triode radar transmitter. At that time, the proposal to develop triodes to give this power at this frequency was most visionary. Conventional ultra-high-frequency tubes[3] of the period employed planar electrodes with circular symmetry and the cathode area which could be usefully employed at higher frequencies was limited by variations in electric field across the cathode surface. However, by employing the elongated-electrode-principle previously developed and operating in a mode such that the electric field would be uniform along the length of the electrodes, there was promise of a practical solution to this problem.

In theory, the elongated-electrode-principle would make it possible to increase the cathode area indefinitely were it not for the possibility

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* Decimal Classification: R351 × R339.2.

[1] U. S. Signal Corps Contract W-3434-sc-326.

[2] Naval Research Laboratory Contract 173s-4815.

[3] E. D. McArthur, "Disk-Seal Tubes", *Electronics*, Vol. 18, No. 2, pp. 98-102, February, 1945.

of mode instability. In the case of a cylindrical array, the axial length of the elements would be kept small and the area would be increased by increasing the diameter of the elements; operation would be accomplished in a mode wherein the voltage varies along the axial length of the electrodes but is uniform around the circumference. In the case of a linear array, the width of the elements would be kept small and the area would be increased by increasing the length of the elements; operation would be accomplished in a mode wherein the voltage varies along the width of the electrodes but is uniform along the length. In practice, the maximum size may be set by mechanical limitations.

In the initial phases of the work, consideration was given to a number of linear-array elongated-electrode-triodes of novel design. It subsequently appeared that these structures were not well adapted to existing manufacturing techniques and our effort was transferred to an electrically-equivalent double-ended triode with concentric cylindrical electrodes. By October 1943, preliminary tests of this design had been completed, but the needs of the Services had further changed and it appeared that a greater contribution could be made by developing tubes and circuits for operation at 600 megacycles instead of the original 1200 megacycles. At this frequency, the axial length of the electrodes was set by mechanical and thermal considerations rather than by variations in electric field. Accordingly, there was no reason to retain the double-ended construction and the design was further modified to provide a single-ended tube with coaxial cylindrical electrodes. This paper will be concerned only with this latter phase of the work.

II. TUBE DEVELOPMENT

The effectiveness of the single-ended cylindrical triode at 600 megacycles had by this time been demonstrated by the A-2212.[4] To reach the new objective of 500 kilowatts, all that appeared necessary was to increase the cathode area by increasing the cathode diameter. On the basis of the initial experience with the A-2212, the new tube should have a cathode area of about 40 square centimeters. The previous double-ended tube had employed a cathode of this area, and because many of the double-ended tube parts could thereby be employed, this cathode was retained in the new design. It subsequently proved to be advantageous to reduce the length of the cathode; also, the anode-grid interelectrode spacing which had initially been two millimeters was

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[4] L. S. Nergaard, D. G. Burnside, R. P. Stone, "A Developmental Pulse Triode for 200 Kilowatt Output at 600 Megacycles", Presented before the New York Section of I.R.E., April 6, 1946.

increased to three millimeters. As will be seen later, these changes were instrumental in greatly improving the performance.

This tube is designated the A-2231. It is an air-cooled, 500 kilowatt peak power, 500 watt average power, triode transmitting tube designed for pulse operation at 600 megacycles. The complete tube and some details of its construction are illustrated in Figures 1 and 2. The cathode area is 27 square centimeters, the cathode-grid interelectrode spacing is one-half millimeter, the anode-grid interelectrode spacing is three millimeters, and the transconductance is approximately 85,000 micromhos. Its low voltage static characteristics are portrayed in Figure 3.

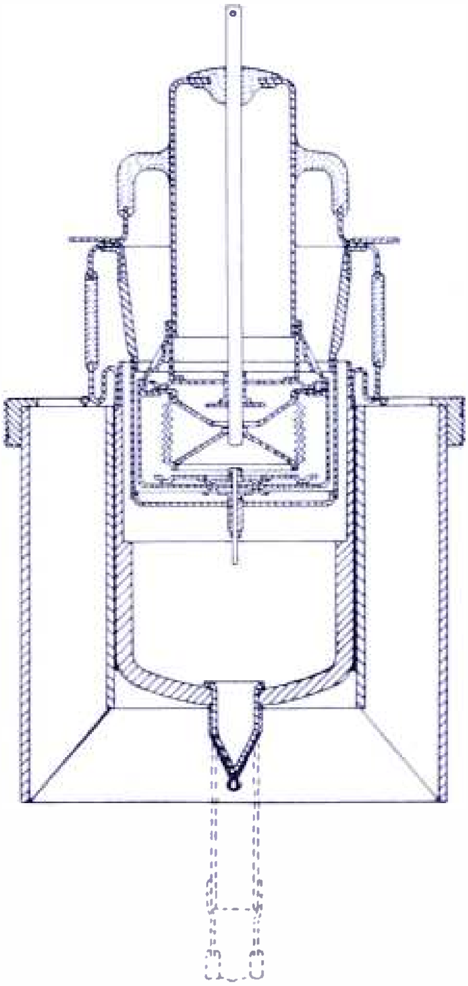

Fig. 1—Cross-Section of the A-2231 Pulse Triode.

The various stages of assembly and certain details of the component parts may be seen in Figure 2. Starting at the lower left and proceeding clockwise around the photograph may be seen: 1) the stem assem-

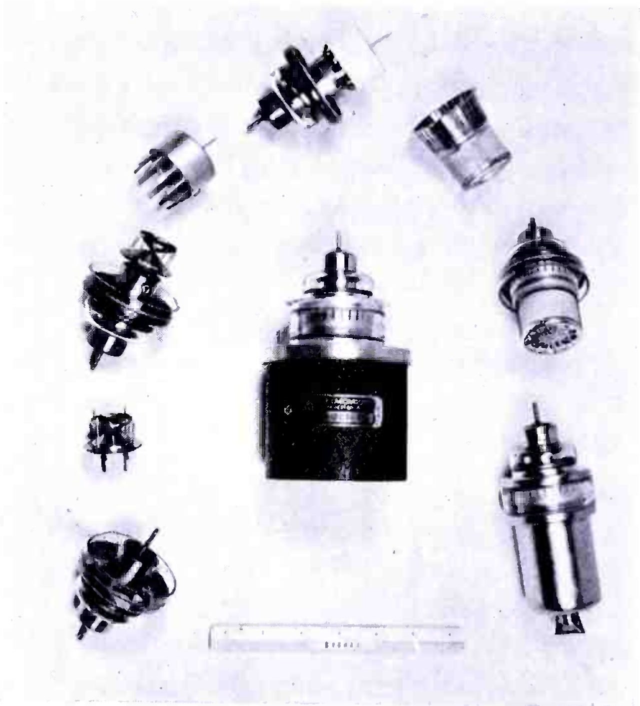

Fig. 2—Stages in Assembly of the A-2231 Pulse Triode.

bly; 2) the heater assembly; 3) the heater-stem assembly; 4) the cathode assembly; 5) the cathode-stem assembly; 6) the grid assembly; 7) the grid-stem assembly; 8) the final tube assembly; and finally, in the center of the photograph, the complete tube including air-cooled radiator.

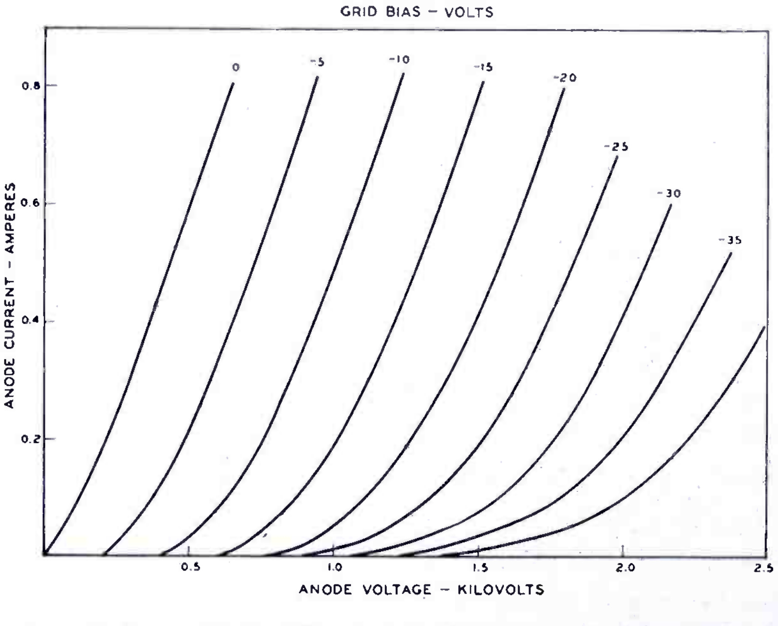

Fig. 3—Low Voltage Static Characteristics of the A-2231 Pulse Triode.

The heater consists of twelve helical strands of 0.005 inch diameter tungsten wire suspended between tantalum supports. The heavy wires to be seen in the heater assembly serve only to align the heater until it is mounted on the stem. The heater circuit is from the central pin to the cathode support. A heater power of 120 watts, 16 amperes at 7.5 volts, is required.

The grid consists of 180 wires of 0.007 inch diameter platinum-clad-molybdenum[5] spot welded to a nickel grid cap and heavy copper grid support cone. In the early designs, a relatively thin copper-plated-steel grid support cone was employed, but in an effort to provide better grid cooling, the heavy copper cone was substituted. As may be seen in the photograph, the grid wires are slightly twisted. Inasmuch as the grid surface is cylindrical, each individual wire has a slight outward bulge. This was found to be very important in practice. In the initial stages of development straight wires were used and many cathode-grid shorts resulted from wires inadvertently bowed inward. This circumstance is aggravated by the fact that if one of the wires is bowed inward more than its neighbors it will receive more than its proportionate share of the current and will become hotter and bow inward still farther.

Although there were miscellaneous mechanical problems and difficulties with cathode poisoning, the real obstacle was that of grid emission. It was relatively easy to build tubes that would give 500 kilowatts or even 700 kilowatts peak power at low duty, but as the average power was increased grid emission set in causing the efficiency and peak output to drop off.

To improve grid cooling, the grid was shortened and a massive copper grid flange and support cone were adopted. This provided a continuous heavy copper heat conducting path from the base of the grid wires to the external circuit. Unfortunately the elements required to provide flexibility between the glass and this massive copper grid flange led to low efficiency, possibly because of a shift in the position of the current maximum.

At this same stage in the development, circuit flashover in the anode cavity was also a serious problem. Although individual tubes could be tested in the pressurized circuit, it was undesirable that the final unit should operate under pressure. A major improvement was required. In the two-tube circuit, a pair of the original tubes gave 700 kilowatts before circuit sparkover, whereas a pair of the newer massive-grid-flange tubes was limited to about 500 kilowatts. Examination of the circuit flashover problem revealed that the radio-frequency voltage at

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[5] G. A. Espersen, "Fine Wires in the Electron-Tube Industry", *Proc. I. R. E.*, Vol. 34, No. 3, pp. 116-120, March, 1946.

certain points of the circuit may greatly exceed the voltage across the tube because of impedance mismatch between the anode-grid region of the tube and the circuit. Also, the voltage stepup depends upon the location of the impedance discontinuity; as the region of discontinuity approaches a current maximum the stepup increases.

To improve this situation, the anode-grid interelectrode spacing was increased from two millimeters to three millimeters. Not only did this result in a better impedance match, but it had the very beneficial effect of lowering the cathode current required for a given peak power output. This made it practicable to operate satisfactorily with the reduced cathode area of 27 square centimeters occasioned by shortening the grid.

In the meantime, grid temperature measurements indicated that the grid was still so long that the top half was indifferent to cooling at the bottom. Inasmuch as an almost equivalent amount of grid cooling could be realized by merely substituting a copper grid support cone similar to the steel one originally employed, there seemed little reason for adhering to the troublesome massive copper grid flange. Consideration of these factors led to the final design.

Due to the length of the grid wires and the high power output, the requirements on the grid were still unusually severe. The grid temperature measurements indicated that at full power output the top half of the grid might be hotter than the cathode. Nevertheless, some of these tubes were good, while others had severe grid emission. On closer inspection it appeared that good tubes could consistently be made from certain spools of wire; whereas, tubes with severe grid emission invariably resulted when other spools of wire were used. This seemed direct evidence that some samples of wire could withstand these unusually severe conditions while other samples could not. If some simple test could be employed to differentiate between the two kinds of wire, the satisfactory wire could be selected beforehand. This led to a program of testing samples in special wire-study tubes.

In the special wire-study tubes, the objective was to simulate conditions in the final tube. This was accomplished in the following manner. A sample of the wire to be studied was suspended between two oxide-coated cathodes to approximate the extreme barium exposure encountered in the large tube. The oxide-cathode and the sample wire were heated to 950° C; the wire by bombardment with electrons from the cathode, the cathode by indirect heating and bombardment by electrons from the wire. This was accomplished by applying an alternating voltage between the wire and cathode so that they alternately interchanged role of cathode and anode. After the initial adjustment, the voltage to the unit was held constant and the emission from the wire was traced out as a function of time by a recording meter. In the beginning the emission was small, but after a period of minutes (for unsatisfactory samples) or hours (for satisfactory samples), the wire activated and emission rapidly rose several hundredfold. The length of time that the wire withstood barium exposure before activation was an indication of its quality. Figure 4 shows a wire-study tube and typical records of satisfactory and unsatisfactory wire.

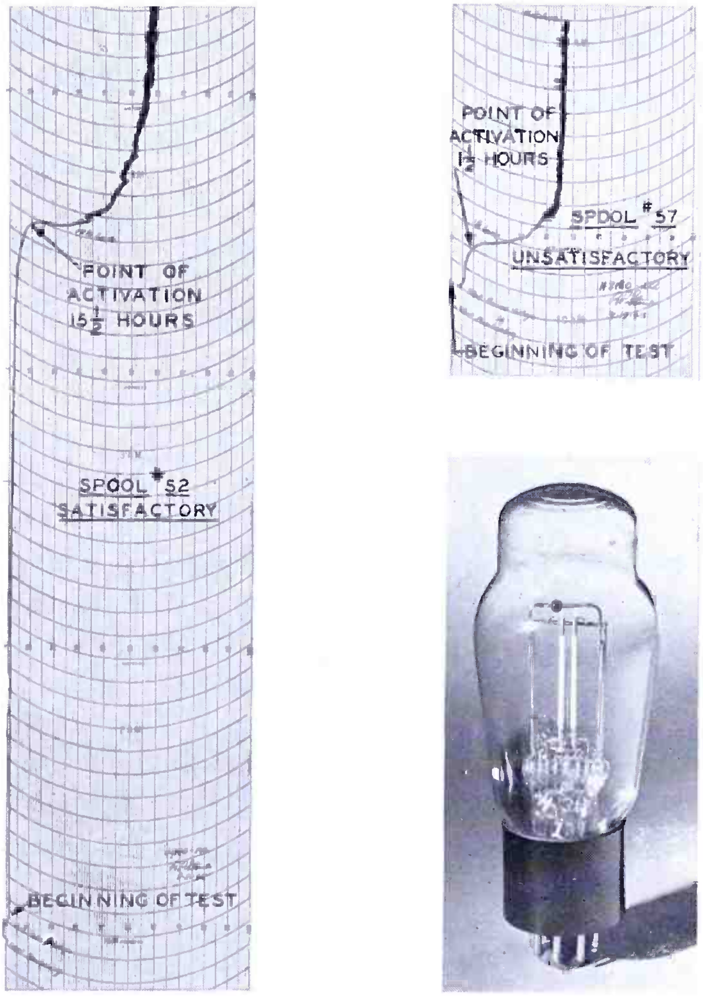

Fig. 4—Wire-Study Tube for measuring Grid-Emission and typical records showing performance of satisfactory and unsatisfactory wire.

The advantages of selecting wire by this means were clearly evident. Before the selection tests were employed, 50 per cent of all operable tubes had intolerable grid emission; after the tests were adopted and only predicted-satisfactory-wire was used, shrinkage due to grid emission dropped to less than 17 per cent.

III. CIRCUIT DEVELOPMENT

As before mentioned, individual tubes were tested in a single-tube circuit. Very early in the program, it was found that the limit of power output was set by circuit flashover. Sometimes flashover set in across the anode system, at other times it first showed up in the feedback system. Only if special care were taken was it possible to take measurements up to 400 kilowatts. In order that tests might be conveniently made to rated power level or higher, this unit was pressurized. In many instances, when operating at 600 to 700 kilowatts it was convenient to use pressures of as much as two atmospheres so that tuning could be accomplished without sparkover. On the other hand, pressurizing was undesirable for the final transmitter.

On the basis of experience with the single-tube oscillator, it appeared possible to operate a two-tube unit at the megawatt level without pressurizing provided the anode-line spacing were reasonably large and provided the anode-line impedance were kept low. To attain this result, the most suitable internal anode-line diameter appeared to be five inches with four and one-half inch diameter cylinders at the lower ends to accommodate the tubes. By this means the larger diameter section could be made to slide over the smaller diameter section for tuning.

For a two-tube oscillator, push-pull operation was preferable to parallel operation. Push-pull operation simplified the mechanical and direct-current supply lead connections, for in this mode the location of the midpoint radio-frequency voltage minimum is the same for all tuning positions. Furthermore, push-pull operation appeared advantageous from the standpoint that a single load loop could be conveniently positioned to provide balanced loading of both tubes.

An important design consideration was to provide access to the tubes for servicing. For this purpose the front half of the outer conductor may be removed as shown in Figure 5. The size of this outer conductor was chosen to be seven and one-half inches effective diameter providing an anode line with a spacing of one and one-quarter inches. Such a line has an impedance of about 24 ohms.

The motion was designed to cover the 560 to 640 megacycle frequency range. Mechanically, the most difficult problem was to move the five-inch-diameter cylinder-unit without putting undue strain on the tubes or adding insulation losses to the system. The method adopted was to use an internal yoke to support the tubes from an insulating cylinder at the top. The lower edge of the five inch section was arranged to be midway between the voltage maximum and voltage minimum at the mid-frequency of 600 megacycles. This precaution was taken to avoid excessive current through the contacts as would occur at a current maximum or excessive voltage across the circuit at a sharp edge as would occur if this junction were made at a voltage maximum.

To provide the mechanical movement for an 80 megacycle frequency change with space for the tubes and sufficient clearance for the smoothly curved line, it was necessary to operate in the five-quarters mode; i.e., the electrical length from the midpoint of the anode line to the interelectrode anode-grid space was five-quarters of a wavelength. As may be seen in Figure 5, the end of the five inch diameter section was carefully rounded and the contact fingers were recessed to minimize flashover and corona.

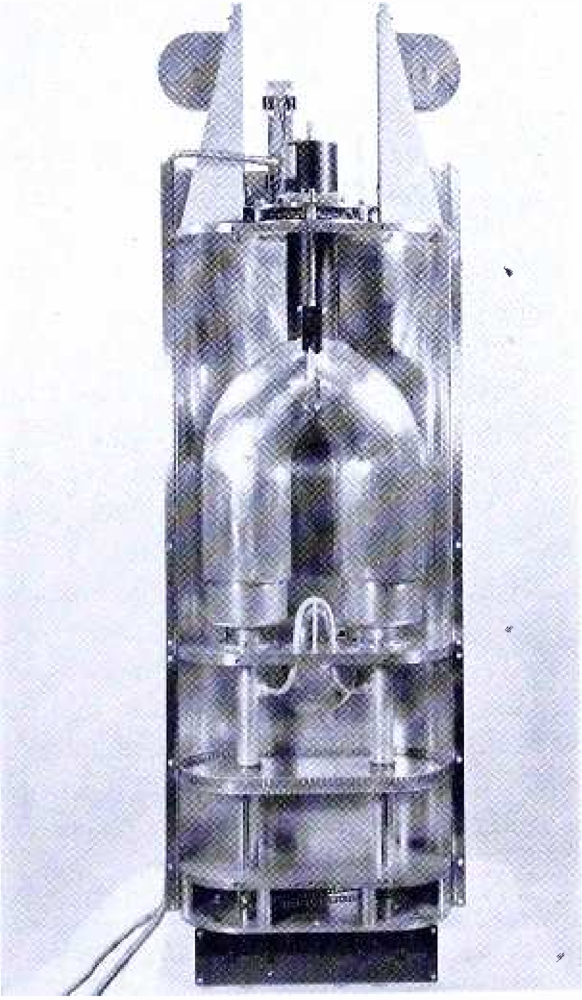

Fig. 5—Internal View of Two-Tube 600-Megacycle One-Megawatt Oscillator.

For cathode tuning, a sliding short circuit connecting the inner and outer conductors at a voltage minimum point was employed. The details of this part of the circuit may also be seen in Figure 5. The minimum operating line length was three-quarters of a wavelength since the tubes had an internal cathode-grid effective length of more than one-quarter wavelength at 600 megacycles. Condensers in the inner conductors made it possible to supply bias by external resistors.

During the course of the development, various feedback systems were examined. The first arrangement used a tuned loop common to the anode and cathode sections. Tuning was accomplished by an external stub. Various sizes of loops were tried, but none of them were as satisfactory as the untuned cathode-to-cathode loop shown in Figure 5. This untuned cathode-to-cathode loop had been previously developed by Dr. L. S. Nergaard for the A-2212.[4] This loop provided the same degree of feedback as the tuned loop; it practically eliminated the problem of sparkover to the grid flange; and finally, it did away with one tuning control.

The load is coupled to the anode section of the oscillator by a loop adjacent to the grid flange. Care was taken to place this loop symmetrically with respect to the ends of the anode line so as to equalize the load on the two tubes. This portion of the load line may be seen just behind the feedback loop in Figure 5. Other features of the load line and matching stubs may be seen in Figure 6. Because of the high voltage at the one megawatt level, it was desirable to use a three inch diameter load line.

Measurements of anode and cathode tuning indicated that the tuning of these systems was collinear within 2 per cent which was within the tolerance of the cathode tuning requirements. By using the proper gear ratio it was possible to combine the anode and cathode drive. A motor with speed rheostat and reversing switch makes it convenient to operate with remote control. This motor and the common driveshaft may also be seen in Figure 6.

IV. PERFORMANCE OF TUBES AND CIRCUIT

The performance of the final unit is indicated in Figure 7. This data was taken with a pulse length of 5.5 microseconds and a repetition rate of 180 pulses per second which corresponds to a duty cycle of 0.1 per cent. No change in performance was observed at lower duty cycles. Efficiency is defined as the ratio of peak power output to peak power input; the peak power input is defined as the product of anode voltage and anode current less the power loss in the 2.75 ohm cathode bias resistor.

This plot shows how the various factors depend upon anode voltage as anode voltage alone is varied. It will be observed that the peak

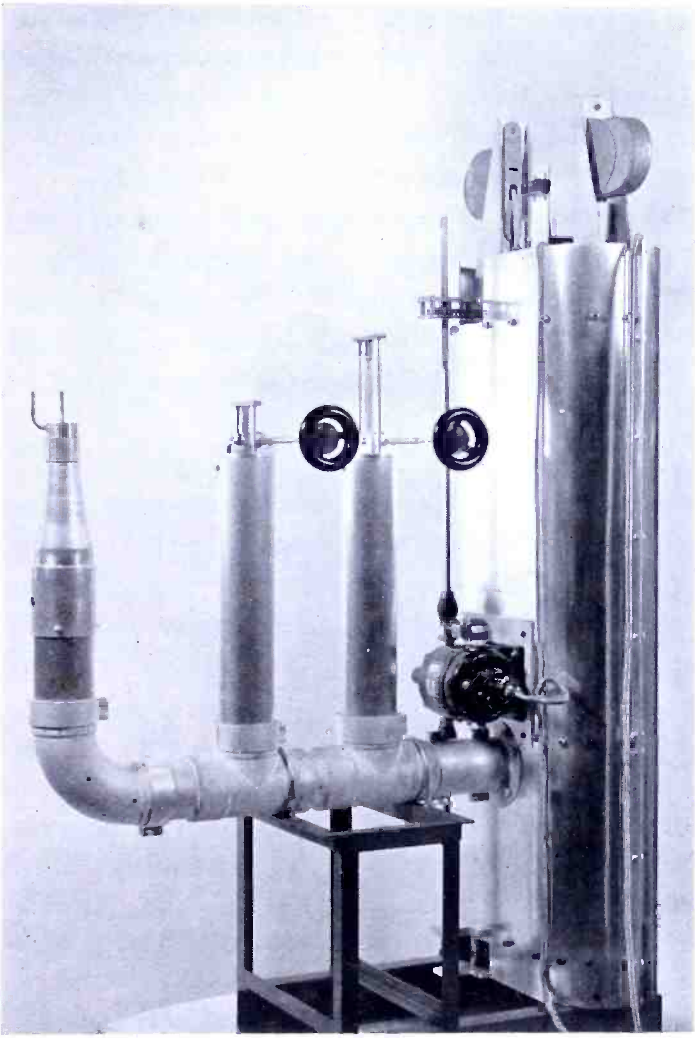

Fig. 6—External View of Two-Tube 600-Megacycle One-Megawatt Oscillator.

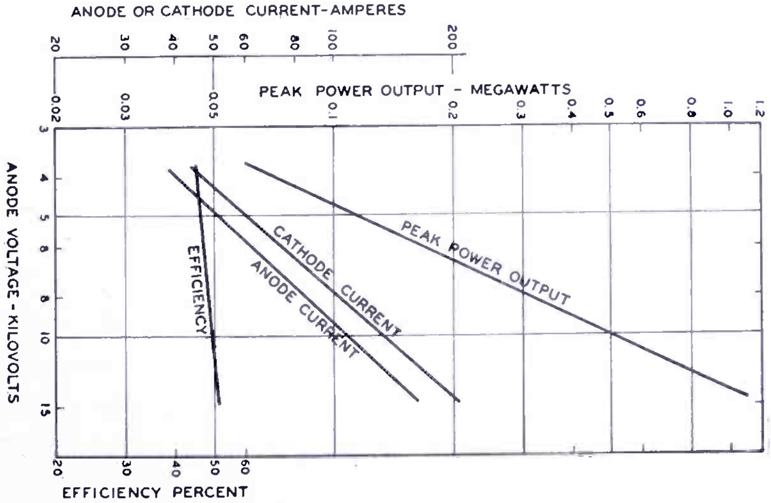

Fig. 7—Performance of Two-Tube 600-Megacycle One-Megawatt Oscillator.

power output increases almost as the five-halves power of the voltage while the cathode and anode current increase approximately as the three-halves power of the voltage. The peak power output reaches 1.1 megawatts at 14 kilovolts. Inasmuch as the duty cycle is 0.1 per cent, this corresponds to an average power of 1.1 kilowatts.

The fact that the plot of cathode current and anode current remain parallel and that the efficiency continues to rise with increased voltage and output is particularly significant. Even a trace of grid emission would manifest itself by lowering efficiency, while heavier grid emission would give rise to disproportionally larger anode current at higher power levels.

The stability of the unit is demonstrated by the fact that the frequency may be varied throughout the 560 to 640 megacycle tuning range with no tendency toward sparkover at the maximum power level. No variation in performance was observed over this range. If the mechanical design were such as to permit greater motion of the adjustable elements, the tuning range could undoubtedly be extended.

Tests of individual tubes in the single-tube circuit were run at 710 megacycles. The performance at this frequency was indistinguishable from that obtained in the 560 to 640 megacycle range. Preliminary tests indicate that these tubes will perform well at 1200 megacycles.

A METHOD OF MEASURING THE DEGREE OF MODULATION OF A TELEVISION SIGNAL*

By

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Summary—*A method of measuring the degree of modulation on a standard television signal is described. The double sideband output of the transmitter energizes a linear diode monitor, the output of which contains a direct current component in addition to the visual signal. Means are provided to interrupt this composite signal periodically by short-circuiting the diode output load impedance for a brief interval, thus establishing a reference zero signal. The resultant modified signal, including the zero reference level, may be observed by means of a cathode ray oscilloscope capable of handling only alternating current signals. The trace on the face of the oscilloscope will contain all of the information required to measure the degree of modulation attained.*

INTRODUCTION

THE need for determining the degree of modulation which was attained on the signal radiated by a television transmitter was apparent very soon after experiments were begun with television transmission. Most of the modulation monitoring methods which were developed for sound broadcasting were not applicable to television broadcasting. The method of measuring the degree of modulation by observing the carrier frequency envelope on a cathode-ray oscilloscope was applicable to television provided that the information given by the trace was properly interpreted. The current television standards require that the carrier envelope achieve maximum amplitude at the peak of the synchronizing signal and that this maximum amplitude shall be independent of light and shade in the picture signal. As a consequence of this method of operation, the peak carrier envelope amplitude becomes a constant, whereas the average carrier envelope amplitude becomes a variable dependent upon the content of the picture signal. Therefore, modulation measurements under existing standards for television transmission must be made in terms of the peak carrier envelope amplitude, in contrast to sound broadcasting practice, wherein such measurements would be referred to the constant which in that case would be average carrier envelope amplitude.

When the radio frequency envelope of the visual transmitter was

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* Decimal Classification: R254.1.

monitored on a cathode-ray oscilloscope, the operators were in a position to assert with confidence that the signals being radiated were in accordance with the current standards. This method was reasonably satisfactory, but the location of the cathode-ray oscilloscope was determined by the probable accuracy of results rather than by operating convenience. The cathode-ray oscilloscope, a relatively expensive piece of equipment, was made unavailable for other purposes when frequent monitoring of the radio frequency envelope was considered necessary. A more expedient method of obtaining the information offered by the cathode-ray oscilloscope envelope monitoring method had been sought for some time.

An article by A. W. Russell[1] suggested the use of a vibrating switch to "preserve the direct current level in oscillograph amplifiers." While the usefulness of this method in studying the operating characteristics of many vacuum tube circuits was immediately evident, its application to the measurement of modulation was not conceived until several months had elapsed. During the course of the experimenting which followed, the switching mechanism which was used became identified as the "Vibroswitch."

A diode rectifier, which derived its signal from the coaxial radio frequency transmission line between the transmitter and the vestigial sideband filter, has been used for many years as a radio monitor. The quality of the picture was observed on a kinescope while the wave form and amplitude of the composite signal were observed on a cathode ray oscilloscope as a regular operating procedure. The "Vibroswitch" was applied to the diode monitoring system.

THEORY

The circuit diagram of the diode rectifier, "Vibroswitch," and cathode ray oscilloscope arrangement is shown in Figure 1. When the circuit constants have been properly chosen, the instantaneous potential difference developed across the diode load impedance Z_c is substantially proportional to the instantaneous carrier envelope amplitude. In a constant peak carrier amplitude system of modulation (direct current transmission), which is currently standard for television, the peak carrier amplitude is attained during the synchronizing pulse interval. The minimum carrier amplitude occurs when a maximum white signal is present. If the modulation were complete during a given maximum white interval, the concurrent instantaneous carrier envelope amplitude would be zero, and as a result the concurrent instantaneous potential

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[1] A. W. Russell, "Preserving the D. C. Level in Oscillograph Amplifiers," *Electronic Engineering*, Vol. XV, No. 175, page 173; Sept., 1942.

difference across Z_c would also be zero. It, therefore, appears that if we periodically short-circuit Z_c, we will artificially create the conditions which would obtain during complete modulation. If the rate at which the short-circuiting occurs is sufficiently rapid, the resultant revised signal will be passed by the cathode-ray oscilloscope amplifiers, and the amplitude of the resultant trace should be proportional to the instantaneous potential drop across Z_c and, therefore, within certain limitations, proportional to the instantaneous carrier envelope amplitude. One limitation is imposed by the degree of linearity possible between the voltage applied to the diode circuit and the resultant current. Another limitation is imposed by the effective diode circuit time constant. These circuits must be so designed as to permit the rate of change of potential difference across Z_c to follow the rate of change of carrier envelope amplitude required to transmit the desired intelligence. Further, the information being transmitted during the short-circuiting interval cannot be recorded by the cathode-ray oscilloscope. The interpretation of the results must be made in the light of these limitations.

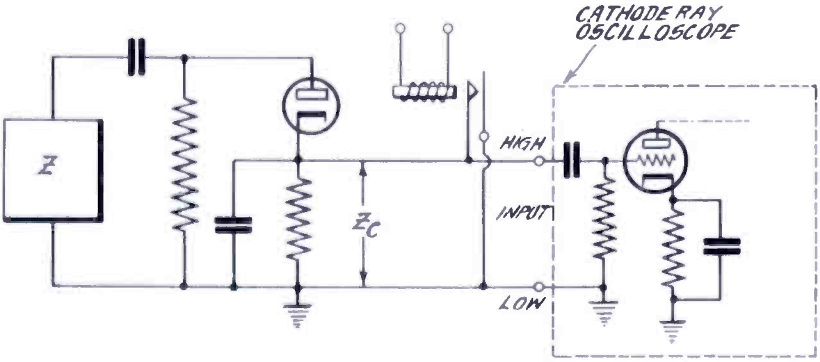


Fig. 1—Diode rectifier, "Vibroswitch," and cathode ray oscilloscope circuit arrangement.

THE "VIBROSWITCH"

The original "Vibroswitch" was a standard vibrator such as is used in automobile receiver power supply units, but revised for 60 cycle alternating current operation. However, the contact spring tension varied with use to a degree that rendered this instrument too unreliable for regular use under operating conditions. Experimentation then proceeded through the use of a motor driven segmented disc, a motor driven cam, a loudspeaker element equipped with contacts and, more recently, a specially constructed switch using the coil and magnet from a Baldwin headset. The mechanical schematic diagram of this unit is shown in Figure 2. The physical appearance is evident in Figure 3. The fundamental problem insofar as the "Vibroswitch" is concerned is to obtain a short closed contact period with clean make and break. Most of the earlier models suffered from mechanical oscillation of the swinger, causing variation in contact resistance at the

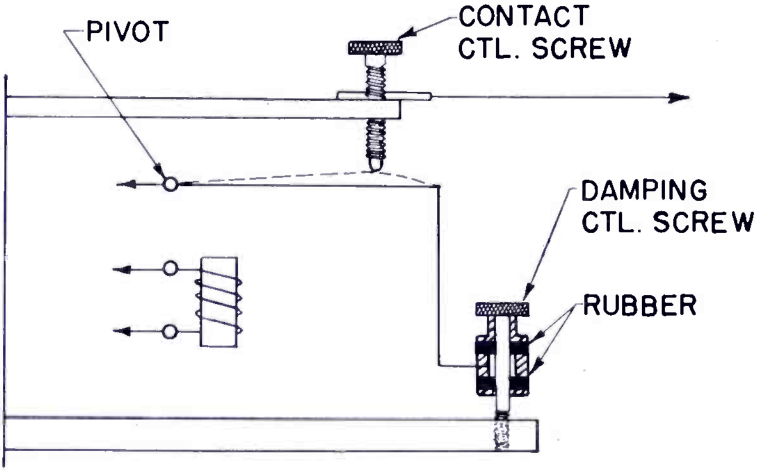


Fig. 2—Mechanical schematic diagram of the "Vibroswitch."

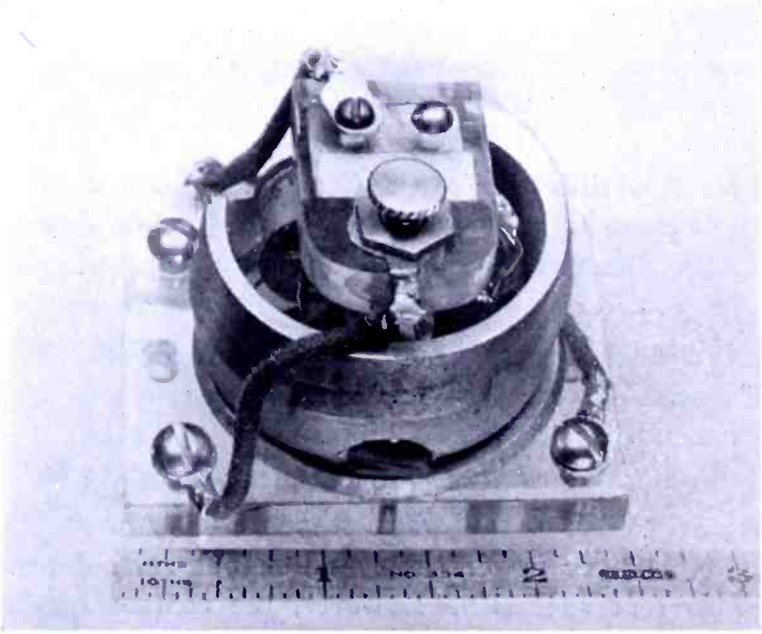
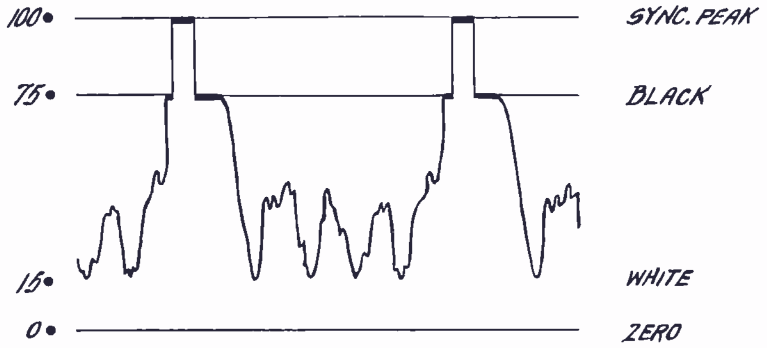


Fig. 3—A recent physical form of the "Vibroswitch."

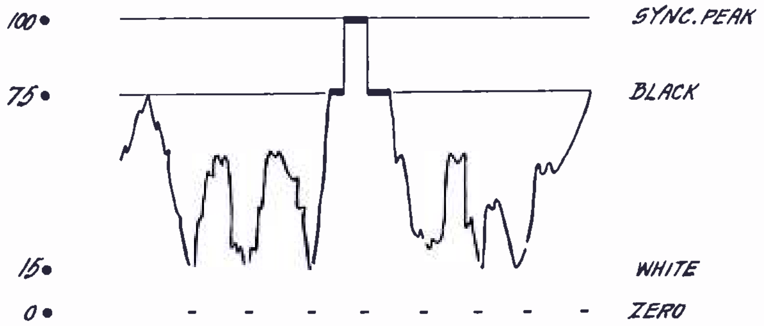
instant that the contact was closed. This led to a confused trace on the oscilloscope.

INTERPRETATION OF THE OSCILLOGRAMS

Figure 4 gives the expected oscilloscope traces. The actual appearance of the trace on an oscilloscope is shown in the photographs



(a) Horizontal deflection rate approximately one half the field repetition rate.



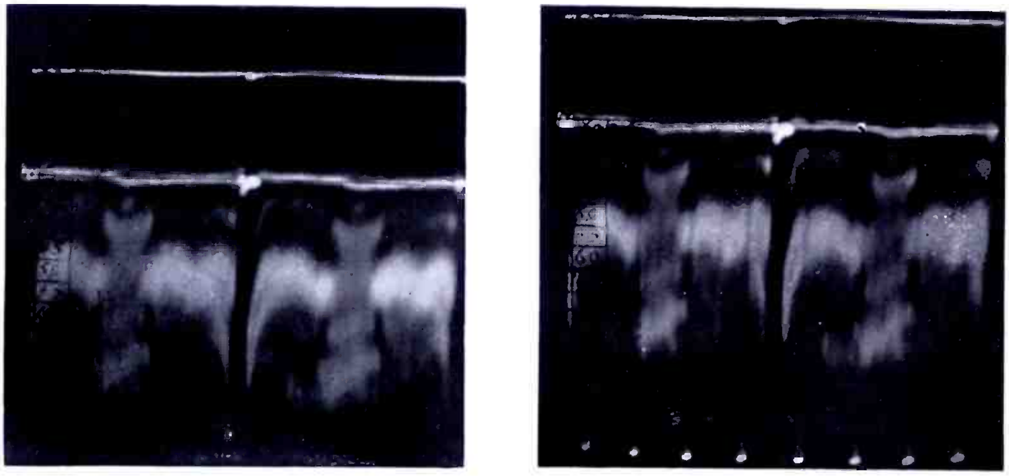
(b) Horizontal deflection rate approximately one half the line repetition rate.

Fig. 4—Representation of the expected Oscilloscope Trace:

included in Figure 5. If the vertical deflection circuit of the monitoring oscilloscope operates with the direct current component of the signal re-inserted, it is possible to set up a scale reading 0 to 100 on the face of the oscilloscope and using the zero carrier level indication provided by the short-circuiting interval of the "Vibroswitch" cycle, set the gain of the oscilloscope amplifier so that the peak of sync falls at 100 and the zero carrier dot or line falls at zero. The amplitude of the white signal and black level can then be read directly in per cent of peak carrier envelope amplitude. Similarly, variation of black level or peak carrier as a function of average brightness can be observed and read in per cent of peak carrier envelope amplitude.

GENERAL COMMENTS

The optimum repetition rate of switching would probably vary with each application. Experience with monitoring standard television transmissions indicates that a repetition rate in the order of 800 to 1000 cycles per second is acceptable. The switching rate should be nearly, but not exactly, in synchronism with the signal being observed.



(a) Horizontal deflection rate one half the field repetition rate —"Vibroswitch" not operating.

(b) Same horizontal deflection rate —"Vibroswitch" operating.

(c) Horizontal deflection rate one half the line repetition rate —"Vibroswitch" operating.

Fig. 5—Photographs of oscilloscope traces:

The mark or short-circuiting interval should be short, perhaps on the order of 10 per cent, but long enough so that there can be no doubt that the circuit has been fully discharged and that a positive mark is evident at the zero carrier level. The cathode ray oscilloscope amplifiers must be linear over a sufficient swing to pass the composite signal without compression.

Measurements of black level in per cent of peak carrier envelope amplitude, white signal in per cent of peak carrier envelope amplitude, and variation of black level as a function of average brightness using the "Vibroswitch" technique have been checked against the envelope cathode ray oscilloscope method. The results of the two methods were found to be in substantial agreement.

This device permits measurements on low power equipment which would not provide sufficient voltage to deflect the plates of an envelope cathode ray oscilloscope directly.

ACKNOWLEDGMENT

The actual device described herein is the result of the work of many engineers who have been associated with the author. Their contributions have been directly responsible for the processing of an "idea" into a practical and useful tool.

DEVELOPMENT OF AN ULTRA LOW LOSS TRANSMISSION LINE FOR TELEVISION*

By

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Camden, N. J.

Summary—*The development of a low loss 300-ohm parallel wire polyethylene dielectric transmission line is described. Loss curves, as well as a photograph of a production run sample of the line, are included.*

Introduction

TRANSMISSION lines for use on home television receiver installations have been very unsatisfactory to date primarily because of their very high losses. In addition to the high signal attenuation these lines have had many other undesirable characteristics.

Twisted Pair Lines

Transmission line losses in twisted pair lines have been so great that installation men have recommended installing television receivers on top floors in buildings so as to shorten the transmission line and thereby improve the signal intensity by eliminating as much of the transmission line loss as possible. It was not uncommon to find a receiver installation within a mile of the transmitting antenna that did not have sufficient signal to override the local noise level. Two such installations recently investigated had transmission lines 600 and 400 feet in length and attenuations of 400 to 1 and 275 to 1 respectively. Each of these installations was less than a mile from the transmitting antenna and there was not enough signal to operate the receivers satisfactorily due to the long length of high loss transmission line used. Typical line losses varied from 5 to 12 decibels per 100 feet at 50 megacycles.

The manufacture of transmission lines has involved many different operations with a resultant high cost. Typical construction is as follows:

(a) Small gauge copper wire is tinned so as to prevent corrosion from the various compounds in the wire covering.

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* Decimal Classification: R320.41.

(b) The small tinned copper conductors are twisted forming a flexible stranded conductor.

(c) The stranded conductor is rubber covered.

(d) Two of the stranded rubber covered conductors are twisted together.

(e) The twisted pair is rubber covered. (On the less expensive lines this operation is omitted.)

(f) A cotton braid is placed over the line to prevent the rubber from deteriorating in the sunlight.

(g) The line is given an impregnating dip in an asphaltic compound for weatherproofing.

Coaxial Lines

Coaxial cables and twin coaxial cables having medium loss characteristics have been available for some time. However, the cost of these lines has been so high as to prohibit their general use on home television receiver installations. One example is a twin coaxial cable having a loss of 1.4 decibels per 100 feet at 50 megacycles and selling for $1.25 per foot. The average home receiver installation requires 70 feet of transmission line, thus making a total cost of $87.50 for the transmission line alone. Therefore, practically all of the home receiver installations have been made with one of the twisted pair lines.

DEVELOPMENTAL SPECIFICATIONS OF LINE

The developmental problem was to produce a line that did not have the undesirable characteristics previously enumerated. The following developmental specifications were established.

(a) *Low Loss*—Loss should be less than any twisted pair of coaxial transmission line available in the pre-war period for the receiver installation. 1 decibel per hundred feet at 50 megacycles was set as the goal.

(b) *Low Cost*—The manufacturing cost of the line should be very low to permit the installation of both the receiver and antenna in the most desirable locations. A goal of six cents a foot list price was established.

(c) *Weather Resistance*—The average life of transmission lines used in the pre-war period was very low. In a few months the cotton braid failed and the sunlight hardened the rubber covering which cracked and permitted the absorption of moisture with a resultant increase in line losses. A minimum life of five years was desired for the new line.

(d) *Deterioration Due to Heat*—The asphaltic impregnating compounds used on the cotton braided lines softened and came off on the hands, clothing, woodwork, furniture and rugs in hot weather. The elimination of this undesirable characteristic was of primary importance.

(e) *Flexibility at Low Temperatures*—The asphaltic impregnating compounds used on the cotton braided lines hardened in cold weather and movement on the line during installation, or by the wind after installation, caused the line to crack and break the cotton fibers in the braid. This soon resulted in failure of the line insulation. The new line should be flexible under all temperature conditions.

DEVELOPMENT OF THE LINE

Work was begun to develop a transmission line meeting the specifications outlined above. A thorough check was made on all available transmission lines to determine what might be done to reduce their electrical loss.

With a parallel wire type of transmission line the loss varies inversely with impedance (See Figure 1). If such a transmission line has an impedance of 72 ohms and a loss of 6 decibels per hundred feet at 50 megacycles and the wires are separated far enough to produce an impedance of 144 ohms, the loss will decrease to 3 decibels per hundred feet at 50 megacycles or one half of its original value. It was thought that a high impedance transmission line of the conventional twisted pair type could be produced which would meet the specifications. However, it was found that the maximum improvement that could be obtained by increase in impedance was about 2:1.

(1) *Dielectric*

Along with the work on conventional transmission lines, one manufacturer developed a parallel wire transmission line with a spun glass woven web. This line had excellent low loss characteristics which met the loss specifications. However, the line was very hygroscopic and required impregnation. Eventually several good weather-proofing compounds were found which did not increase the line loss appreciably. The cost of this line however did not meet the tentative specifications.

Prior to the war, research work was done by this company on some relatively high impedance parallel wire transmission lines insulated with polystyrene. These lines had desirable electrical characteristics, but were unsatisfactory mechanically due to the brittleness of the polystyrene.

Polyethylene, suitable for transmission line insulation, was developed during the war for use at ultra-high-frequencies. This dielectric, while expensive, has very excellent electrical and mechanical properties. A full description of this material is beyond the scope of this paper and the reader is referred to one of the excellent papers on polyethylene.[1, 2, 3] Polyethylene has a power factor of approximately .0003 at frequencies as high as 1000 megacycles and a dielectric constant of about 2.29. It is a very strong, tough and flexible material that is not affected by acids, alkalis, ozone, sunlight and water. These properties

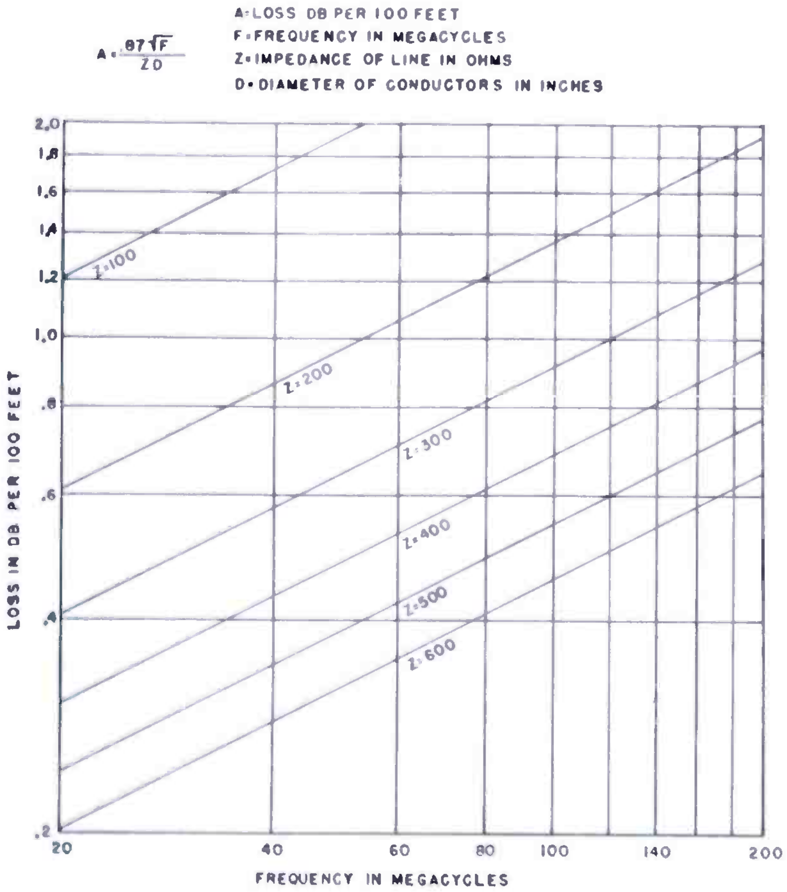

Fig. 1—Computed loss of open wire transmission lines using No. 20, A.W.G. wires.

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[1] M. C. Crafton, Jr. and N. B. Slade, "A New Dielectric For Cables", *Modern Plastics*, Vol. 21, No. 11, pp. 90-93, pp. 168-170, July, 1944.

[2] "Polyethylene Plastic—It Floats", *Modern Industry*, Vol. 9, No. 1, pp. 45 and 137-140, January 15 1945.

[3] "War Time Trends in Insulated Wire and Cable", Publication C-56, Anaconda Wire & Cable Company, 1944.

make it an outstanding dielectric for use at high- and ultra-high-frequencies. Several experimental lines were made of both twisted pair and parallel wire types. Measurements and field tests on these samples indicated a line could be constructed using polyethylene as the dielectric that would meet the specifications.

(2) *Line Conductors*

The conductor should be stranded to give the required flexibility and prevent breakage during use. The choice of conductor size is a compromise between mechanical strength, line loss and cost. Past experience on transmission lines proved that seven strands of No. 28 AWG would meet the structural requirements. A conductor of this size was also found to be satisfactory from the standpoint of line loss and cost. In the past transmission lines have had the copper conductors tinned because the bare copper wire was attacked by the various compounds in the insulating materials. Polyethylene is very inert and contains nothing that will react on copper, therefore bare copper conductors can be used. This is a fortunate condition because a lower loss line is obtained at reduced cost. At 100 megacycles the radio frequency currents are all on the outer surface of the conductors. As a matter of fact, the skin depth at this frequency is only .00067 inches. This means that with tinned wire most of the current is flowing in the tin surface layer, and since tin is a poorer conductor than copper the line loss is increased. The reduction in cost is an important item since the cost of the tin is saved as well as the expense of the tinning operation.

(3) *Line Impedance*

The development of the transmission line departs radically from past practices in connection with its surge impedance. Most of the transmission lines used in conjunction with television receivers have had surge impedances of between 70 and 125 ohms. A resonant dipole in free space has an impedance of approximately 72 ohms, therefore a 72-ohm line gives the best transfer of power when it is desired to receive signals on but one frequency. The problem of receiving television signals on a number of television bands is an entirely different problem. If a one-half wave dipole is designed to be resonant at 50 megacycles and used as an antenna, it will have an impedance of approximately 72 ohms at 50 megacycles and an impedance of about 2000 ohms at 100 megacycles. If a reflector is used in connection with this dipole the antenna's impedance can be as low as 200 ohms. Therefore the antenna's impedance may vary from some 20 ohms to 2000 ohms.

If a fixed antenna is to be used to cover a two-to-one or greater frequency range, it is desirable to use a line having an impedance such as to provide a maximum amount of energy over the desired frequency band. The line impedance would then be something less than one half the difference between the lowest and highest value of impedance, probably near 600 ohms. The actual value of optimum impedance is a complex affair and dependent upon many things such as the frequency response of the antenna, type of antenna load, impedance of antenna load, loss characteristics of the trasmission line, and other factors. It is sufficient to say here that the value of impedance would in all cases be many times higher than 72 ohms or the impedance of transmission lines used in the past. From an electrical viewpoint the line impedance should be high and probably between 300 to 600 ohms with the higher value of impedance favored, because the line loss is inversely proportional to its impedance for any given set of conditions.

There are, however, other considerations which have a bearing on line impedance. The line should be of such a size that standard hardware equipment can be used for the installation of the line. Standard bakelite screw eyes have a 9/16″ hole. This type of screw eye has been produced by various manufacturers for years and represents a standard transmission line support. The outside dimensions of the line should not be greater than 9/16″ if standard hardware equipment is to be used. With seven strands No. 28 AWG conductors this will limit the line impedance to a maximum value of about 400 ohms.

The amount of polyethylene used in a web line construction is approximately proportional to the square of the conductor spacing. If the web spacing is doubled the thickness of the web must also be doubled to maintain good mechanical design and have the web of sufficient thickness that the line cannot be crushed by the hands during installation and use. The use of a minimum amount of polyethylene favors lower line impedance.

The line impedance therefore should be approximately 300 to 400 ohms, with the cost favoring the lower value and the line losses favoring the higher value. A folded dipole antenna has an impedance of 288 ohms and was a deciding factor in choosing a line impedance of 300 ohms as the best value to give an ultra low loss transmission line for a minimum cost. The folded dipole is useful in receiving signals in a relatively narrow frequency band and provides a higher signal level than is obtained from simple wide band antennas.

The 300-ohm line used in connection with a half wave dipole gives a broad frequency response and permits multi-channel reception without cutting the antenna elements or changing their spacing as has been

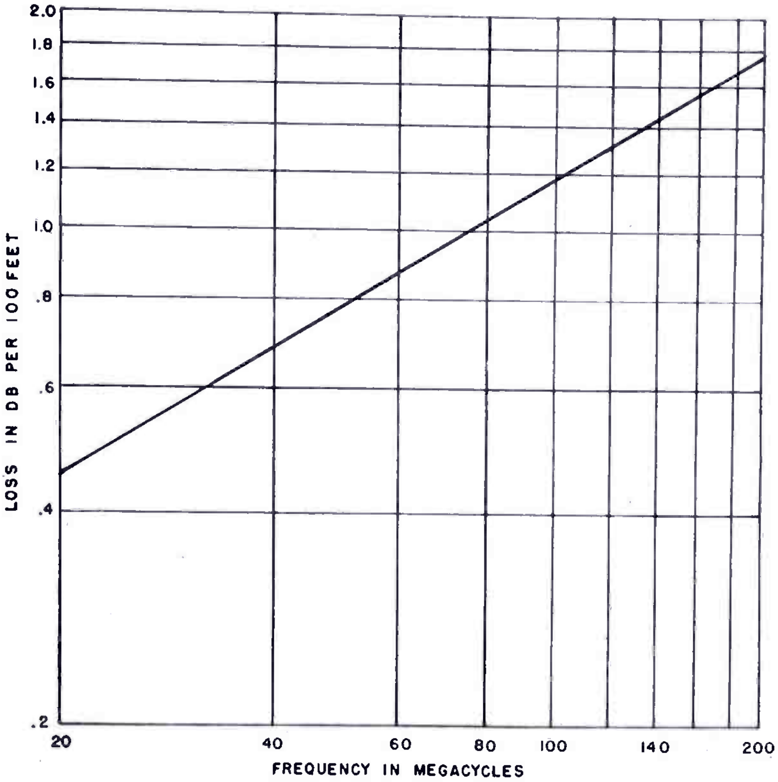

Fig. 2—Loss characteristics of the new television transmission line.

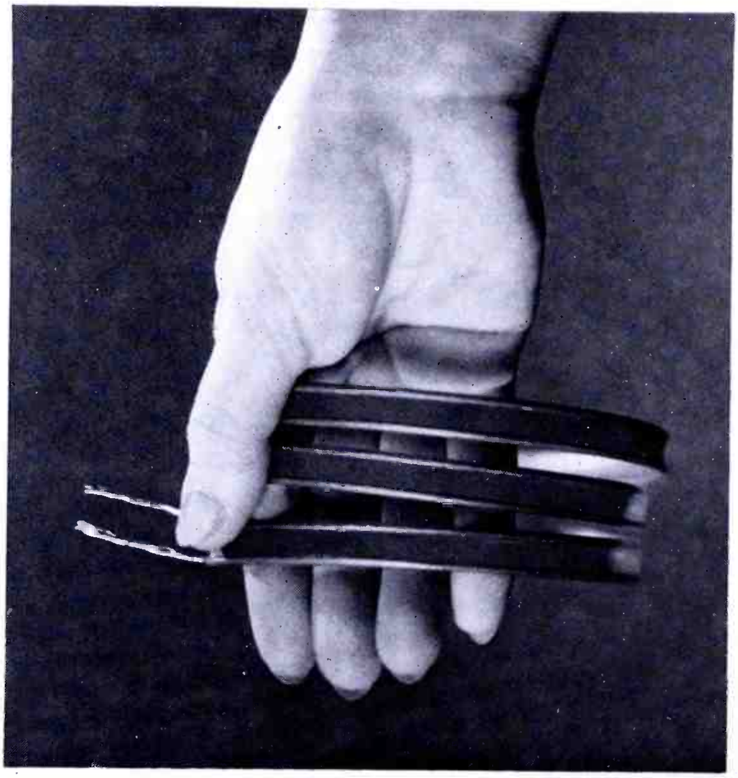

Fig. 3—Sample of production run transmission line.

required in the past. Figure 2 shows the loss characteristics; Figure 3 is a photograph of a sample of the production run transmission line. Figure 4 (Curve A) shows the relative response with frequency of a 44-megacycle half-wave dipole and reflector in conjunction with the 300-ohm line. Curves C1 to C6 give the relative response frequency characteristics of folded dipoles adjusted for each of the first six television channels and used with the 300-ohm line.

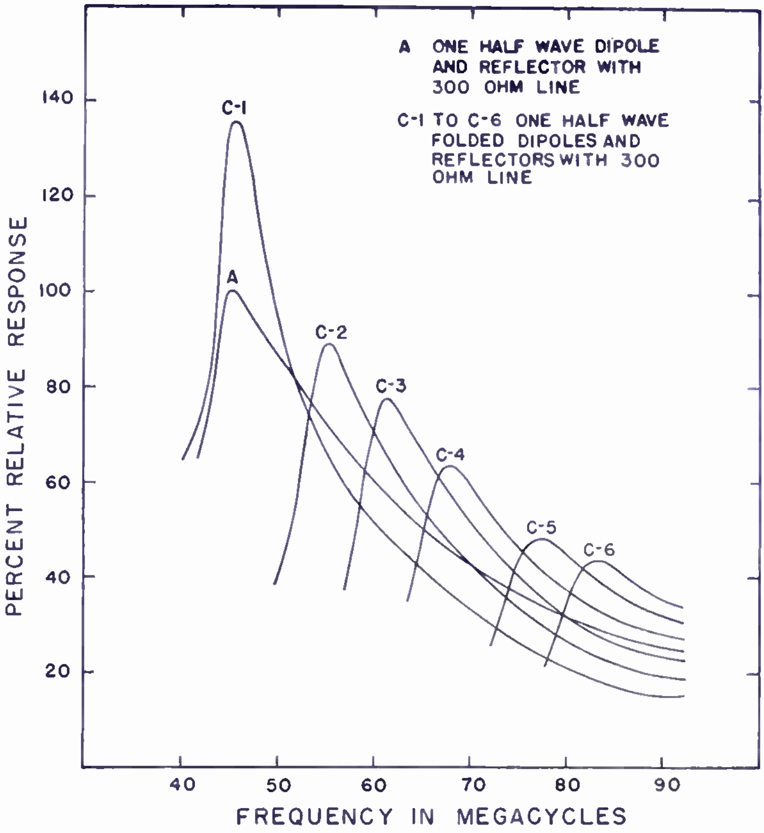

Fig. 4—Television antenna characteristics using the new 300 ohm transmission line.

FIELD TESTS

A quantity of the 300-ohm transmission line was made on a developmental basis and installed, for field test purposes, in forty-seven test locations in the New York and Philadelphia areas prior to April, 1945. Some of the lines have been in service for over two years. Loss measurements on these lines show they have not changed by any measurable amount.

CONCLUSIONS

This developmental project resulted in an ultra low loss transmission line of unusual characteristics. It more than meets the specification requirements set forth. The line has a loss of less than 0.8 decibel per hundred feet at 50 megacycles. Polyethylene is a very strong, tough flexible material which is not affected by acids, alkalis, ozone, sunlight or water. This produces a line which does not crack during cold weather or soften during hot weather, and which give long trouble-free service. The line can be used with folded dipoles or dipole antennas giving high gain single channel or medium gain multi-channel reception respectively.

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First Quarter, 1946

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