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"To promote the advancement of radio, electronics and kindred subjects by the exchange of information in these branches of engineering."

(from the objects of the Institution)

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THE INSTITUTION IN INDIA

During the post-war years the Council has supported the aim of promoting co-operation between all engineers in the Commonwealth. Towards this end considerable effort has been made in making known more widely the benefits and privileges conferred by membership of the Institution. Such advantages are not necessarily confined to the individual, since the objects of all professional Institutions find fulfilment in benefiting mankind in general.

One of the responsibilities of the Institution is to encourage high standards of technical training and efficiency and to secure recognition of such standards for the radio and electronic engineer. This was the approach to the establishment of Brit.I.R.E. Sections throughout the Commonwealth and has resulted, during the last five years, in 938 Indian candidates entering for the Institution's examinations.

The recent growth of membership throughout the Commonwealth is evidence of warm support for the Institution's policy, and having established that background of properly qualified membership the Council has been anxious to provide full opportunity for Indian members to contribute to the Institution's work. This requires the provision of adequate facilities, principally by the formation of Sections wherever there is a sufficient number of members.

After members in India had expressed their views, discussion took place with the appropriate Government Departments. It is particularly pleasing to record that the General Secretary of the Institution was not only invited by the Government of India to visit that country, but was also given generous practical assistance in the formation of Indian Sections.

India plays a very important part, industrially and economically, in the Commonwealth. The vast territory of the sub-continent is a great potential in the field of technical education and, more important, has great need of development in field communications. It is patently clear therefore that great benefit will derive from the establishment of the new Sections in the capital cities of India—Madras, Bangalore, Bombay, Delhi and Calcutta.

In providing these new Sections the Institution hopes, through its Indian members, to make an important contribution to the development of their country. A great step is already being taken in furthering co-operation between the Institution's members all over the world; the new Indian Sections not only enjoy the goodwill of their colleagues in the Institution, but also have the advantage from the outset of encouragement from executives and public administrators within their own country.

The Secretary's report on his Indian tour and references to the activities of the new Sections will appear in future issues of the *Journal*. Already, the visit of the Chairman of Council to India, subsequent to the General Secretary's return, confirms the generous welcome given by our Indian colleagues to the Council's tangible work in promoting mutual interests. In order to develop those interests to the full, members who visit India are urged to advise the Secretary of the Institution and/or the Secretaries of the new Indian Sections.

G. D. C.

NOTICES

Interference Suppression Committee

On March 26th the Assistant Postmaster-General announced that the following Committee were advising his department on draft regulations dealing with interference with wireless telegraphy caused by small electrical motors:—

Chairman: Mr. J. R. Beard, C.B.E., M.Sc.
Mr. L. Austin, M.I.P.E.
Mr. A. H. Ball, A.M.I.E.E.
Mr. J. I. Bernard, B.Sc., M.I.E.E.
Mr. N. R. Bligh, B.Sc.(Eng.), A.M.I.E.E.
Mr. J. S. Boyd.
Mr. A. H. Cooper, B.Sc.
Mrs. M. Courtney, J.P.
Mr. W. J. Edwards, B.Sc.
Mr. J. Flood, Associate I.E.E.
Mr. F. Gratwick, A.C.I.S.
Dame Caroline Haslett, D.B.E.
Mr. H. J. B. Manzoni, C.B.E., M.I.C.E.
Major C. A. J. Martin, G.C., M.C., B.A.
Mr. W. A. Parker, M.I.E.E.
Mr. E. L. E. Pawley, M.Sc.(Eng.), M.I.E.E.
Mr. G. F. H. Peirson, M.I.E.E.
Mrs. C. Renton Taylor.
Mr. V. A. M. Robertson, C.B.E., M.C.
Mr. W. A. Scarr, M.A.
Dr. S. Whitehead, Ph.D., M.A., M.I.E.E.

Television Course for Overseas Engineers

The British Council has just announced details of the 1952 series of courses to be held in this country for visitors from overseas. Most of the courses, which it is expected will attract about 1,000 oversea visitors, are of educational or general interest, but during the autumn a course for Senior Radio and Television engineers concerned mainly with the administration side of Television is to be held in London.

Organized by the B.B.C. in conjunction with the Post Office and leading British radio firms, the course will last two weeks—from September 21st to October 4th. The first week will be devoted to the B.B.C. Television organization and will include lectures by engineers concerned with all aspects of engineering—research, planning and design—and visits will be made to studios, transmitting stations, etc.

During the second week, the work of the Post Office in providing facilities for television will be dealt with, lectures being accompanied by visits. There will also be a number of visits to the factories of leading television manufacturers.

There will be vacancies for 15 engineers on the course, the charge being £33 including accommodation. Applications to attend or for further details should be made to the local representative of the British Council or to the Courses Department, British Council, 65 Davis Street, London, W.1.

The Indian Journal of Physics

The attention of members is drawn to the following papers of interest to the radio engineer which have recently been published in the *Indian Journal of Physics*. This periodical may be borrowed from the Institution's library.

J. P. Srivastava and V. D. Rajan. "Anomalous Variation in the Angle of Downcoming Radio Waves and their Bearing on the Fading of Short Wave Signals," June 1951, pp. 287-297.

B. M. Banerjee. "A Study of the Switching Action in a Multivibration Circuit," Part I, August 1950, pp. 361-370; Part II, July 1951.

K. V. Krishna Prasad, "On the Approximate Solutions of Maxwell's Equations in an Infinite Medium with Regions of Finite Conductivity," August 1951, pp. 403-407.

R. B. Banerji. "Studies on the Sporadic E—Layer," August 1951, pp. 359-374.

S. Deb. "On the Unified Theories of Thermal and Shot Noise," August 1951, pp. 391-402.

K. V. Krishna Prasad, "Rigorous Solution for the case of Electromagnetic Wave Propagation along a Circular Waveguide of Finite Conductivity," September 1951, pp. 417-423.

K. R. Saha. "Overland Refraction of High-Frequency Radio Waves in India," September 1951, pp. 437-450.

K. V. Krishna Prasad. "Harmonic Distortion in Frequency-Modulation Reception," Part I, October 1951, pp. 504-510; Part II, November 1951, pp. 513-524.

Correction

Attention is drawn to a small error in the paper "Random Phase Variations of C.W. Signals in the 70-130 kc/s Band" by W. T. Sanderson, published in the March issue of the *Journal*. Equation (1) on page 196 should read:

$$\sigma = \frac{1}{2\pi\sqrt{2}} \cdot \frac{S}{G} = k \cdot \frac{S}{G}$$

THE EVALUATION OF PICTURE QUALITY WITH SPECIAL REFERENCE TO TELEVISION SYSTEMS*

by

L. C. Jesty, B.Sc.,† and N. R. Phelp†

A Paper presented at the Fifth Session of the 1951 *Radio Convention on August* 24*th in the Cavendish Laboratory, Cambridge*

SUMMARY

A new method of assessing the performance of a picture reproducing system is described. The effect of the simultaneous variation of the four parameters—brightness, contrast, resolution, and viewing distance—was explored. Measurements were made under conditions of best picture reproduction, with the system maintained at this level of adaptation. Various photographic and television systems were examined. The work involved a similar investigation of the behaviour of the "average observer."

The experimental results show useful correlation with system performance, and lead to a possible explanation of the interaction of the three limits—resolving power, brightness characteristic, and signal/noise (graininess). The measurements need to be extended to lower values of contrast to confirm these ideas. A fundamental performance factor, Q_e, related to signal/noise limitations, is proposed, measured in terms of the number of quanta per picture element per picture required for a signal/noise ratio of unity. Non-linear transfer characteristics are shown to have advantages at the low brightness end. An extension of the "C.I.E. Observer" to cover the variables explored in the experiments is desirable, with the object of replacing the human observer with electronic measuring apparatus. It is shown that both the ratio viewing distance/picture height and the viewing distance must be specified before system comparisons can be made. The results support the importance of low contrast test objects. 35-mm motion pictures appear to provide about half the resolving power of the eye over the range of brightness and contrast explored, and a tentative estimate shows that this can be equalled by a properly engineered 600-line television system using spot wobbling. Band saving techniques are considered, e.g. restriction of definition at low brightness and contrast.

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* This paper was first published in two parts in the *Marconi Review*, 14, 1951, Nos. 102 and 103, and it is reprinted here with akcnowledgments.

† Marconi's Wireless Telegraph Company, Limited.

U.D.C. No. 621.397.5.001.8.

LIST OF SYMBOLS

B = Input highlight brightness (ft.-lamberts)

B' = Output highlight brightness (ft.-lamberts)

bB = Input brightness (ft.-lamberts)

$b_{max}\,B$ = Maximum useful input brightness limit of transfer characteristics (ft.-lamberts).

$b_{min}\,B$ = Minimum useful input brightness limit of transfer characteristics (ft.-lamberts).

$b'B'$ = Output brightness (ft.-lamberts)

$b'_{max}\,B'$ = Maximum useful output brightness limit of transfer characteristics (ft.-lamberts).

$b'_{min}\,B'$ = Minimum useful output brightness limit of transfer characteristics (ft.-lamberts).

$b_l B$ = Brightness of light lines of test object (ft.-lamberts)

$b_d B$ = Brightness of dark lines of test object (ft.-lamberts)

r_t = Transfer characteristic input brightness range $= \dfrac{b_{max}}{b_{min}}$

r'_t = Transfer characteristic output brightness range $= \dfrac{b'_{max}}{b'_{min}}$

r_p = Test pattern (input) brightness range $= \dfrac{b_l}{b_d} = \dfrac{1}{1-C'}$

C = Percentage contrast of test object $= \dfrac{b_l - b_d}{b_l}$

C' = Contrast of test object* $= \dfrac{b_l - b_d}{b_l}$

H = Height of picture (feet)

T = Resolution (test lines per picture height)

T_{max} = Maximum resolution (test lines per picture height)

N = Numerical aperture of camera lens

τ = Transmittance factor of camera lens

A = Area of camera target (sq. ft.)

Φ = Flux on camera target (lumens) when illuminated uniformly by white object of brightness bB

t_p = Exposure time of camera target for 1 picture or frame (secs.)

Q_p = Number of quanta incident on camera target per picture, i.e., in time t_p with Φ lumens incident

Q_e = Number of quanta incident on camera target per picture element per picture, i.e., in time t_p with Φ lumens incident

F = Frequency band of picture channel (c/s)

I = Primary photo emission current (amperes)

e = Electronic charge —$1{\cdot}59 \times 10^{-19}$ coulombs

S = Signal (arbitrary units)

R = Signal/noise ratio

$\alpha, \beta, \eta, \theta$ = Constants

κ = Measure of degree of visibility

N/J/V/C = Visibility criteria = Not Visible/ Just Visible / Visible / Clearly Visible

1. Introduction

In speaking of the quality of a picture, which has a complex and aesthetic appeal, one is led to consider on what criteria appreciation is based and if the factors contributing to "enjoyment" of the picture can be expressed and related quantitatively. This is particularly the case when dealing with technical methods of reproduction such as are used in photography, cinematography and television. Comparison between the original and the reproduction is then usually in mind.

Ever since the first picture was reproduced by photographic means there has been interest in the possibility of the quantitative evaluation of picture quality. The early work of Hurter and Driffield in measuring and defining the characteristic curve of a photographic emulsion was probably the first step in this direction. Interest in the subject has received an impetus in recent years in connection with television systems. In these, the quality of the picture is so closely related to the scanning standards used and to the ether space available that the subject becomes important not only from the aspect of the viewer's appreciation of the picture but also from an economic viewpoint.

* To simplify algebraic expressions the percentage contrast C has been replaced by C', where $C' = C/100$.

A large number of investigations dealing with the subject have already been published[1] and in 1948 a D.S.I.R. Working Party reported on "Television Appraisal".[2] At that date the work to be described below was already in progress and it was felt that their findings justified its continuance without modification.

The following is a description of a new method of assessing the quality of a reproduced picture and of the results obtained with the various systems tested.

The simultaneous variation of four measurable parameters—resolution, brightness, contrast, and variation of viewing distance—has been investigated in terms of the visibility structure of a picture. The effect of these variations is illustrated in Fig. 1. As the appreciation of a picture is, in essence, subjective, i.e. it must depend to a certain extent on the viewer, small teams of observers were used, and the mean and spread of their reactions taken to give the required basic data.

Previous investigators have attempted to correlate resolving power, tone reproduction, number of scanning lines, photographic graininess, and many other parameters, with picture quality. The important factors of contrast, adaptation and viewing conditions appear to have been largely neglected. Furthermore, the simultaneous variation of these parameters has not been extensively examined. Test charts spread over the picture area have frequently been used in obtaining the necessary data (see Fig. 3). The conclusions reached, therefore, relied on uniformity of response of the whole system over the picture area, which is an unjustifiable assumption, particularly in the case of a television picture which often involves "shading correction." Even a cinematograph picture can vary greatly in brightness between the centre and edges of the screen. In the following work, therefore, an attempt has been made to overcome as many as possible of the above limitations.

There are two main methods of approach to a problem of this type. One is to investigate separately the properties of the individual components contributing to the behaviour of the system. The other is to treat the system as a whole, and to determine the overall performance characteristics when behaving normally, and also when subject to reasonable overloads. The

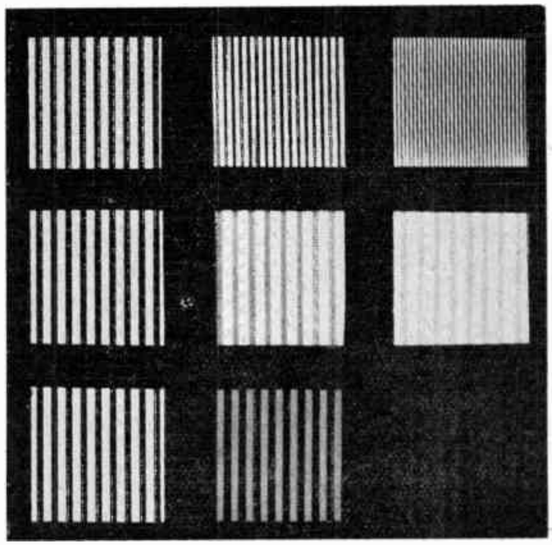


Fig. 1. Illustration of independent variation of the three parameters, Resolution, Contrast and Brightness. (a) Variation of Resolution at fixed Brightness and Contrast. (b) Variation of Contrast at fixed Brightness and Resolution. (c) Variation of Brightness at fixed Contrast and Resolution. (Reproduction process is inadequate to preserve contrast at low brightness.) Note: By increasing viewing distance patterns disappear progressively.

latter are now usually known as "operational tests," and the following work is in this class. There is very little published data on the performance of the eye in conjunction with a picture reproducing system, although special mention must be made of a series of four papers by Schade[3] covering the same general field as the following, but from a different approach. Some similar work was also carried out on camouflage during the recent war.[4]

The present experiments are based primarily on the work of Cobb and Moss[5] who dealt with four variables—resolution, brightness, contrast and time. These were varied simultaneously, but unfortunately their procedure involved a change of adapting brightness with test brightness and the results are not directly applicable to the case under consideration as adaptation is constant when viewing a given picture. When investigating some problems involving time, such as the visibility of flashing beacons, the duration of the flash is important. The present problem is of a different kind, however, as sufficient time is

Fig. 2.—Authors' Standard Picture.

Original 20 in. × 16 in. Transparency

	Relative Brightness	Density
Highlight — cloud	100	0·3
Shadow — under central tree (contains detail visible on close inspection)	2·5	1·9
Average for whole picture	36	0·75

usually available when viewing a picture for it to have little effect on the observer's ability to see. Time has therefore been omitted as a variable. For convenience, a viewing time of 10 seconds has been standardized as representative of the duration of the average cinema "shot." As well as the control of adaptation, viewing distance has been included as a variable additional to those covered by Cobb and Moss.

So far, monochrome pictures only have been considered, although a preliminary survey of colour has begun. Neither flicker nor the stroboscopic effects associated with movement in the picture have yet been investigated. It is felt to be self-evident that with known types of moving picture reproduction, motion of the subject matter produces a type of image degradation which is not to be measured in terms of the above four variables but rather in terms of spurious and stroboscopic effects. This is a matter for separate consideration when assessing the overall performance of a given system.

2. The Basic Test System Employed

All the results to be described, with the exception of the brightness or "transfer" characteristics, were obtained from observers' reactions to test patterns. It was considered important, however, that the picture reproducing system under test should be set up initially to give good quality on normal picture reproduction. Setting up on test patterns inevitably leads to bad picture reproduction! A suitable picture was therefore carefully selected for this purpose, and having adjusted the system under test to give the best reproduction of this, the test pattern was substituted without disturbing the adjustments, and the necessary observations made. In order to check the stability of the system during the course of a given test—an essential requirement of the method—a permanent brightness step wedge and horizontal/vertical resolution chart were incorporated in the test pattern.

The main object of the experiments was to acquire information relating to the choice of commercial television standards, both for home reception and theatre projection. In some measure, information relating to the standard required to satisfy the average eye at its normal level of appreciation rather than at the limit of its capabilities has also been obtained.

2.1. *The Standard Picture*

The picture employed is reproduced in Fig. 2. It has large areas of highlight and deep shadow, facilitating brightness measurements, and considerable detail in half tones and shadows. The

(a) (b) (c) (d) (e)

Fig. 3.—Typical Resolution and Brightness Test Charts.

(*a*) *McKay Photo Test Chart.*
(*b*) *Motion Picture Laboratory Test Frame ("print through gamma control").*
(*c*) *RMA Resolution Chart* 1946.
(*d*) *B.B.C. Television Tuning Signal.*
(*e*) *B.B.C. Television Test Card "C."*

diagonally running telegraph wires (not reproduced in Fig. 2) were useful for focusing. A 20-inch by 15-inch enlargement in the form of a transparency was used, thereby ensuring adequate tone range for all the reproducing systems tested. This transparency and the test patterns were illuminated by a uniform source of variable brightness. The picture could be set up with ease and accuracy, the whole arrangement being compact and portable.

The provision of only one picture with a fixed " gamma " will no doubt be criticised by the studio lighting cameraman who likes to adjust the contrast in his subject matter by using " fill-in " lighting, etc., to give the best pictorial reproduction. The provision of a series of prints of the picture, covering a range of gamma values, is in mind to cover this point, but at the moment this objection is admitted. All the systems tested have been set up on this standard picture, thereby offering the operator no lighting control over his subject matter.

2.2. *The Test Patterns*

Various test patterns were considered, and bearing in mind the requirements described in Section 1 and certain special requirements of television scanning, the form of pattern shown in Fig. 4 was evolved. The pattern consists basically of a uniform brightness adapting field, adjusted to have the average brightness of the standard picture. At selected positions, as shown, the neutral density material forming the adapting field is cut away and a range of resolution/contrast/brightness test patterns inserted in sequence. During the observer tests the patterns are always inserted in apparently random order. By testing at fixed points only, non-uniformity of response is overcome, and, furthermore, can be measured. The onus is now placed on the stability of the system during the test.

One set of components of the complete test pattern is shown separated in Fig. 5. The resolution/contrast and the brightness components (*a*) and (*c*) are varied in combination, the adapting field (*b*) remaining permanently in place during the testing.

The main interest initially was in the performance of systems at the centre of the test field, and the work reported here has been limited to this. Considerable data have already been accumulated for the other positions, although for simplification, much of the work has been carried out with a duplicate set of test patterns made to fit the central aperture only. When these are used, the remaining eight positions and the two code apertures are filled with neutral filter corresponding to picture highlight brightness.

It appeared desirable to make the test pattern as large as possible, so that it could be viewed from a reasonable distance. The size, 19·2-in by 14·4-in, was chosen as the largest which could be conveniently made from standard photographic materials, allowing reasonable margins. Ideally, a series of pattern sizes are required to suit individual tests, and the results so far obtained confirm the necessity for this, if certain ambiguities are to be avoided. In the direct viewing experiments, the conditions must be considered as approximating to those of a home projection picture.

As already stated, a fourth variable—relative viewing distance—has been introduced. The correct viewing distance is controversial, one school of thought advocating that it should be variable to correspond to the viewing angle of the camera lens! Opinion now seems to be converging on a value of four times the picture height—this corresponds to the best seats in modern cinemas, at the front of the circle. As viewing distance bears a first order relationship to the standard of performance of the reproducing system, it was decided to vary it, if only to illustrate its importance. Relative viewing distance was therefore varied in three steps: close inspection of the screen $(0 \times H)$; four times the picture height $(4 \times H)$; and eight times the picture height $(8 \times H)$. In the cinema theatres visited during the experiments this last value was never exceeded and often not attainable. When testing a reproducing system the camera/test pattern distance was not, of course, varied, the camera always being adjusted to cover the whole of the pattern exactly.

The test objects used in the composite test pattern were approximately 2 inches square. At a viewing distance of four times the picture height they subtend an angle of 2 deg. at the observer's eye, giving normal foveal coverage.

2.2.1. Resolution Variation

A number of different types of resolution test elements were considered, e.g., Sayce, Cobb, Landolt " C," National Bureau of Standards,

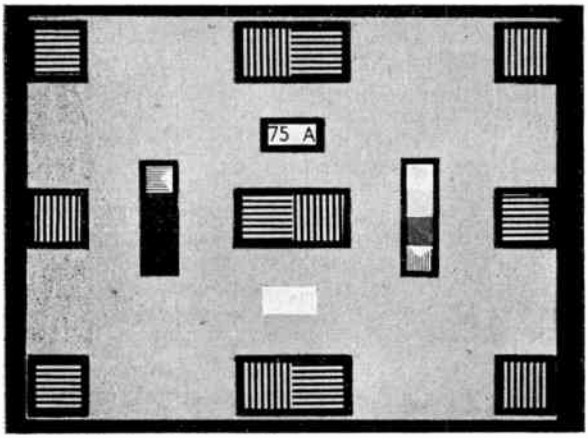


Fig. 4. Authors' test pattern showing one degree of Brightness, Contrast and Resolution.
Note disposition of test stations in constant brightness adapting field; arrangement of horizontal and vertical test lines; permanent reference wedge and test lines; numbering apertures.

parallel test lines, etc.[4, 5, 6, 7] (see Fig. 6). Of these, parallel test lines of uniform brightness in a square of fixed size were chosen for the following reasons:—

(1) The observer had no clue from the constant size of the test object as to the standard of resolution it contained, or whether the test lines were vertical or horizontal.

(2) They were relatively easy to produce, and reproduce, with accuracy and uniformity, by photographing a master ruling.

(3) They were suitable for testing television systems. Vertical lines gave frequency response tests; horizontal lines revealed stroboscopic and spurious (" moiré ") patterns associated with scanning and interlacing; they were capable of electronic generation.

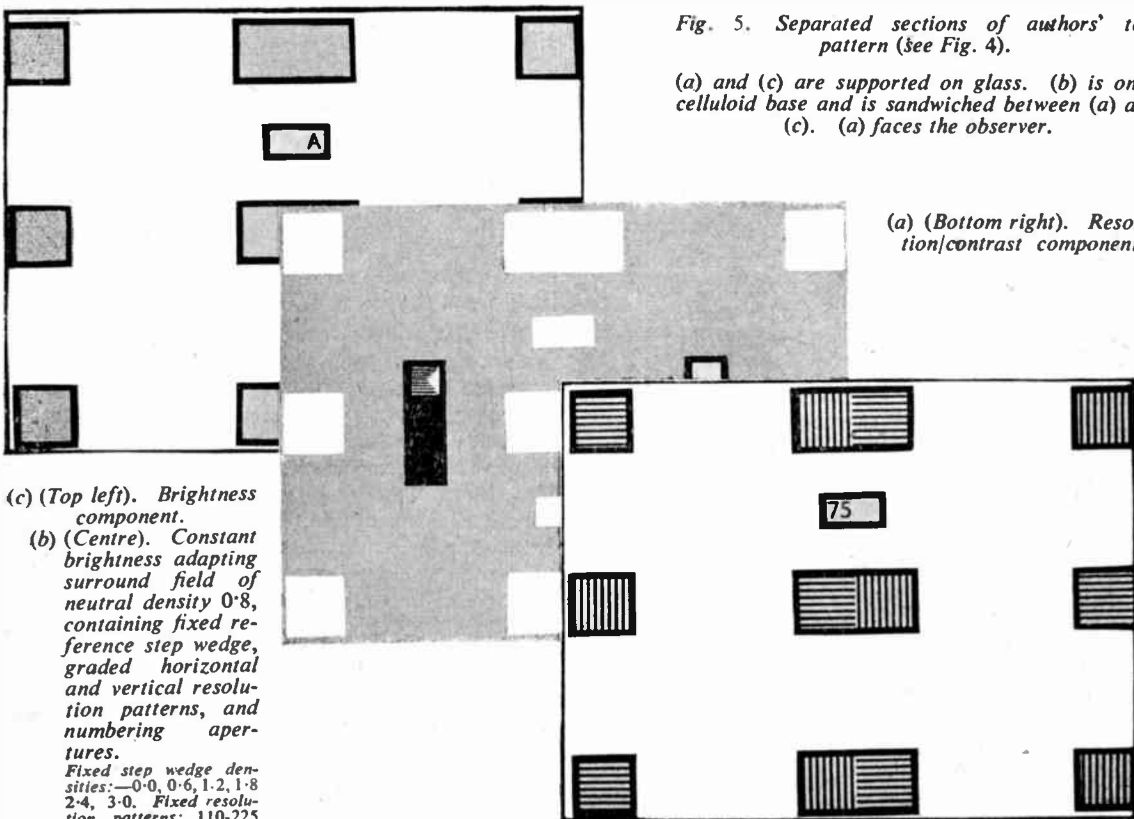


Fig. 5. Separated sections of authors' test pattern (see Fig. 4).

(a) and (c) are supported on glass. (b) is on a celluloid base and is sandwiched between (a) and (c). (a) faces the observer.

(a) (Bottom right). Resolution/contrast component.

(c) (Top left). Brightness component.
(b) (Centre). Constant brightness adapting surround field of neutral density 0·8, containing fixed reference step wedge, graded horizontal and vertical resolution patterns, and numbering apertures.
Fixed step wedge densities:—0·0, 0·6, 1·2, 1·8 2·4, 3·0. Fixed resolution patterns: 110-225 test lines/picture height.

It was felt that any advantage gained by using a sinusoidal distribution of brightness[7] instead of a square wave would be completely outweighed by the difficulty of construction and standardization of the patterns.

The test elements were presented to the observers in a random order. When observing the centre pair of patterns, the observer knows that one will be horizontal and the other vertical. Certain tests (Figs. 10 and 11) were therefore run through twice with each half alternately masked. This gave a complete check for astigmatism.

The range of resolution covered was from 60 to 680 test* lines in the height of the field. This range was divided into a geometric progression with a ratio of the fourth root of 2, thus giving four steps to the octave and a total of 15 steps.

2.2.2. Contrast Variation

In order to avoid the complication of making and operating elaborate variable contrast optical systems, the resolution patterns were made up with various fixed degrees of contrast. Although this necessitated the preparation of a large number of patterns, the operation of testing was greatly simplified.

The limits of contrast variation available depended on the photographic processes. A density difference of 0·1 from clear film could be repeated with reasonable accuracy. At the other extreme, a value of 1·5 was readily obtained without undue spread of the photographic image. An intermediate density difference of 0·25 was chosen from Cobb and Moss's data to give roughly equal visual sensitivity steps between 1·5 and 0·1.

The patterns were measured on a recording microdensitometer and the resulting contours showed good approximations to square waves. The high contrast patterns showed density deviations of ±0·17. The medium contrast deviation was ±0·05 and the low contrast deviation ±0·02.

Contrast has been defined as the percentage ratio of the difference between the brightness of a test object and its surround, and the surround brightness.[5] In the present case, the test element does not contain the surround brightness as one of its components, but is quite independent and made up of two different brightnesses. The above method has been used, however, to calculate the contrast *C* using the two brightness components of the test element. This difference must be borne in mind when making comparisons such as those shown in Fig. 8. The three values of contrast chosen, corresponding to density differences of 1·50, 0·25, and 0·10, give *C* values of 97, 44 and 21 per cent respectively.

2.2.3. Brightness Variation

It was found adequate in the preliminary investigation associated with the range of resolution to cover approximately 1,000 : 1 in brightness. The brightness of the test element was controlled by placing neutral density filters, mounted on separate glasses (Fig. 5*c*) behind each resolution/contrast test pattern, thus enabling the brightness variable to be combined with the resolution tests with the minimum number of test patterns. The brightness range was covered in steps of neutral density 0·3 (approximately 2 : 1 in brightness), giving 11 values. The key value was the highlight brightness, or maximum picture " white " to be dealt with. The test patterns extended to twice this value, so that any system could be overloaded to see if there were any tendency to saturation or other defect in the highlights. Picture highlight brightness therefore corresponded to density 0·3. It was necessary to use transparencies for the pattern system, as for the standard picture, in order to obtain the required brightness range.

The illuminator consisted of a light-tight box with a flashed opal glass front, illuminated by tungsten lamps inside. By adjusting the lamp positions, it was possible to obtain a brightness uniformity better than ±5 per cent over the whole surface. Large adjustments in key brightness were catered for by changing the wattage of the lamps. Small adjustments were produced by voltage control. Some variation in colour was obviously introduced, but was considered to have a negligible effect.

Care had to be taken to avoid detrimental reflections from the front glass of the test patterns, and photometric measurements made on them (Fig. 21 curve (*a*)) show almost an exact 1/1 relation to the measured densities. In making the photometric readings precautions were taken to eliminate veiling glare in the photometer.

* Test lines should not be confused with television lines. A test line consists of a black line separated from adjacent black lines by a white line of equal width.

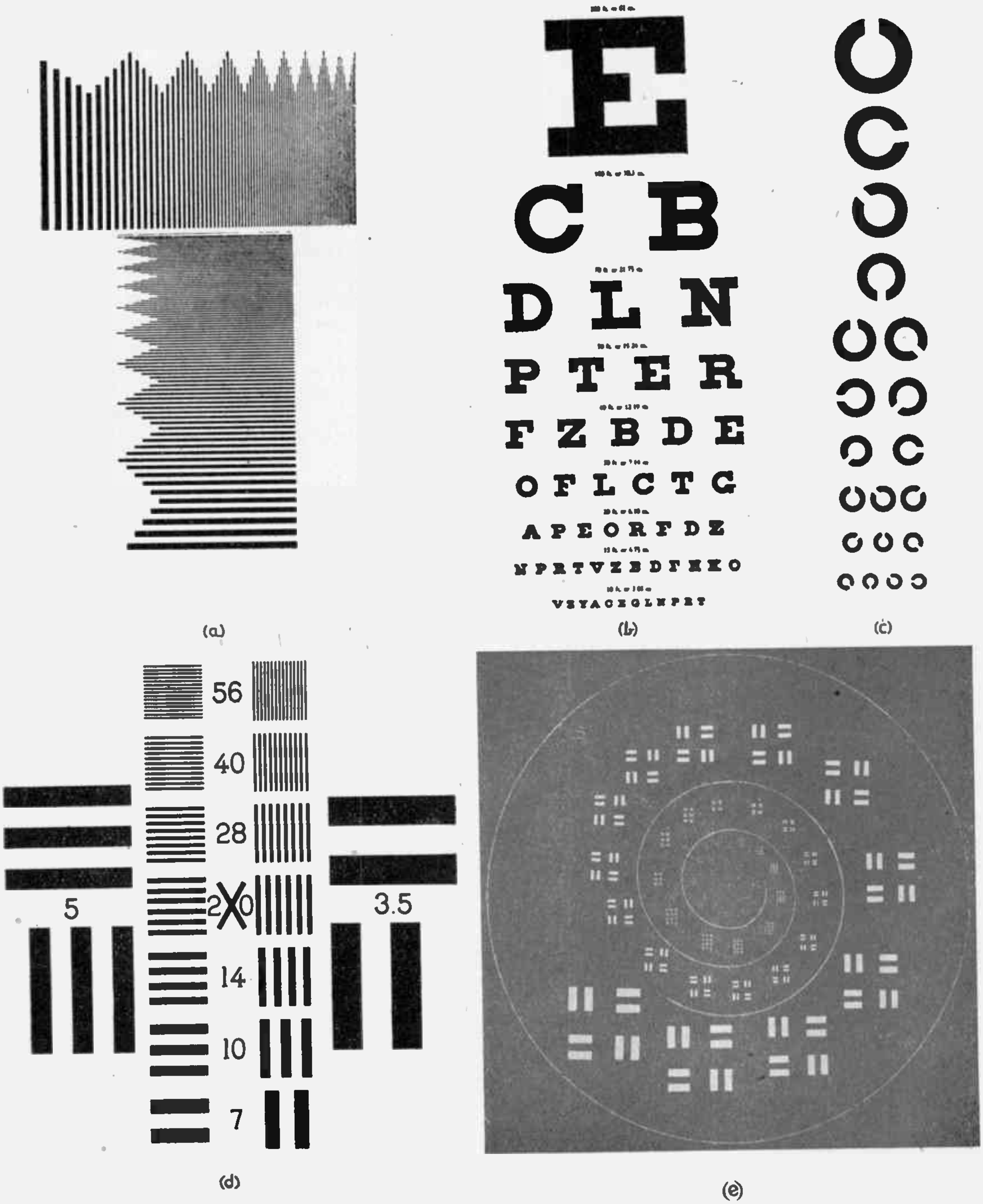


Fig. 6.—Selection of resolution test patterns.
(*a*) *Sayce.*[7] (*b*) *Snellen.*[6] (*c*) *Landolt "C"*[6]. (*d*) *National Bureau of Standards.*[6] (*e*) *Low contrast Cobb.*[4, 5]

The brightness scale in Figs. 8–19 assumes that the steps are exactly 2/1 (or density difference 0·3). This is not the case, the density steps not being exact multiples of 0·3 (see the values plotted in Fig. 21). On a logarithmic plot, however, this slight error can be neglected.

2.2.4. The Adapting Field

When testing a reproducing system, it is necessary to keep the adaptation constant, and representative of the general picture brightness. As an illustration, curve (*c*) in Fig. 20 was taken with everything except the central test position of the pattern covered. Other conditions were as for curve (*b*). The latter is the standard condition, with adapting field, and the presence of this loss is undoubtedly due to veiling glare in the camera and projector optical systems, and is present during normal picture reproduction. It is essential that it should also be present with the test patterns to the same degree, if a proper evaluation is to be made.

In deciding the adapting field for the test pattern, the average picture brightness is the controlling factor. Published data,[8] and the authors' preliminary measurements on various subjects, showed that highlight to average-brightness ratio was of the order 3/1. As the highlight in the series of brightness steps corresponded to a density of 0·3, a density of 0·8 (ratio 3·2/1) was chosen for the surround. The measured average density of the photographic transparency of the standard picture (Fig. 2) was 0·75, which, with a highlight density of 0·3, was in good agreement.

During the direct vision tests, low intensity lighting, directed on to the wall behind the test patterns, provided general illumination. When testing television and photographic systems, this back lighting was not used, the condition corresponding to screening the camera lens with a hood.

2.3. *Experimental Test Procedure*

The data presented in Figs. 8–19 is subjective statistical data, obtained by teams of observers recording their ability to see the test elements presented to them, either directly or via the various picture reproducing systems. Observers of both sexes were chosen, of various occupations and ages. The same observers were used throughout (except in the tests shown in Figs. 11, 18 and 19) to obtain high relative accuracy. It was realized that high absolute accuracy could only be obtained by using some 100 or more observers, which was quite outside the facilities available. Statistical examination of the results shown in Fig. 7, and comparison between two entirely separate teams of ten observers, shown in Figs. 10 and 11, indicates the degree of relative and absolute accuracy which can be claimed for the data. Results obtained with "scratch" teams of observers (Figs. 18 and 19) have shown no abnormality.

Preliminary tests were made on the observers with the test patterns as part of their training, and during this period those with any obvious irregularity of vision were excluded. Tests for colour vision with the Ishihara and Farnsworth tests were also used, and defectives eliminated.

An observer was stationed close to the screen ($0\times H$) to record the limit of resolution of the system under test. In the photographic and cinematographic experiments, observations on negative and positive material were also made at low magnification.

In the preliminary tests, the observers only recorded whether the lines on the test pattern were visible or invisible. Ultimately, at the request of the observers themselves, degrees of visibility were recorded by grading into four steps—"Not Visible" (N); "Just Visible" (J); "Visible" (V); and "Clearly Visible" (C).

The results have been plotted in the form shown in Figs. 8–19. The three vertical columns are allocated to the three values of contrast, 97%, 44% and 21% (except in Fig. 9); the horizontal rows (*a*), (*b*) and (*c*) to the viewing distances $0\times H$, $4\times H$ and $8\times H$ (except in Fig. 12). The dividing lines separating the four degrees of visibility form the three curves plotted on the individual graphs. These are coded N/J, J/V and V/C. The close inspection ($0\times H$) and low magnification data only consists of the Not Visible/Just Visible (N/J) curve, as here the limit of performance of the system has been the sole interest.

In all cases, the data for horizontal and vertical test lines were obtained separately in the first analysis. With the television systems there were very obvious differences between the two, and they are plotted separately. In all other cases, whilst individual observers showed definite astigmatic characteristics, the average values showed no significant differences—i.e. both the

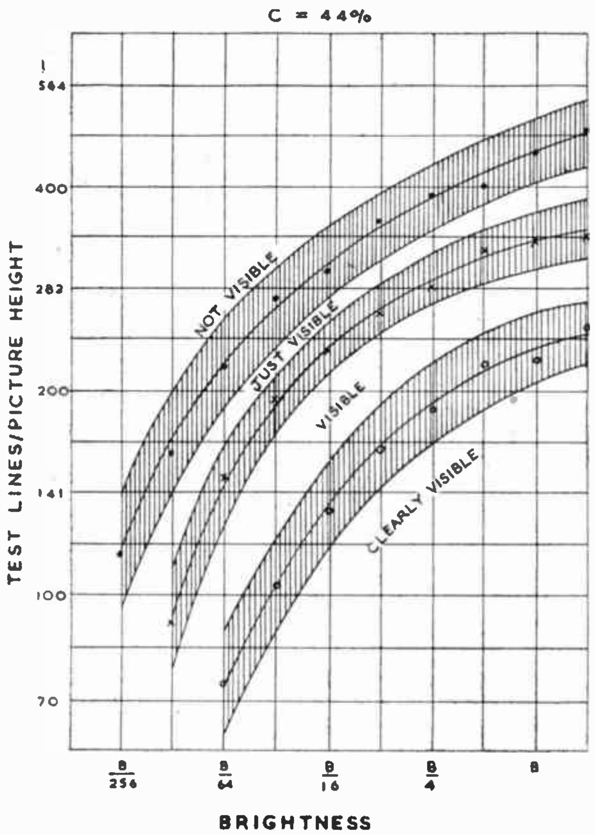


FIG. 7. *Typical Plot of Observer Data for one value of Contrast and Viewing Distance showing Visibility Zones and Limits of Accuracy.*

Direct Viewing. Highlight Brightness B = 10 *foot-lamberts. Picture size*—19·2" × 14·4". 4 × H; 10 *Observers*; N ● J × V ○ C.

Vertical Test Lines. (Shaded areas show 0·95 *Probability Limits for mean of* 10 *Observers.)*

average observer and the remaining systems of reproduction involved showed no characteristic astigmatism in the two directions examined. In these cases, the information has been condensed into the average of the two directions. In the television tests, the horizontal test lines produced spurious patterns with the scanning lines in certain cases, as expected, which the observers were asked to record. Examination of the observer data showed considerable inconsistency in defining the upper limit of this region of spurious patterns, but the boundary between it and the " Just Visible " zone appeared to be as well defined as in the other tests. The region of spurious patterns has therefore been ignored in plotting the results, but its existence must not be overlooked.

It must be emphasized that the values of brightness plotted in Figs. 12–19 when a system is under test, refer to the original test patterns and not to their reproductions. It is important to consider the effect of the latter, which is given in the data underneath the curves. Cobb and Moss and others[9] have shown how the performance of the eye can vary with adapting brightness.

It was decided to keep the highlight brightness of the reproductions in the region of ten foot-lamberts. This value is representative of current motion picture practice[10] and is in the range of present domestic television pictures. There has, however, been a recent trend to increase the brightness of television pictures to provide comfortable viewing during daylight, and figures as high as 100 foot-lamberts have been quoted. In considering this proposal, it must be remembered that the acuity of vision and susceptibility to flicker will be increased. A higher standard of performance will be demanded from the reproducing system. It has been found with motion pictures, that graininess becomes objectionably noticeable at about 15–20 foot-lamberts.[10]

A limited set of tests was carried out under the conditions of Fig. 10, but at both 100 foot-lamberts and 1 foot-lambert highlight brightness. Only the N/J criterion was recorded, at $C=44\%$ and $4\times H$. The result showed an average increase of about 15 per cent in resolving power at 100 foot-lamberts, and a decrease of 30 per cent at 1 foot-lambert, compared with Fig. 10 at 10 foot-lamberts. The reproduced highlight brightness in the experiments varied, in fact, from 4 foot-lamberts (motion picture projection) to 30 foot-lamberts (television monitor).

Measurements of the overall brightness characteristic of each system were made, using the neutral test patterns and adapting field without the resolution/contrast patterns. Errors due to veiling glare in the measuring equipment were avoided as much as possible.

Returning to the discussion of the brightnesses plotted in Figs. 12–19, the curves can be interpreted as showing the amount of the original subject matter in the picture which is visible (to the various standards defined) in the reproduction. Should the distortions of the reproducing system result in either an increase in relative brightness or an increase in contrast at any part of the characteristic, it is possible that the reproduction will show more than the original. This effect is observable in the case of the quarter-plate camera (Fig. 12*b*) where a number of the curves, particularly at $C=21\%$, lie above the corresponding curves of Fig. 10*b*.

In setting up the equipment, the standard picture was illuminated to an appropriate key brightness, decided by experience or by trial, until the best reproduction was obtained. Without altering the brightness of the illuminator, or the performance of the picture reproducing system, the picture transparency was then replaced by the test pattern and the measurements of brightness characteristic and observer data obtained.

3. Experimental Results

The tests carried out on the observer team, and on the various reproducing systems, will now be described and briefly discussed. Further discussion of the results, including comparisons of the systems, is given in Section 4.

3.1. *Direct Viewing Tests* (Figs. 8, 9, 10 and 11)

In this series of tests, no use was made of the standard picture. The observers recorded their reactions solely to the test patterns.

As the eye fixates upon the object in which it is interested at any instant, it was considered sufficient to carry out these tests only at the centre of the test field. Over 300 observations were made by each observer for each line direction at each distance—a total of more than 1,200 for a complete test. A suitable period was allowed before each test for the observers to become adapted to the viewing conditions, and after some 200 observations had been recorded, taking about one hour, a rest of 15 minutes was given. It was found convenient to have two sessions—morning and afternoon—so taking each observer a day and a half to complete the investigation. It is considered that the results are not, therefore, noticeably modified by visual fatigue.

The limit of resolution of the average eye under the conditions of test is given by the point of intersection of the N/J line and brightness B at maximum contrast ($C=97\%$) in Fig. 10. This corresponds to 595 test lines/picture height. A frequently adopted convention in determining resolving power is to use the distance between the centres of adjacent black lines, which for the above figure gives a value of 1·4 minutes of arc. Cobb and Moss, however, use the distance between the edges of the two black bars of their test element in calculating visual angle. This has been taken into account in determining the number of test lines/picture height for their results as plotted in Fig. 8, by choosing the distance between their test bars to be equal to the distance between two adjacent black lines in the authors' test pattern.

An interesting effect was noted by some of the observers during the course of the experiment. In the first fraction of a second after lifting the eyes to the pattern, test lines could sometimes be seen and then disappeared immediately. The observers were asked to ignore this short period effect in recording the results.

3.1.1. *Direct Viewing of Additive Primary Colours*

As a preliminary excursion into the field of colour reproduction, direct viewing tests were repeated with the central test element masked in succession with red, green and blue tricolour filters. Only the central test element was coloured, the adapting surround, etc., remaining grey. By the addition of suitable neutral filters, they were adjusted to "add up" to a white highlight brightness B of 10 foot-lamberts. This involved increasing the brightness of the opal light source, and the density of the surrounding filter was correspondingly increased to maintain correct balance. The relative values of the correcting filters were calculated from the spectral absorption of the colour filters, and the assumed spectral emission of the opal light source. The object was to obtain no colour change in the latter when the filters were illuminated additively by it. The filters were finally checked by mounting a set in a colour wheel and spinning them in front of the opal light source. The combined colour/neutral filters were then measured with a photo-electric photometer (through a liquid filter) having the standard C.I.E. visibility response, whilst illuminated by the opal light source. The brightness values obtained were: Red—4·65, Green—4·65, and

Blue—0·70 foot-lamberts. The red component appeared to be rather large, but this was attributed to the "warm white" colour of the illuminant, which was not specially colour matched for this purely exploratory experiment.

The results are shown in Fig. 9. There appears to be little difference between the red and green curves and the white data in Fig. 10*b* at $C=44\%$. On the other hand, the blue curves show a considerable drop in response, as was expected. The shift of the blue curves along the brightness axis corresponds to a brightness drop of about 25/1 compared with the red/green/white curves. The measured brightnesses given above have a ratio of approximately 7/1. The drop in blue resolution is therefore not entirely a brightness effect.[11]

3.2. *Quarter-Plate Photographs* (Figs. 12, 20*a*, 21*b* and 22*a*)

Systems of photography fall into two main groups, one in which the picture is viewed the same size as it is taken, and the other in which the picture is enlarged from the negative. It is intended to apply the investigation to both groups eventually, but so far it has been restricted to the first as being the one likely to yield the highest quality result. Quarter-plate size was chosen, as it gave the smallest contact print, which when viewed at four times the height (about 13 inches) was sufficiently beyond the near point of vision to be comfortably accommodated by the eye.

A number of trial quarter-plate negatives were made of the standard picture and the most acceptable of these chosen. The test patterns were then photographed under similar conditions. The negatives were developed in a tank in batches of 25, care being taken to keep the processing conditions as constant as possible. The maximum negative density varied between 1·80 and 2·38, the gamma at the highlight point of the curves varying between 0·67 and 0·88. The neutral density brightness steps were also photographed, giving the curve (*a*) of Fig. 22. Contact prints were made from all these negatives.

Inspection of the negatives and prints at low magnification yielded Fig. 12(*a*). Only one point appears for the negative, indicating that all the remaining patterns were resolved. Observations on the prints were made at an illumination of 15 foot-candles, resulting in a highlight brightness of 8 foot-lamberts. This is the E.L.M.A. recommendation for the illumination in library reading rooms. The results are shown in Fig. 12(*b*). A second run was made at 150 foot-candles, and the observers commented spontaneously on the increased visual comfort. The improvement in performance, shown in Fig. 12(*c*), was of the same order of magnitude as that already described for direct viewing. It was found necessary for print exposures to be regulated to within $\pm 10\%$. The results which have been obtained are, therefore, probably better than would be the case where laboratory facilities are not available. The effect of a deliberate change in print exposure is shown in Fig. 12(*a*). Comparison of Fig. 12(*b*) with Fig. 10(*b*) shows that at all three values of contrast, the curves for the photograph come very close to those for direct vision except in the extreme highlights and shadows.

3.3. 35-*mm Motion Picture Film* (Figs. 13, 20*b* and *c*, 21*c* and *d*, 22*b*)

It is not proposed to give a detailed account of 35-mm film processing technique as this has been dealt with elsewhere.[12] Briefly, the development processes for negative and positive are controlled to very close limits of gamma and density, which are independent of the exposure in the camera. The one variable in the processing which is permitted is the "printer light" control. This, as its name implies, controls exposure given in printing the positive from the negative, in twenty-one fixed steps. The appropriate printer light for a given negative is chosen by inspection of the picture by an expert grader. Optimum exposure of the negative on an average subject should require the middle printer light (No. 11). The range 8-14 is normally considered satisfactory.

The illuminator and standard picture were set up on an optical bench with a Debrie 35-mm motion picture camera, and a number of trial films, using Plus X negative, were shot at various brightnesses and lens apertures. These showed that with a highlight brightness of 160 foot-lamberts at f/4 a satisfactory print could be obtained at printer light 10. This meant that the various brightness tones in the original were reproduced on a fairly straight part of the overall characteristic. Normal studio lighting is 100-150 foot-candles at f/2·8, using Plus X negative stock. Allowing 70 per cent. reflectance for highlights, this corresponds to 140-210 foot-lamberts at f/4.

From the opinions of experts and from comparison with good quality motion pictures, it was evident that the conditions conformed closely to standard practice in the motion picture industry. To obtain maximum sharpness, it was found necessary to follow visual focusing by a film run in which the pattern distance was varied slightly in steps on either side of the visual position. The best focus position was ascertained by examination of the processed negative at low magnification. A negative was then made of the complete set of patterns under the same conditions. About 18 ft. (10 seconds) of each combination was shot.

The negatives were examined at low magnification (about x12) and those "takes" where the lines were not resolved were removed. The remainder were spliced up in random order with 3 feet of clear spacer between them, so that after prints had been made, each pattern would be exhibited for 10 seconds when projected on the screen, spaced by dark intervals of 2 seconds.

Examination of the negative and print at x12 magnification gave results as shown in Fig. 13*a*. Extrapolation of the $C=97\%$ curve for the negative shows that the limit of resolution at the highlight brightness B is *circa* 800 test lines/picture height, or 53 lines/mm. This agrees well with the manufacturer's claim of 55 lines/mm for this stock. The curves in Fig. 13*a* show that there is very little lost in printing the positive.

The test film was exhibited at a suburban theatre, and the result is shown in Fig. 13. The overall brightness and density characteristics were also determined, and the results given in Figs. 20*b*, 21 *c* and *d*, and 22*b*. A special additional determination of the brightness characteristic to enable veiling glare to be demonstrated and measured has already been referred to in Section 2.2.4 (see Fig. 20*c*).

3.4. 405-*line*; 50 *fields/sec*, 2/1 *interlaced*, 3 *Mc/s Television* (Figs. 14, 15, 20*d* and 21*e*)

It is generally considered that the highest quality television pictures so far demonstrated have been those generated from 35-mm film by means of a flying spot cathode-ray tube scanner. The authors were fortunate in having access to telecine equipment*, giving a 405-line signal of extremely good quality. It is felt that the results obtained when transmitting the films of test patterns described in the previous section are representative of the best that can be obtained with this scanning standard. The test film was transmitted by line to a 20-inch aluminized cathode-ray tube monitor, with the usual arrangement of observers. The general surrounding brightness was about 1 foot-lambert. The various spurious ("moiré") patterns, due to interference between the test lines and the scanning lines, were ignored, as already explained.

* Now in regular service at Alexandra Palace.

The line structure of the picture was easily visible at $4\times H$, owing to the uniformly good focus of the cathode-ray tube. The interlace crawl was clearly visible. The video chain was corrected for amplitude and phase, and for afterglow and aperture distortion. At first, the observers had some difficulty in differentiating between the scanning lines and horizontal test lines. After a little practice, however, consistent observations were obtained.

The density step film was run through the machine, and the relative brightness of the central test position was measured on the monitor tube, using a barrier layer photocell, suitably positioned to avoid saturation due to short-burst, high-intensity excitation from the scanning spot. The highlight brightness was measured with a visual telephotometer.

3.5. 405-*line Television "Spot Wobbling"* (Figs. 16 and 17)

The idea of reducing the visibility of the line structure and line crawling in a television picture by applying a high-frequency vertical oscillation of controlled amplitude is an old one.[13] The idea was revived in 1947 in connection with television film recording systems.[14] In one arrangement, it was used to fill the gaps between the lines of a single field of a television frame photographed at twenty-five pictures/sec. with a standard cine camera (180° shutter). The equipment was designed to produce a photographic record in which the spot oscillation caused the appearance of two lines for every line in the television raster. Thus with the 405-line pictures being recorded, vertical resolution dropped to 200 lines, but the line structure was not objectionable either on direct projection or on rescanning.

A 10-Mc/s vertical oscillation of adjustable amplitude was applied to the spot of the 20-inch monitor receiver of the equipment used in the

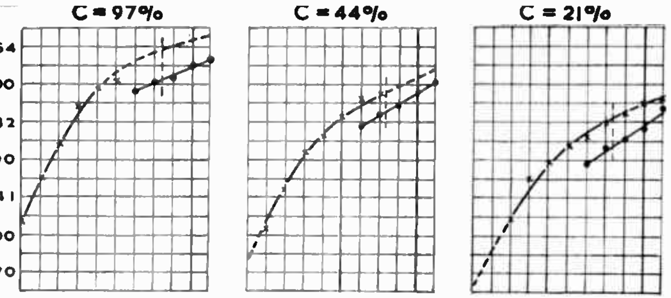


Fig. 8. COMPARISON OF COBB AND MOSS'S AND AUTHORS' RESULTS

× 4 × H, 10 Observers, N ✱ J (Fig. 10b).
● Cobb and Moss[5]. 4 × H, 9 Observers. N ϕ J. Exposure 170 milli-seconds. Adapting field varied with object brightness. Vertical line indicates points of direct brightness comparison.

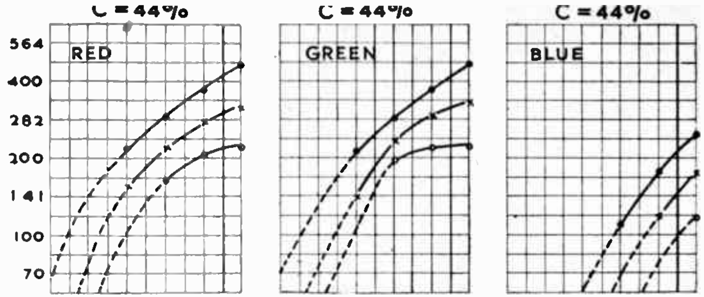


Fig. 9. TRI-COLOUR ADDITIVE SYSTEM.
Highlight Brightness Red 4·65 ft. lamberts, Green 4·65 ft.-lamberts, Blue 0·70 ft. lamberts. 4 × H, 3 Observers. N ϕ J ✱ V ϕ C.

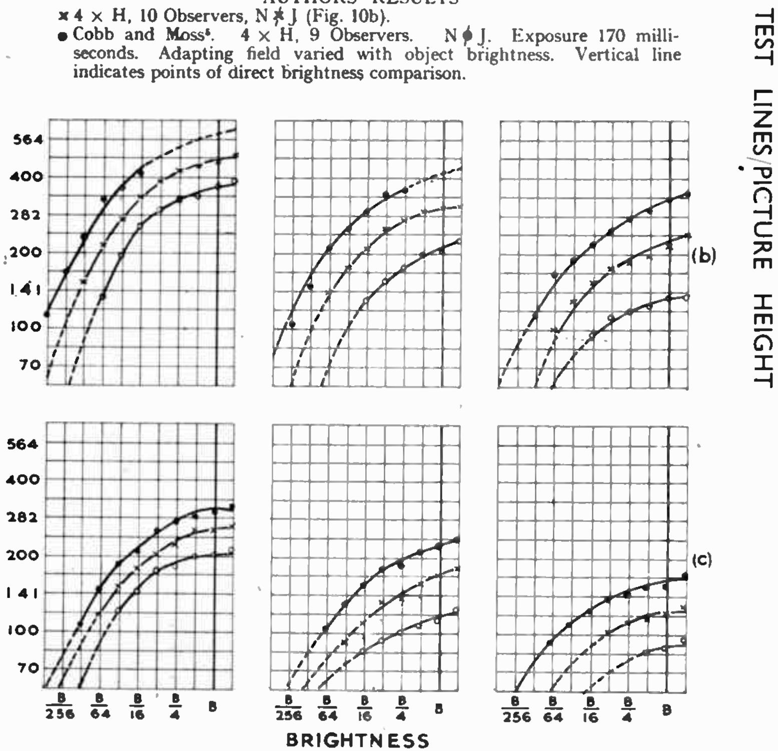


Fig. 10. (b) 4 × H. 10 Obs. N ϕ J ✱ V ϕ C
(c) 8 × H. 10 Obs. N ϕ J ✱ V ϕ C } January, 1949.

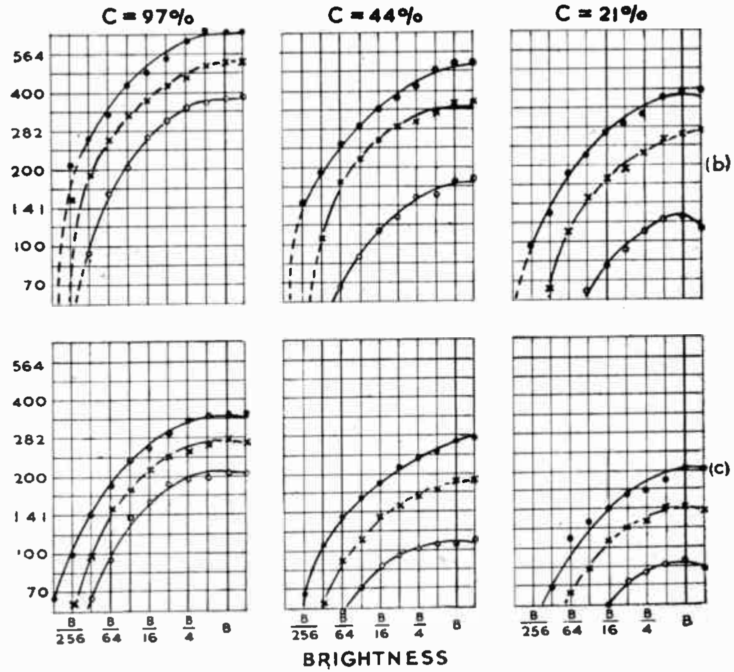


Fig. 11. (b) 4 × H. 10 Obs. N ϕ J ✱ V ϕ C
(c) 8 × H. 10 Obs. N ϕ J ✱ V ϕ C } December, 1949. Different observers from Fig. 10.

Figs. 8, 9, 10, 11. DIRECT VIEWING.
Highlight Brightness B = 10 ft.-lamberts. Picture size = 19·2" × 14·4".
AVERAGE HORIZONTAL/VERTICAL TEST LINES.

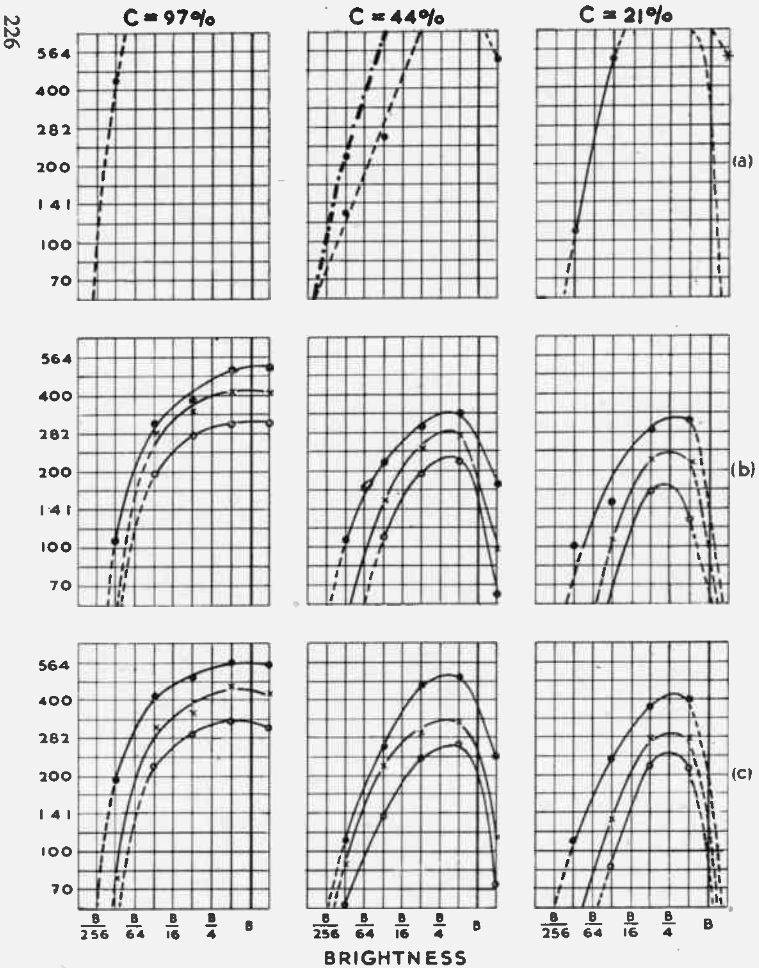


Fig. 12. QUARTER-PLATE PHOTOGRAPHS ($4\frac{1}{4}'' \times 3\frac{1}{4}''$).
15 cm. Tessar lens, unbloomed, f/4·5 at f/4·5. 1/10th sec. P.300 plates glossy paper (unglazed). Highlight B at camera = 325 ft.-lbts.
(a) Low magnification examination of —✱— Negative —●— Print. —·—●— 84% Exposure Print. N ɸ J.
(b) 8 ft.-lamberts } Viewing highlight brightness. 4 × H, 5 Obs.
(c) 80 ft.-lamberts } N ɸ J ✱ V ɸ C.
AVERAGE HORIZONTAL/VERTICAL TEST LINES.

TEST LINES/PICTURE HEIGHT

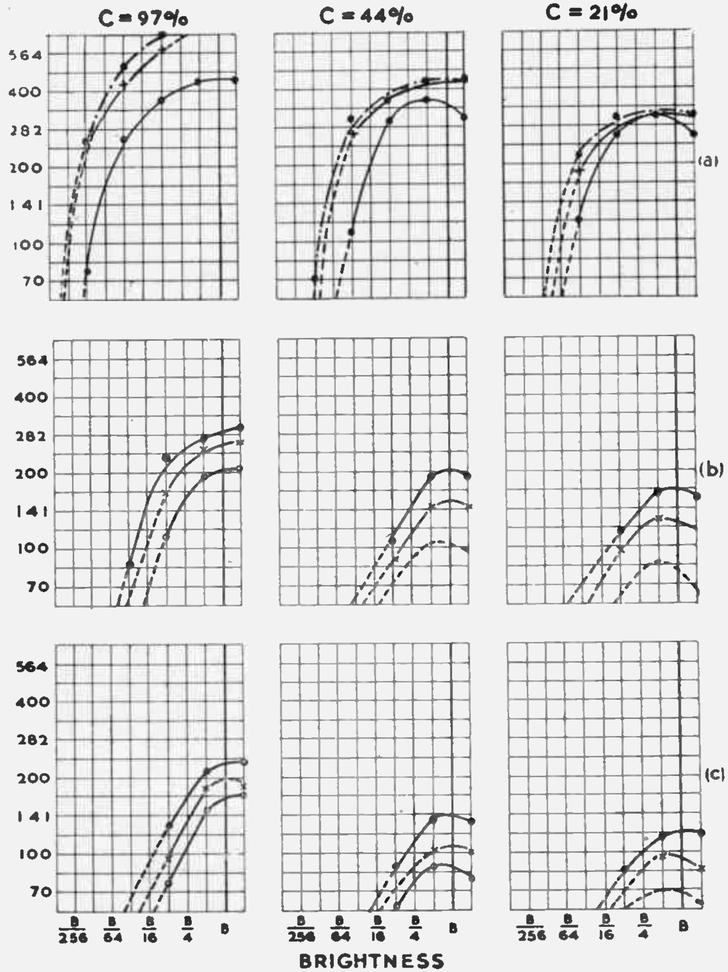


Fig. 13. 35 mm. MOTION PICTURE FILM.
50 mm. Tessar lens, unbloomed, f/3·5 at f/4. Plus X negative ; 1302 positive. Highlight B at camera = 160 ft.- lbts. Printer light 10. Picture size $0{\cdot}825'' \times 0{\cdot}600''$. 24 frames/sec. Exposure 1/48 sec.
LOW MAGNIFICATION EXAMINATION. N ɸ J. (a) -·-●-·- Negative ; —+— Positive.
THEATRE PROJECTION. Screen 18′ × 14′. Highlight 4 ft.-lbts. Feb., 1949
(a) —●— O × H, 1 Obs. N/J , (b) and (c) 4 × H and 8 × H, 12 Obs N ɸ J ✱ V ɸ C.
AVERAGE HORIZONTAL/VERTICAL TEST LINES.

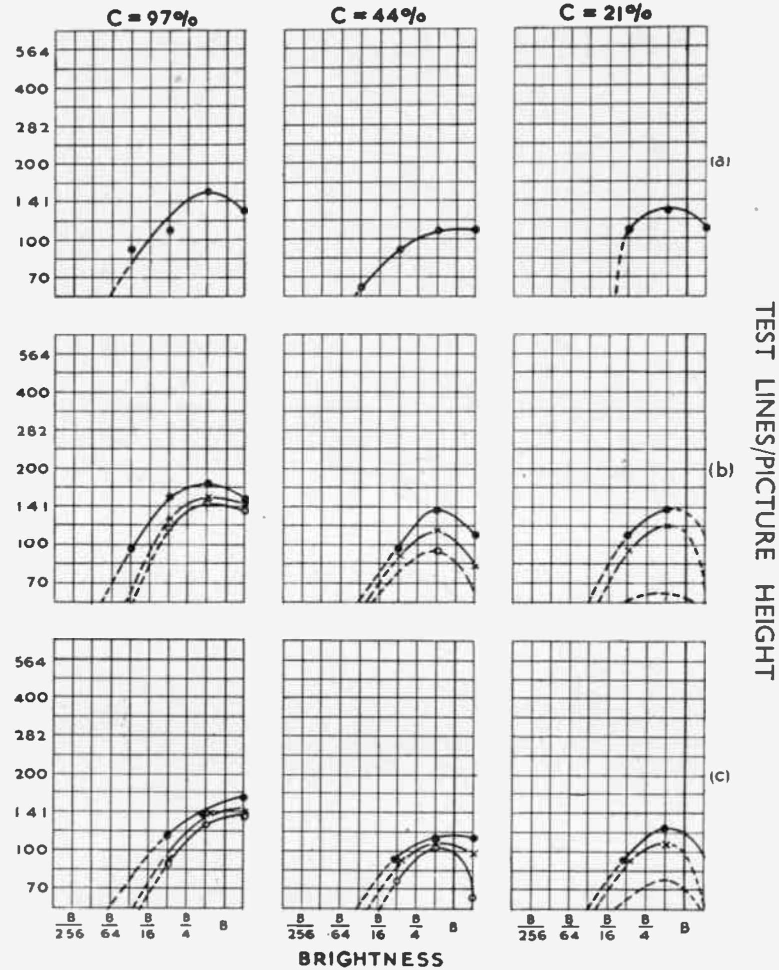


Fig. 14. HORIZONTAL TEST LINES.

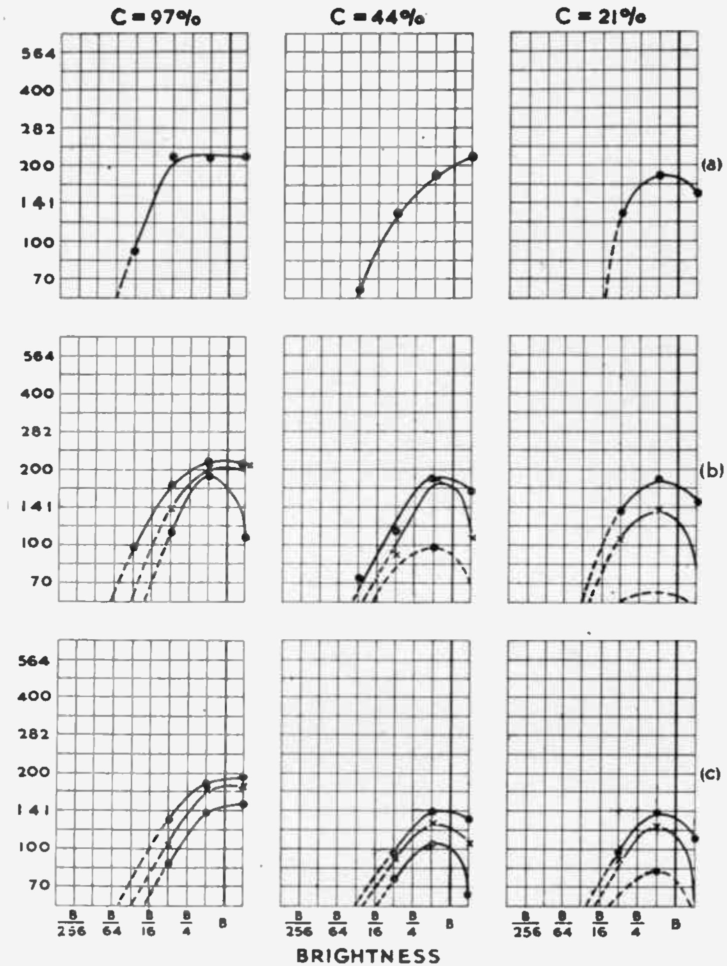


Fig. 15. VERTICAL TEST LINES

Figs. 14 and 15. 405-LINE 50 FIELDS SEC. 2/1 INTERLACE FLYING SPOT C.R.T FILM SCANNER TRANSMITTED BY LINE TO 20" MONITOR C.R.T

Transmission of test film (Fig. 13a).
Receiver Highlight Brightness = 30 ft. lamberts.
Picture size = 15" × 11·25"

(a) O × H, 1 Observer. N ● J
(b) 4 × H, 6 Observers. N ● J × V o C.
(c) 8 × H, 6 Observers. N ● J × V o C.

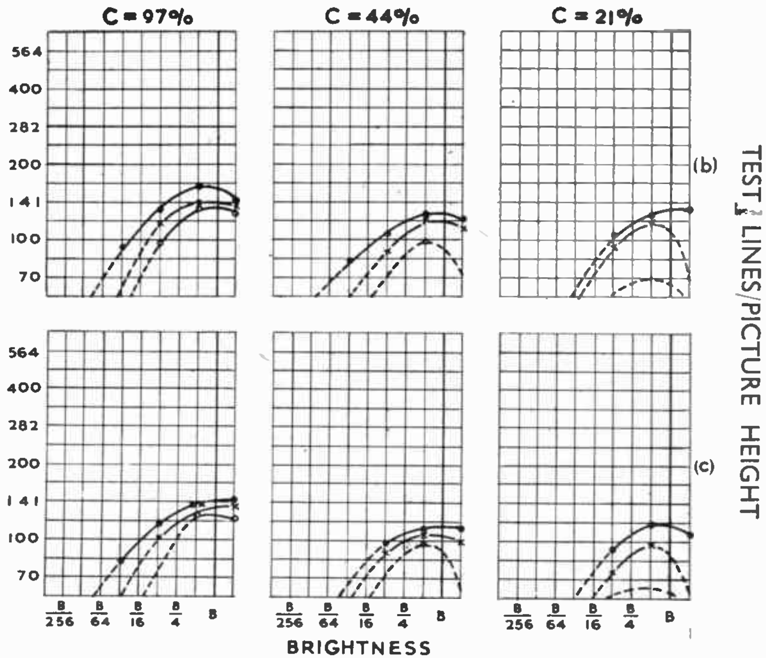


Fig. 16. HORIZONTAL TEST LINES.

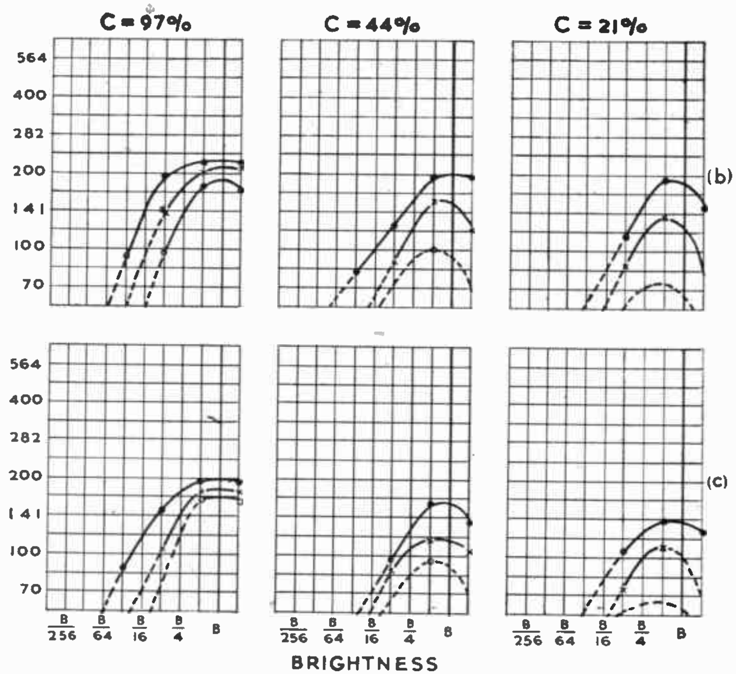


Fig. 17. VERTICAL TEST LINES.

Figs. 16 and 17. 405-LINE 50 FIELDS/SEC. 2/1 INTERLACE FLYING SPOT C.R.T. FILM SCANNER TRANSMITTED BY LINE TO 20" MONITOR C.R.T. 10 MC/S. OSCILLATION ON MONITOR SPOT IN VERTICAL DIRECTION. AMPLITUDE ADJUSTED TO DESTROY LINE "CRAWLING."

Transmission of test film (Fig. 13a). Receiver Highlight Brightness = 30 ft-lbts.

Picture size = 15" × 11·25".

(b) 4 × H, 6 Observers. N ● J ✱ V ○ C.

(c) 8 × H, 6 Observers. N ● J ✱ V ○ C.

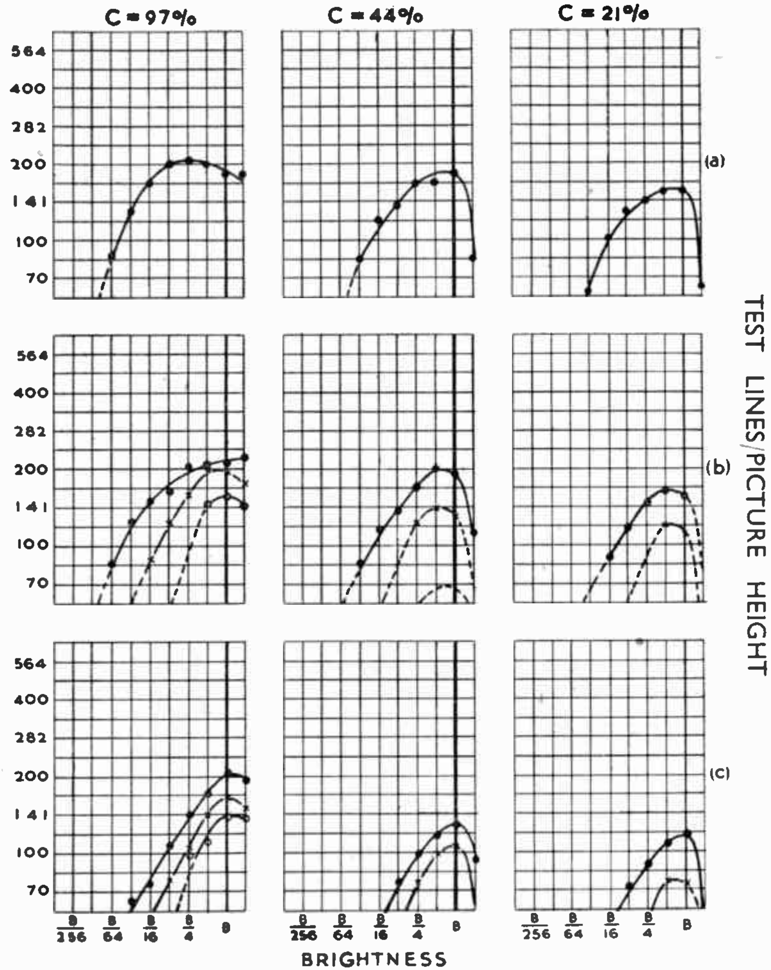


Fig. 18. HORIZONTAL TEST LINES. AVERAGE OF TESTS AT 6 MC/S. AND 4·5 MC/S.

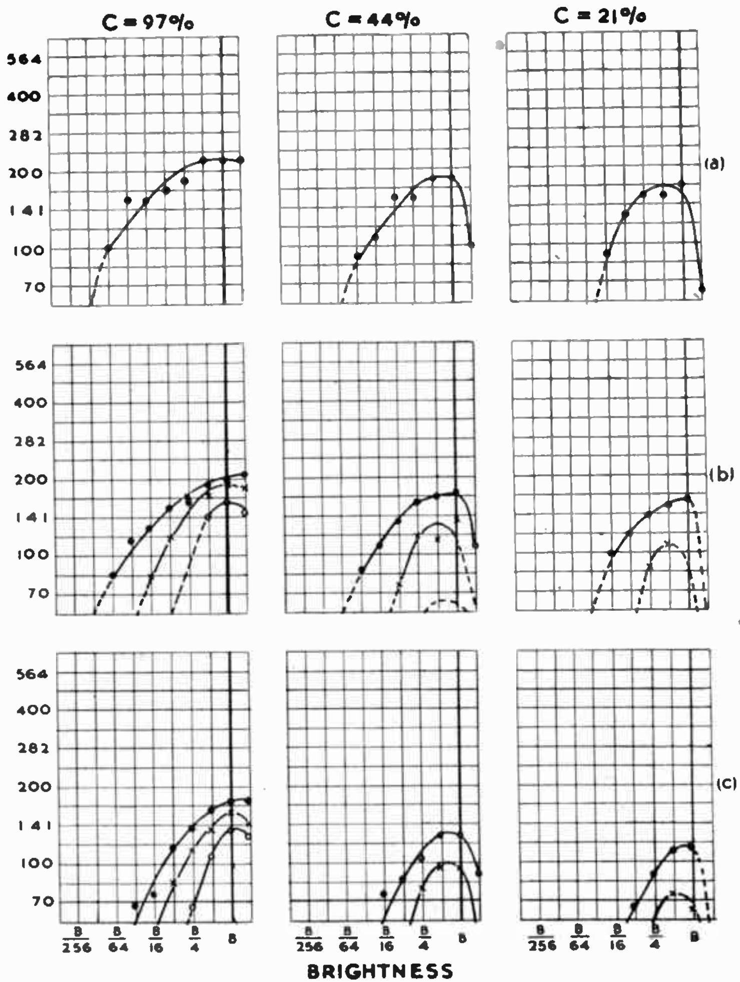


Fig. 19. VERTICAL TEST LINES. 4·5 MC/S. CHANNEL

Figs. 18 and 19. 625-LINE 50 FIELDS/SEC. 2/1 INTERLACE IMAGE ORTHICON CAMERA TRANSMITTED BY LINE TO 15" MONITOR C.R.T.

Image Orthicon camera Type 5655; target size 1·2" × 0·96". 3" Dallmeyer Pentac lens, unbloomed, f/2·9 working at f/5·6. Highlight Brightness B at camera = 50 ft.-lamberts. Receiver Highlight Brightness = 5 ft.-lamberts. Picture size = 12·5" × 10·0".
(a) O × H, 1 Observer. N ● J. (b) 4 × H, 3–4 Observers. N ● J × V ○ C. (c) 8 × H, 5 Observers. N ● J × V ○ C.
Not regular observers.

previous section. By suitable adjustment of amplitude, the lininess of a single field could be made practically the same as that of an interlaced frame due to the double-humped brightness distribution given by the sinusoidal oscillation. Line crawling was practically eliminated, and the line structure was generally less visible, the appearance approaching that of a sequential scanning system. There was some loss of vertical resolution as measured by horizontal test lines. Vertical test lines, however, sometimes appeared more sharply defined, owing to the smoothing out of their " dot " formation. The overall effect on picture reproduction was considered to be very pleasing. The test film was run through under these new conditions and the observers' results are given in Figs. 16 and 17. Comparison with Figs. 14 and 15 shows a general falling off in vertical resolution of approximately 10 per cent. On the other hand, there is an apparent slight improvement in horizontal resolution of about 5 per cent.

3.6. 625-*line*, 50 *fields/sec*, 2/1 *interlaced Television* (Figs. 18, 19 and 20*e*)

The system used was an experimental 625-line Image Orthicon camera chain transmitting the picture by line to a 15-inch cathode-ray tube monitor. Two video channels were available, the normal one of 6·0 M/cs and one with a restricted response of 4·5 Mc/s. A complete test was made under each of these conditions. The regular team of observers was not available, so that absolute comparisons with the other tests must be made with caution. The whole system was quite stable, requiring no readjustment of the controls during an experiment.

The vertical resolution (horizontal test lines) was not significantly different in the 6·0 Mc/s and 4·5 Mc/s tests, and the average of the two is given in Fig. 18. The horizontal resolution with the 4·5 Mc/s channel is given in Fig. 19. The horizontal resolution for 6·0 Mc/s has not been plotted, as it only differs from the 4·5 Mc/s data in rising to a higher maximum at the high brightness end of the high contrast curves. Typical values will be given where necessary in the later discussion.

The most significant quality shown by the curves is the apparent inability to reproduce low contrast test elements at the higher grades of visibility (J/V and V/C).

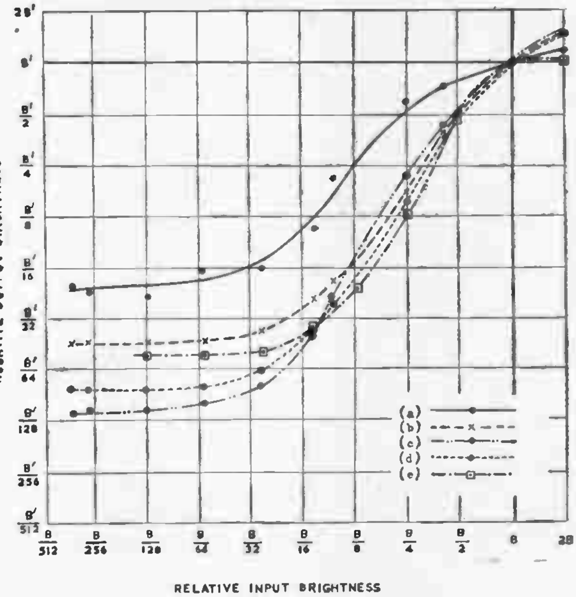
4. Examination of Results

A thorough examination and analysis of the data so obtained is too formidable a task to accomplish here. It will only be possible to deal with the broader issues, and other more detailed considerations will have to await publication elsewhere. The work is, by its own manifestation, incomplete in certain respects. It may be considered, however, to provide useful data in a field which has hitherto been treated largely hypothetically.

Before proceeding to discuss the results, it is desirable to emphasize certain essential features of the experimental method and to explain the system of presentation used for the data in Figs. 8-19. It will be remembered that all the picture reproducing systems were adjusted to give good picture reproduction before testing, and *not* set up on a resolution chart or test pattern. Four parameters—brightness, resolution, contrast and viewing distance—were varied, and their effects on the visibility in the reproduction determined. These are the data plotted in Figs. 8-19. For a complete test on a system nine graphs are usually required—see for example Fig. 14. The three rows are for the viewing distances used, and the three columns for the different values of contrast. Each graph consists of as many as three curves, dividing the four visibility zones (see Fig. 7). It is important to remember that the brightness values plotted on the horizontal axes are those of the original test patterns and not those of the reproduction. The latter can be determined from the transfer characteristics in Fig. 20. The top row of the graphs—row (*a*)—is for close inspection ($0 \times H$) of the reproducing screen and is considered to be representative of system performance independent of observer characteristics. This is not strictly true, of course, as a pattern "just visible" under these conditions implies some undefined statistical visual comparison (e.g. signal/noise ratio) which must be partly an observer characteristic. The usefulness of the method is, however, supported by a wealth of photographic experience. The justification would appear to lie in the assumption that the rate of change of visibility under these conditions depends more on the performance of the system than on the observing mechanism, so that variations between observers, for example, produce only very small changes in chosen limits. Only one observer was used in these tests, and only the

Fig. 20. (Right), Brightness (" Modulation " "Transfer") characteristics of complete picture reproducing systems.

	B (Ft. L.)	B′ (Ft. L.)
(a) Quarter plate print .. .. (Fig. 12)	325	8
(b) 35-mm motion picture projection .. (Fig. 13)	160	4
(c) 35-mm motion picture (black adapted)	160	4
(d) 405-line film scanner monitor .. .. (Figs. 14, 15, 16, 17).	160	30
(e) 625-line Image Orthicon monitor .. (Figs. 18, 19)	50	5



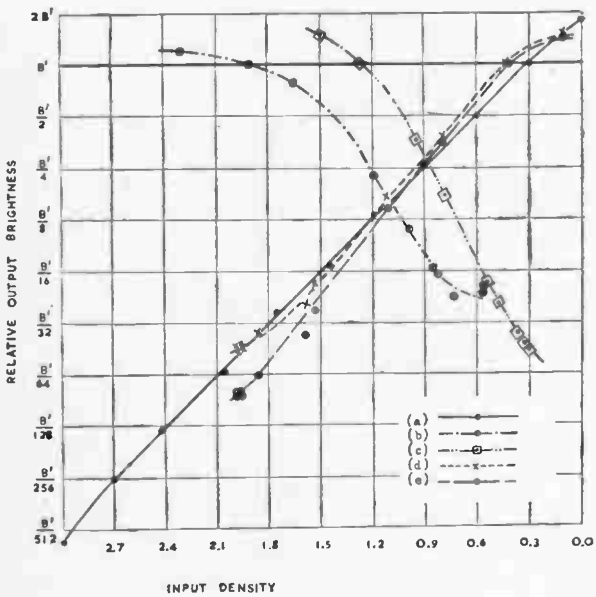


Fig. 21. (Left), Density/Brightness Characteristics.

(a) Direct photometry of neutral density brightness steps. (Figs. 10 and 11.)

(b) Quarter plate print. Negative density v. $B'=8$ foot-lamberts. (Fig. 12.)

(c) 35-mm motion picture. Negative density v. $B'=4$ foot-lamberts. (Fig. 13.)

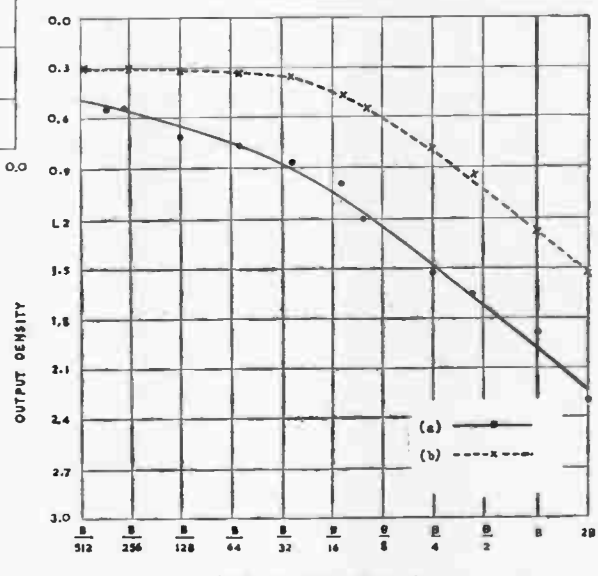
(d) 35-mm motion picture theatre projection. Positive density v. $B'=4$ foot-lamberts. (Fig. 13.)

(e) 405-line film scanner monitor. Positive density v. $B'=30$ foot-lamberts. (Figs. 14, 15, 16, 17.)

Fig. 22. (Right), Brightness/Density characteristics.

(a) Quarter plate negative. $B=325$ foot-lamberts. (Fig. 12.)

(b) 35-mm negative. $B=160$ foot-lamberts. (Fig. 13.)



"not visible/just visible" criterion. Data for low magnification examination of negatives and positives produced in the photographic and cinematograph experiments (Figs. 12 and 13) are included in row (*a*) where available. Density/brightness data for these are given in Figs. 21 and 22.

Rows (*b*) and (*c*) in the set of nine graphs are for viewing distances of four and eight times the picture height ($4 \times H$ and $8 \times H$) and represent a combination of the characteristics of the system alone, given by row (*a*), and those of the observer team alone, given in Fig. 10. As viewing distance is increased it is obvious that the results will tend to become asymptotic to direct observation of the original at the same viewing distance, i.e., the difference in appearance between original and reproduction becomes progressively less as viewing distance is increased. In using the data rows (*b*) and (*c*) it is essential to remember that they include the limitations of vision of the observer team.

Resolving power is plotted as the vertical axis of all nine graphs, and is measured in Test Lines*/Picture Height. This convention is based on that of the photographers who use test lines/unit length and is deliberately *not* that frequently used by television engineers, who have tended to rate resolving power in terms of "television lines." The vertical resolution of a television system does not bear any simple relationship to the number of lines in the picture, partly due to spurious patterns produced between the scanning lines and the test pattern used, and other similar considerations,[15] and partly due to the lines lost in meeting synchronization requirements. The authors deprecate the use of television lines to define resolution for this reason, and favour the use of the photographic convention, but with the modification of substituting "picture height" for "unit length."

It must be realized that Figs. 12-19 show how much of the original brightness/contrast/resolution data presented to the camera can be seen in the reproduction and include the brightness distortion shown separately by the transfer characteristics of Fig. 20. Furthermore, as pointed out in Section 2.1, a picture which has already been "lit" is used for setting-up, whereas a competent cameraman with lighting control available to him would almost certainly light his original scene to give the most desirable effect in the reproduction. It seems highly probable that in doing this he would compress the tone values into the brightness regions where resolution is a maximum, but this is at the moment a matter for speculation.

* See footnote Section 2.2.1.

4.1. *Consistency of Data*

Before attempting to interpret the data it is desirable to examine their accuracy, and also to compare them with similar published work.

A typical set of results from one test with ten observers is given in Fig. 7, which shows mean values plotted and their expected variation for 0·95 probability limits.† These same observers were used in obtaining the data in Figs. 8-10, 12-17. Fig. 7 indicates an expected variation of the order of ± 11 per cent. in resolution for the mean of ten observers at the high brightness end of the curves, increasing to $\pm 17{\cdot}5$ per cent. at the low brightness end. In comparing complete curves it might be thought that a smaller variation could be inferred owing to the cumulative effect of the individual points forming the curve—for example, roughly inversely proportional to the square root of the number of points involved. This is not to be relied on, however, as examination of the individual observer curves shows that they tend to lie consistently high or low throughout. The experiment of Fig. 10 was repeated using some of the same team of observers and the result (data not shown) lay within the above expected limits. Note that in Figs. 8-13 the results for horizontal and vertical test lines have been averaged, thus giving effectively double the number of observations. In view of the observer characteristic mentioned above, however, this would not be expected materially to reduce the variation.

The results obtained with a totally different team of observers at a later date are given in Fig. 11. Careful comparison with Fig. 10 shows that whilst the general behaviour of the second team was in every way consistent with that of the first, the actual values differed by amounts greater than those to be expected from Fig. 7. Combining the results from the two teams increases the variations given above to $\pm 13{\cdot}5$ per cent. and ± 25 per cent. respectively, and these latter values would appear to be the best

† Only differences in means of 10 greater than these limits are considered significant. 1 in 20 would exceed them purely by chance.

estimates available for the data on an absolute basis. For relative performance, however, e.g., comparing results obtained using the same team of observers, the former figures may still be considered suitable.

Considerable reduction of probable error can be expected from an increase in the size of the observer team. Conversely, the opinion of a single observer (even if unbiased, e.g., not a television engineer) must be regarded with considerable suspicion. He is not likely to do better than ± 40 per cent. for a 0·95 probability limit at the highlight end of the curves, and ± 75 per cent. at the low brightness end. In evaluating the C.I.E. Visibility Curve some hundreds of observers were used, but, of course, facilities did not permit such a large team to be used in the present investigation. It is useful to estimate, however, that if one hundred observers had been used the expected variation on an absolute basis would have been reduced to about $\pm 4\frac{1}{2}$ per cent. and ± 8 per cent. instead of the figures given above.

Some initial experiments were carried out with deliberate changes in the constants of the test patterns, e.g., in the proportion of black to white line width (which should, of course, be equal). These showed that the accuracy of pattern manufacture could easily be maintained within limits which produce no measurable difference in the observers' readings.

Even though the test patterns cover a range of 10/1 in resolution, this sometimes proved insufficient for certain individuals. At the extreme ends of the curves it was not always possible to record all ten observations, and a process of weighting was therefore adopted in order to plot the extremities of these curves. Where this has been done they are shown as broken lines. With the convention adopted resolution values tend to be lower than the true value at the high end of the curves and vice versa at the low end.

Coming now to the comparison of the present results with previously published work, some values have already been mentioned in Sections 3.1 and 3.3. A figure of 1·4 minutes of arc for the limit of visual acuity was obtained, which is in good agreement with previous estimates. The comparison with Cobb and Moss's data in Fig. 8 is also satisfactory. The limiting resolution of 35-mm Plus X film works out at 53 lines/mm, which compares with the manufacturer's published figure of 55 lines/mm.

Results of the television systems tested have not yet been referred to, and it is of interest to compare the measured limiting horizontal and vertical resolution with the number of scanning lines and video bandwidth. Briefly these show: In Fig. 14(a) for $C' = 0{\cdot}97$, a maximum vertical resolution of 155 test lines/picture height for 385 lines displayed in the picture area—a ratio of 40 per cent. Similarly, Fig. 18(*a*) gives values of 220 and 580—a ratio of 38 per cent. Expressing resolution in terms of the much deprecated "television lines" to permit comparisons to be made, doubles these values giving 80 per cent. and 76 per cent. respectively, which are in satisfactory agreement with published figures. Figs. 15(a), 19(a), and the results for the 625-line system tested at 6 Mc/s (not shown) indicate limiting video frequencies of 3·5 Mc/s for the 405-line film scanner, and 5·1 and 7·3 Mc/s for the 625-line Image Orthicon chain. These are somewhat higher than the expected values, even allowing for the mean observer variation, especially for the film scanner which had a sharp cut-off at 3 Mc/s.

It is important to note that, in all the comparisons, only one point on one curve (out of some eighteen or more curves per system) is being checked against known data, with the exception of the limited range in Fig. 8.

4.2. *Fundamental Considerations*

The data presented in Figs. 8-19 are effectively a display of five variables—brightness, resolution, contrast, viewing distance, and degree of visibility. This complex array appears highly indigestible on first acquaintance and it is desirable, therefore, to find ways of promoting the flow of mental saliva. Viewing distance lends itself well to separate study, and discussion of this will therefore be postponed until Section 4.4. The remaining four variables can be largely co-ordinated as follows.

The elimination of viewing distance reduces the data to any given horizontal row of three graphs. These two-dimensional figures may be considered as sections of a three-dimensional solid where any set of data for a given visibility criterion become a three-dimensional surface such as shown in Fig. 23. The axes of this model are brightness, resolution and contrast as shown.

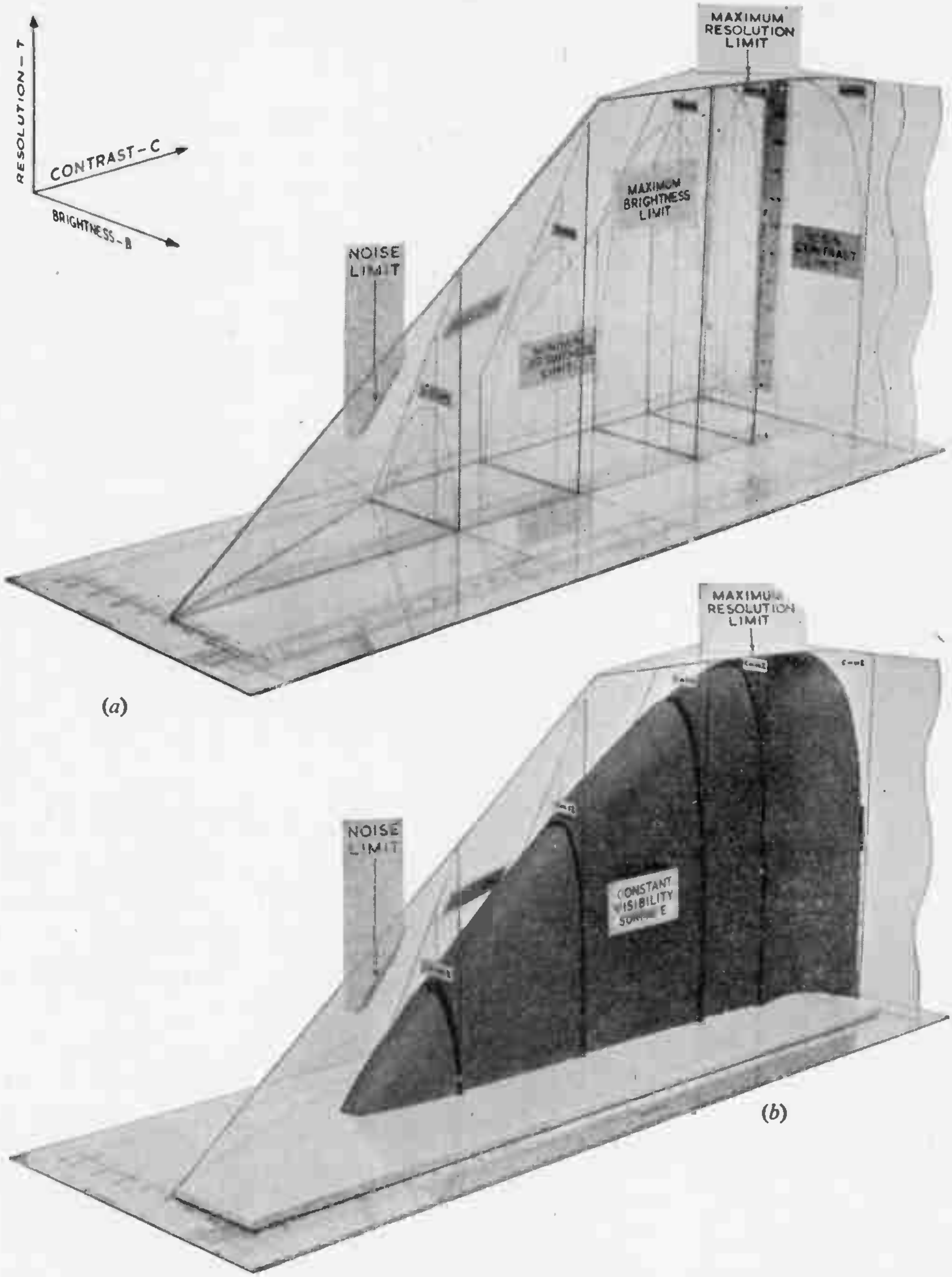


Fig. 23.—Three-dimensional model illustrating a possible relation between brightness, resolution and contrast for a constant degree of visibility and a fixed viewing distance.

(*a*) *Reference axes and limiting surfaces.*

(*b*) *As* (*a*) *but with constant visibility surface in position and maximum brightness limit removed.*

Various typical sections of the solid are given in Fig. 24, which are to the same scale as Figs. 8-19 but with the ranges of the variables suitably extended. Whilst the construction of the three-dimensional surface is largely hypothetical, as will be explained, it has been based on the data for 35-mm motion picture projection given in Fig. 13(a); $0 \times H$; N/J criterion, and in Fig. 20(b).

Consider the factors limiting the boundaries of any given surface of equal visibility. Contrast cannot extend higher than 100 per cent.; resolution cannot be less than 1 test line/picture height, corresponding to the picture being divided into two horizontally, the upper part having one value of brightness and the lower an appropriate different value to produce the desired contrast between the two. In the practical case under consideration, with the fixed adapting field surrounding the test object, the size of the latter does not permit a resolution of less than 7 test lines/picture height to be obtained. Figs. 23 and 24 have been given a convenient minimum resolution of $T = 6\frac{1}{4}$. A third limit is the maximum resolving power T_{max}, due to such factors as lens aberrations; scanning spot diameters and video bandwidths (in the case of television systems); grain size (of photographic emulsions); number of receptors per unit area (in the case of the eye), etc. On the basis of Fig. 13(a), a limit of $T_{max} = 480$ has been chosen. Examination of Fig. 20(b) shows that the transfer characteristic flattens out completely below an input brightness of $B/128$, i.e., $b_{min} = 1/128$, so that it is incapable of reproducing any test object whose light lines are equal to, or less than, this brightness. An upper brightness limit can be determined by reference to Fig. 20(a) as follows. The data indicate that the transfer characteristic flattens out above an input brightness given by (say) $b_{max} = 4$, so that it is incapable of reproducing a test object whose dark lines are equal to, or greater than, this value. As the brightness of a test object has been defined in these experiments as that of its light test lines, it follows that the maximum limit of brightness

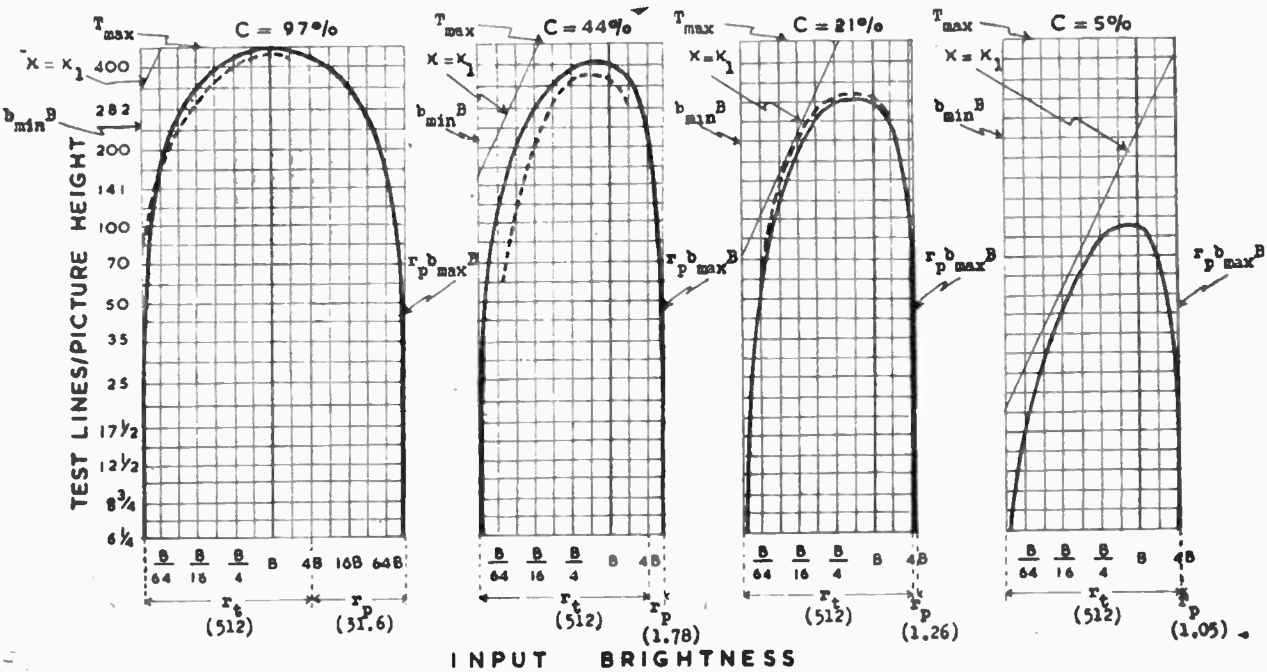


Fig. 24.—Constant contrast cross sections of Fig. 23.

Maximum resolution limit:—$T_{max} = 480$. Input brightness limits:—$r_p b_{max} B = r_p 4B$; $b_{min} B = B/128$

$$\text{Noise limit:—} \kappa = \kappa_1 \text{ in } b = \frac{1}{1{\cdot}6 \times 10^7} \left(\frac{\kappa}{\kappa_1}\right)^2 \frac{T^2}{(C')^2}$$

Dotted curves show experimental results for 35-mm motion picture projection (Fig. 13a: $0 \times H$; N/J).

reproducible under the above conditions is given by $b = r_p \times b_{max}$. This represents a surface with a linear cross-section in any constant contrast plane, asymptotic to the plane $b = 4$ at low contrast, and asymptotic to the plane $C = 100$ per cent. at the other extreme, as shown.

The constant visibility surface has now been enclosed by the limit surfaces $T_{max} = 480$; $T = 6\frac{1}{4}$; $b = 4r_p$; $b_{min} = 1/128$; and $C = 100$ per cent. Only the low contrast limit remains undefined. One limiting factor of a picture reproducing system, not so far considered, is the signal/noise ratio R. The fact that the performance of all the systems tested, including the eye, is reduced as the contrast of the test object is reduced suggests that this is a function of signal/noise. The following line of reasoning is based on a paper by A. Rose.[16] On the basis that the noise in the system is pure fluctuation noise, i.e., proportional to the square root of the signal at any value ($R = \text{Const.}S^{\frac{1}{2}}$), Rose derives two formulæ which are relevant. These are his equations (3) and (8), relating the input brightness, resolution, contrast and signal/noise ratio of a system. Converting these two equations to the symbols adopted in the present paper, they become,

$$bB = \eta . R^2 . T^2 \quad \ldots\ldots(1)$$

$$C' = \frac{\kappa}{R} \quad \ldots\ldots(2)$$

where η and κ are constants.

Combining these gives:

$$bB = \frac{\eta \kappa^2 T^2}{(C')^2} \quad \ldots\ldots(3)$$

An assumption which seems reasonable is that at low brightness (i.e., away from the limit of resolution) the value of the constant κ is related to the visibility criterion, a small value of κ corresponding to "N/J" and a much higher value to "V/C," i.e., a higher probability of the test object being seen in the latter case.

It will be obvious that for any given value of κ—say $\kappa = \kappa_1$—equation (3) represents a surface cutting through the three-dimensional system of Fig. 23 at an angle, as shown. With the logarithmic scales chosen for the three axes, it becomes a plane surface and proves to be, in fact, a limit at the low contrast end of the diagram. If this assumption is justified, it will be seen that the three-dimensional curved surface representing a constant visibility criterion will tend to become tangential to this inclined plane at the lower values of contrast. It should be noted that this inclined plane is a "noise limit" to the constant visibility surface and not a "constant signal/noise" limit.

Continuing the attempt to fit the data of Fig. 13(a) into this system, therefore, a value has been chosen for the constant in equation (3) of

$$\frac{B}{1 \cdot 6 . 10^7 \kappa_1^2},$$

to derive the plane shown in Fig. 23 and the inclined limit lines shown in the sections (Fig. 24). This value gives the best fit to the experimental curve at the lowest value of contrast measured ($C' = 0{\cdot}21$). The equation to this (plane) surface is (remembering $\kappa = \kappa_1$)

$$b = \frac{T^2}{1 \cdot 6 . 10^7 (C')^2}$$

and for any other value of κ—say κ_2,

$$b = \frac{\left(\frac{\kappa_2}{\kappa_1}\right)^2 T^2}{1 \cdot 6 . 10^7 (C')^2}$$

which gives a family of parallel planes whose distance apart is a measure of the ratio κ_2/κ_1. For example, supposing the low contrast regions of the data given in Figs. 10 and 11 for the eye are tangential to three such planes for the three degrees of visibility, then it can be seen from the experimental curves that the ratios κ_3/κ_2 and κ_2/κ_1 for these are of the order of 2/1. Returning to Figs. 23-24, it may be said that, as a curve fitting exercise, the three-dimensional curved surface which has been purposely made a reasonable fit to the experimental data in Fig. 13(a) is also a passable fit to the tangent planes derived in the way described, and that the general shape of all the experimental data is consistent with such a system of limits, including the idea of the increasing value of κ corresponding to improving visibility criterion. It is very desirable, of course, that these surfaces should be capable of direct mathematical derivation from the constants of the limit planes and the transfer characteristic. It is hoped to discuss this elsewhere.

It is realized that Figs. 23-24 are an over-simplified presentation and that various corrections must be applied which may be of assistance. One of these relates to the brightness of the test object, which at the moment is plotted as the brightness of the light lines. It might be preferable to plot the average brightness, in view of the existence of the constant adapting field. Again, the type of test object used may be inconsistent with Rose's formulæ. The latter are calculated for an element of equal width and height. $1/T^2$ in equation (1) above is, therefore, supposed to be a measure of the area of the test element. With the line test objects used in the present experiments a correction will obviously be required for this. Alternatively dot test objects might be preferable. Another correction may be needed to deal with other forms of noise in the system.

To resolve these points further experimental data are needed, particularly in the regions of lower contrast and resolution. Fig. 23 indicates a minimum value of $C' = 0{\cdot}00078$ where the $\kappa = \kappa_1$ plane meets the intersection of the maximum brightness surface and the plane $T = 6\frac{1}{4}$. Further experiments must obviously be carried out in the region of these lower values.

There are many interesting features of Figs. 23-24, but it must be sufficient here to point out the interaction of the noise limit plane and the maximum resolution limit plane. In the example chosen for this illustration the former has little effect at high contrast, and the latter becomes ineffective below $C' = 0{\cdot}05$. It might well be, however, that the signal/noise conditions were so bad that they rendered the resolution limit inoperative, even at the high contrast end of the diagram. This is the kind of effect which would occur in changing television standards from a given number of lines and video bandwidth to a higher number of lines with correspondingly increased bandwidth. Raising the maximum resolution limit of the system may possibly be rendered ineffective by the increased noise due to the additional bandwidth. With a given type of pick-up tube it is not, of course, possible to compensate for this by increasing the illumination on the photo-cathode as this already has a maximum limit, set by the shape of the transfer characteristic. In making assessments of this kind, of course, the effect of the observer's average vision must be included, and it is specifically with this in view that the experimental data obtained include variation of viewing distance.

The considerations of system performance discussed above have so far been on a purely relative basis. This is implied by the use of B—the highlight brightness of the original scene—in equation (1). The absolute values of B are given in the tabulated data under Figs. 8-19, along with such other relevant information as camera lens aperture, size of pick-up target or photographic emulsion, etc. The question of the "absolute performance factor," "sensitivity," "figure of merit," etc., for pick-up devices has been discussed by Rose[16, 17] and others, and more recently by Bedford,[18] and it is desirable to reduce the results of the present investigation to some common level of comparison. In the present case it is important to remember that the measurements made do not apply to the pick-up device alone, but to the whole system. The method of test used is, of course, directly applicable to pick-up tubes alone, provided they are coupled to suitable metering devices.

The fundamental performance of a system may be rated in various ways, some of which are independent of each other. For example, Fig. 23 indicates that maximum resolution is independent of signal/noise, the former depending on the physical size of scanning elements and photoreceptors, etc., and the latter depending on such factors as the light flux reaching the camera target, efficiency of photo-emission or of photographic emulsions, etc. The saturation limits of the transfer characteristic provide yet another independent limit to performance related to simple brightness sensitivity. The following is an attempt to evaluate the absolute values of these three limits for some of the systems tested, on the basis of Fig. 23, i.e., assuming the latter gives a correct picture of the relationship between them and the experimental data.

Determination of maximum resolving power (T_{max}) is reasonably straightforward provided the necessary precautions are taken to render it free of signal/noise limitation. Fig. 23 shows that this is most likely to occur at high contrast and the highest contrast test object should therefore be used and the limiting visibility criterion, the latter being assisted, of course, by close inspection of the reproduction with or without the aid of low power magnification. Whether noise is still a limitation at this high contrast can be determined by projecting back the limiting noise surface determined from the low contrast measurements into the high contrast plane. Freedom from such noise limitation will also usually be indicated by the shape of the brightness/resolution curve for the high contrast test object, where resolution should appear to flatten off as it approaches maximum (highlight) brightness B. Should there still be indications of noise limitation under these conditions, then an attempt may be made to overcome it by increasing the illumination falling on the pick-up target, but this will usually cause overloading/saturation effects to occur unless the device has some natural adapting properties such as in the eye and, to some extent, evidenced in the image orthicon tube.

Simple brightness sensitivity can best be expressed in terms of the total light flux Φ (lumens) falling on the pick-up target when a uniformly illuminated white test object of picture highlight brightness B is placed in front of it. Rose[16] and Bedford[18] have shown that this figure is fundamental to the pick-up device and independent of aperture/depth-of-field considerations. It is useful to the camera operator as it gives him information relating to his lighting requirements. In the case of still photography or of moving (television or film) pictures taken at speeds different from normal, a correction to the lighting must be made for various exposure times, and this leads to an alternative expression for sensitivity, i.e., in lumen seconds per picture $\Phi \times t_p$ where t_p is the exposure time in seconds for a single picture. For reasons which will become apparent it is useful to express this alternative in terms of the total quanta required per complete picture—Q_p. Φ may readily be calculated from the well-known optical formula:

$$\Phi = \frac{bB.A.\tau}{4.N^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

(τ has been taken as 0·75 in all the following calculations.) Q_p may then be determined from the formula:

$$Q_p = 1{\cdot}3 \times 10^{16}\,.\,\Phi\,.\,t_p \text{ (for white light)} \ldots\ldots (5)$$

since one lumen of white light is equivalent to $1{\cdot}3 \times 10^{16}$ quanta/sec. As well as converting the input highlight brightness B in this way, it is also convenient to convert the limiting brightness, as referred to above, into values of Φ or Q_p, by putting b equal to $r_p\,.\,b_{max}$ or b_{min} in equation (4).

The remaining figure of merit which it is proposed to discuss is that relating to noise limitation, and is perhaps the most interesting of the three. In Fig. 23 the inclined plane representing the noise limit $\kappa = \kappa_1$ becomes tangential to the constant visibility surface for the system at the lower values of contrast. This can also be seen quite clearly in the low contrast cross-sections shown in Fig. 24. As stated above, this limit to performance is dependent on both the illumination falling on the camera target and the particular visibility criterion (value of κ) chosen. These factors are, in fact, concealed in the constant in equation (1); it will be noted that in the particular example used for illustration in Figs. 23-24 the constant works out at $B/(1{\cdot}6\,.\,10^7\,.\,\kappa_1^2)$ which contains both these factors. A comparison of some of the systems tested has therefore been made in Fig. 25, by selecting certain curves (as indicated) of equal visibility criterion (N/J) for the lowest contrast test object used ($C' = 0{\cdot}21$) and replotting them with the relative brightness scales converted into the appropriate values of Q_p calculated as explained above. The position of the original highlight brightness on each curve is indicated by the arrows "B" for reference. This replotting requires no change of shape from the original data—merely a relative horizontal displacement to conform with sensitivity differences. Tangent lines have been drawn to these curves (shown dotted) at a slope given by putting $C' = 0{\cdot}21$ in equation (3), i.e., they are the same slope as the noise limit lines $\kappa = \kappa_1$ in Fig. 24 which, of course, become tangential to the curves at low contrast values. As all the curves have been deliberately chosen to have the same visibility criterion, the relative displacement of the tangent lines represents a measure of the relative noise limitation of the different systems. Each system has its highest sensitivity in this respect at the actual point of contact with its tangent line—indicated by the arrows "A" in Fig. 25.

The equations to these tangents are derived by combining equations (3), (4) and (5), giving:

$$Q_p = 1{\cdot}3\,.\,10^{16}\, t_p \,\frac{A\tau}{4N^2}\cdot\frac{\eta\kappa^2T^2}{(C')^2} \quad \ldots\ldots\ldots (6)$$

For a given value of t_p, A, τ and N, therefore, as for each of the curves in Fig. 25,

$$\frac{Q_p}{\frac{4}{3}.(2T)^2} = \frac{\theta\kappa^2}{(C')^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

where θ is a constant for each system given by

$$\theta = \frac{1{\cdot}3\,.\,10^{16}}{\frac{4}{3}.2^2}\cdot\frac{t_p A\tau\eta}{4N^2}$$

This gives the equation to the tangent line when κ is given an appropriate constant value. The left-hand denominator $\frac{4}{3}.(2T)^2$ in this equation is taken as the number of picture elements per picture. Therefore, in Fig. 25, $Q_p/\frac{4}{3}.(2T)^2$ is a measure of the number of quanta required per picture element per picture to reproduce a

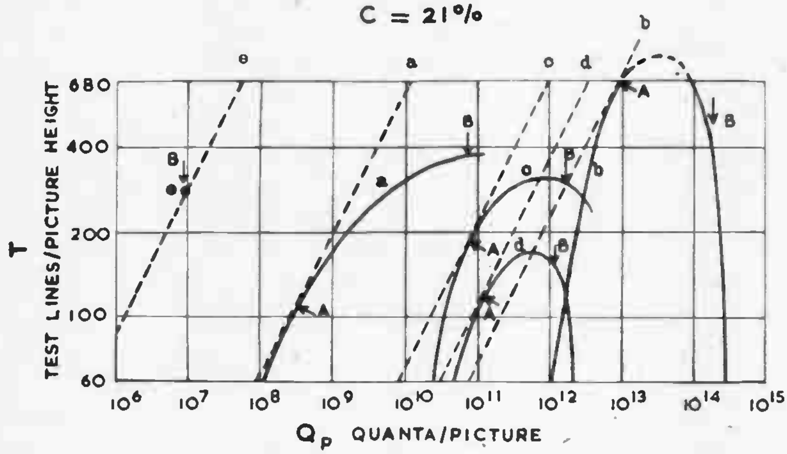


Fig. 25.—Relative performance of different picture reproducing systems in terms of resolution and incident radiation on camera target for low contrast test object, and N/J criterion.

	Viewing Distance	t_p (secs.
(*a*) The Eye—mean of Figs. 10*b* and 11*b*	4 × *H*	$\frac{1}{5}$
(*b*) Quarter-plate photograph—Fig. 12*a*	0 × *H*	$\frac{1}{10}$
(*c*) 35-mm Motion Picture—Fig. 13*a*	0 × *H*	$\frac{1}{16}$
(*d*) Image Orthicon 5655, 625-line—Fig. 19*a*	0 × *H*	$\frac{1}{25}$
(*e*) Quanticon, 625-line	—	$\frac{1}{25}$

contrast $C' = 0{\cdot}21$ in the original test object, with N/J visibility criterion.

At this point it is convenient to introduce Bedford's Quanticon[18]—an idealized pick-up tube—which will materially simplify the remainder of the argument in this section. This device has already been endowed with the following attributes—perfect storage efficiency, a photocathode of full quantum efficiency, and adequate noiseless electron multiplication.

Some preliminary calculations of Quanticon performance in terms of the number of quanta required per picture element per picture revealed a most interesting and valuable property of the tube which renders its conception quite impeccable—it requires one quantum per picture element per picture to obtain a signal/noise ratio of $R = 1$. Reference to Bedford's equation (7)[18], giving the basic signal/noise factor for the tube, establishes this in a very simple manner as follows. Rewriting this equation using the present symbols:

$$R^2 = \frac{I}{2eF} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

F is the maximum frequency of the channel; therefore the maximum number of picture points (alternate light and dark) which can be transmitted per second is $2F$. With an average of one quantum falling on a picture element per picture and 100 per cent. quantum efficiency, this corresponds to an electronic current $I = 2eF$. Substituting this value of I in the above equation gives $R = 1$. Now equations (7) and (2) combined give:

$$\frac{Q_p}{\frac{4}{3}.(2T)^2} = \theta R^2 \quad \ldots\ldots\ldots (9)$$

For the Quanticon, therefore, $\theta = 1$.

In order to plot the Quanticon on Fig. 25, therefore, it is now only necessary to know the value of κ which will permit R to be exchanged for C' in equation (2). Rose[16] has already pointed out that κ corresponds to the "minimum perceivable value of R" for a test object with a contrast $C' = 1{\cdot}0$. He discusses values ranging from the ideal condition of $\kappa = 1$ to measured values of the order of 5. It should be possible to determine the value of κ for the type of test pattern, visibility criterion, etc., used in the present investigation, but this remains to be carried out. The ideal value of $\kappa = 1$ (corresponding to $R = 1$ for $C' = 1$ at N/J visibility criterion) has therefore been chosen for the Quanticon in order that it may be compared with the other data in Fig. 25. The Quanticon line in this figure was obtained by putting $\kappa = 1$, $\theta = 1$ and $C' = 0{\cdot}21$ in equation (7).

It is now a simple matter to determine the best performance in terms of the noise limit of any of the systems plotted in Fig. 25, by comparing them to the idealized Quanticon. This performance factor can be defined as Q_e, the minimum number of quanta required per picture element per picture to give a minimum perceivable value of R ($R = 1$). These can be read off from Fig. 25 as the horizontal displacement measured in terms of the ratio of Q_p for the various tangent lines and the Quanticon at a given value of T. Expressed mathematically, it is obvious that the equation of the tangential noise limit lines is given by putting $\kappa = 1$ and $\theta = Q_e$ in equation (7), giving:

$$\frac{Q_p}{\frac{4}{3}.(2T)^2} = \frac{Q_e}{(C')^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

These values of Q_e along with Φ, Q_p and T_{max} and other constants of the system referred to above, are given in Table 1. Note that the eye has a value of Q_e of the order of 200 quanta per picture element per picture under the particular conditions of adaptation specified, and at the other extreme a photographic plate has a value of 2×10^5.

It must be remembered that the curves in Fig. 25 and the data in Table 1 for the 35-mm motion picture, the image orthicon television system and the Quanticon, are for one complete picture only. When the picture is viewed, however, persistence of vision will integrate about five consecutive pictures, so that about five times as many quanta are needed to satisfy the viewer. The ratio between these systems shown by Q_e will remain unchanged, but the eye and the quarter-plate camera will show a relative improvement of five times.

The Quanticon is unique in Fig. 25 and Table 1 in that its maximum resolving power T_{max} and highlight brightness B are coincident and lie on the noise limit tangent. This implies that the device is entirely noise-limited and has no finite-sized "receptors" or "aperture limit." It would be a useful extension of its behaviour to incorporate idealized limits of this type, which should result in the characteristic bending away from the noise tangent and flattening off as brightness is increased and limiting resolution is approached, but not showing any "highlight droop," of course, as do the practical curves. The maximum resolving power shown by the peaks of the curves for the practical systems in Fig. 25 are not their T_{max} values in Table 1. These were obtained from the high contrast ($C' = 0{\cdot}97$) data. Only a Quanticon could be expected to achieve this, and then only if it were further endowed with an unlimited brightness range.

4.3. *The Brightness, Modulation or Transfer Characteristic*

The transfer characteristics of the various systems tested are shown in Fig. 20. It is obvious that the curve for the quarter-plate photographic print is outstandingly different from the remainder and, furthermore, this difference is of a kind which at first sight would appear to put it at a disadvantage due to the restricted brightness range of the reproduction. However, the picture quality obtained from this system is, in

TABLE 1

Factors Relating to the Performance of Certain Picture Reproducing Systems

Pick-up Device	T_{max}	B	A	N	Φ	t_p	Q_p	Q_e
(a) Eye	600	10	$2{\cdot}6\times10^{-4}$*	4·0	$3{\cdot}0\times10^{-5}$	$\frac{1}{5}$†	$7{\cdot}8\times10^{10}$	2×10^2
(b) Quarter-plate Camera ..	>680	325	$9{\cdot}6\times10^{-2}$	4·5	$1{\cdot}7\times10^{-1}$	$\frac{1}{10}$	$2{\cdot}2\times10^{14}$	2×10^5
(c) 35-mm Motion Picture Camera	450	160	$3{\cdot}4\times10^{-3}$	4·0	$6{\cdot}4\times10^{-3}$	$\frac{1}{48}$	$1{\cdot}7\times10^{12}$	2×10^4
(d) Image Orthicon Camera (Type 5655)	220	50	$8{\cdot}0\times10^{-3}$	5·6	$2{\cdot}3\times10$ [illegible]	1	$1{\cdot}2\times10^{12}$	7×10^4
(e) "Quanticon" ..	280‡	—	—	—	$5{\cdot}5\times10^{-8}$§	$\frac{1}{25}$	$9{\cdot}8\times10^{6}$¶	1

Note.—Value of Φ and Q_p is for highlight brightness B (B arrows in Fig. 25).
Value of Q_e is the minimum for each system (A arrows in Fig. 25).

* For a focal length of 17 mm and a viewing distance $4 \times H$.

† The eye is assumed to integrate over this period.

‡ Calculated from 625-line example given.[18]

§ At $\lambda = 550$ mμ. Reduced from figures of $2{\cdot}4 \times 10^{-5}$ (Ref. 18) to conform with reduction of R from 100 to 4·8 (i.e., $C' = 0{\cdot}21$).

¶ At $\lambda = 550$ mμ. 1 lumen = $4{\cdot}43 \times 10^{15}$ quanta/sec.

most respects, superior to that of the others. These two facts therefore require reconciliation.

The relationship between contrast, brightness and resolution in Figs. 10-11 shows that for a given degree of visibility and resolving power, the eye is capable of exchanging a reduction in contrast for an increase in brightness. This leads naturally to the suggestion that the improvement in visibility in the reproduction over the original, shown, for example, by comparing the result of viewing the quarterplate reproduction with the same conditions of direct viewing (Figs. 10(b), 12(b), $C'=0{\cdot}21$, $4 \times H$) in the region of brightness $B/8$, is due to an improvement in the brightness/contrast combination in the reproduction (see Fig. 28c). The transfer characteristic of the quarter-plate system (Fig. 20a) does, in fact, lie everywhere above the hypothetical straight-line/unity-gamma characteristic except at the point of intersection, viz. the highlight brightness B. The reduction in slope at the "toe" of the curve, giving reduced contrast in the reproduction in these regions, is to some extent compensated by the higher brightness at which they are reproduced. In the middle range of brightnesses, where the slope of the curve equals or is even greater than the straight line characteristic, over-compensation will obviously occur, thus accounting for the improvement of the reproduction over the original in this range of brightness.

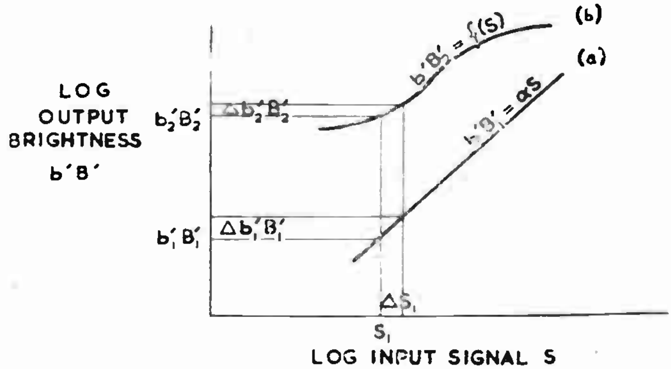


Fig. 26.—Diagram showing effect of (a) linear, and (b) arbitrary transfer characteristics on reproduction of the same input signal.

Considering the idea in more general terms, supposing a pick-up device generates a signal S directly proportional to all the brightnesses in the original scene, and that this is applied to two reproducers having the arbitrary characteristics shown in Fig. 26: (*a*) is a linear, unity-gamma (45 deg. inclination) characteristic, and (*b*) is representative of the characteristics in Fig. 20. Suppose α in (a) is chosen so that for this characteristic all the reproduced brightnesses are equal to the original when viewed direct.*

Consider a small increment in brightness having a certain degree of visibility in the original and producing an increment ΔS_1 in a signal S_1. Characteristic (*a*) will reproduce an increment $\Delta b'_1B'_1$ at a brightness of $b'_1B'_1$ which will be equal to, and therefore just as visible as the original provided that the resolution and noise limitations of the whole system are very small compared with those of the observing mechanism—in this case, the eye. Characteristic (*b*), however, will reproduce the signal and its increment at a higher value of brightness and lower value of contrast as shown—$b'_2B'_2$ and $\Delta b'_2B'_2$ respectively. B'_1 and B'_2 are, of course, the respective reproduced highlight brightnesses of the two characteristics. It has been suggested above that a value of $\Delta b'_2B'_2$ can be found which will make the reproduction of ΔS_1 by the distorted brightness characteristic (*b*) equally as visible as in (*a*) or in the original.

Suppose the detecting device (eye) is operating at a low brightness so that it is limited entirely by random fluctuation conditions of the type already discussed in the previous section. Then the just deetctable increment $\Delta b'_1B'_1$ at brightness $b'_1B'_1$ will be proportional to $(b'_1B'_1)^{\frac{1}{2}}$. Similarly $\Delta b'_2B'_2$ will bear the same ratio to $(b'_2B'_2)^{\frac{1}{2}}$. Taking this to the limit it may be written:

$$\frac{d(b'B'_1)}{(b'B'_1)^{\frac{1}{2}}} = \frac{d(b'B'_2)}{(b'B'_2)^{\frac{1}{2}}} \qquad \text{(11)}$$

Integrating gives:

$$(b'B'_2)^{\frac{1}{2}} = (b'B'_1)^{\frac{1}{2}} + \beta$$

Substituting $f(S)$ and αS as given in Fig. 26:

$$f(S) = \left[(\alpha S)^{\frac{1}{2}} + \beta\right]^2 \qquad \text{(12)}$$

* It is presumed that the illumination on a scene may be artificially increased for reproduction purposes in order to improve signal/noise, for example. This does not invalidate the comparison of the reproduction with the original, the latter being viewed at its normal brightness. To conform with the standardized procedure adopted in the present experimental work, the reproduced and original brightnesses are assumed the same for characteristic (a).

This may be plotted as a family of transfer characteristics as shown in Fig. 27, which will all give the same degree of visibility in the reproduction—with the stated provisos regarding signal/noise, etc. The similarity of the curves lying above the basic linear characteristic and the toe of Fig. 20(a) is immediately obvious. Incidentally, the shape of this family of curves plotted on linear axes, also shown in Fig. 27, is rather surprising, and suggests that it is unlikely that a practical transfer characteristic could have the exact form of one of these curves over an extended brightness range.

So far, the value of α in equation (12) has been specified as the unique value necessary to make (a) in Fig. 26 reproduce all the original brightnesses unchanged. The family of characteristics in Fig. 27 is produced by varying the value of β, which leaves the degree of visibility of all parts of the original unchanged in the reproduction—although their brightness and contrast may be different.

Consider now the effect of variation of α on the degree of visibility. As variation of β for a given value of α produces no change in visibility, it is convenient to put it equal to zero, thus reducing equation (12) to

$$b'B' = \alpha S \qquad \text{(13)}$$

Differentiating gives:

$$d(b'B') = \alpha dS \qquad \text{(14)}$$

so that

$$\frac{d(b'B')}{(b'B')^{\frac{1}{2}}} = \alpha^{\frac{1}{2}} \frac{dS}{S^{\frac{1}{2}}} \qquad \text{(15)}$$

This means that, for any given value of S and dS the left-hand side of the above equation will increase with α, thus giving a bigger increment of the reproduced brightness than that required to give constant visibility discussed above. As the brightness of the reproduction is increased (by increasing α), smaller increments of the original brightness will be detectable. This is, of course, a well-known effect, and results in noise and graininess becoming more visible on the picture as brightness is increased.[10] It must be emphasized, however, that the above equation only applies strictly when the original signal and the reproducing system are noiseless. The case when they are noisy will not be discussed here. It can be shown that an increase in α will still give the same effect in the reproduction, but to a lesser degree, according to the proportion of other noise present.

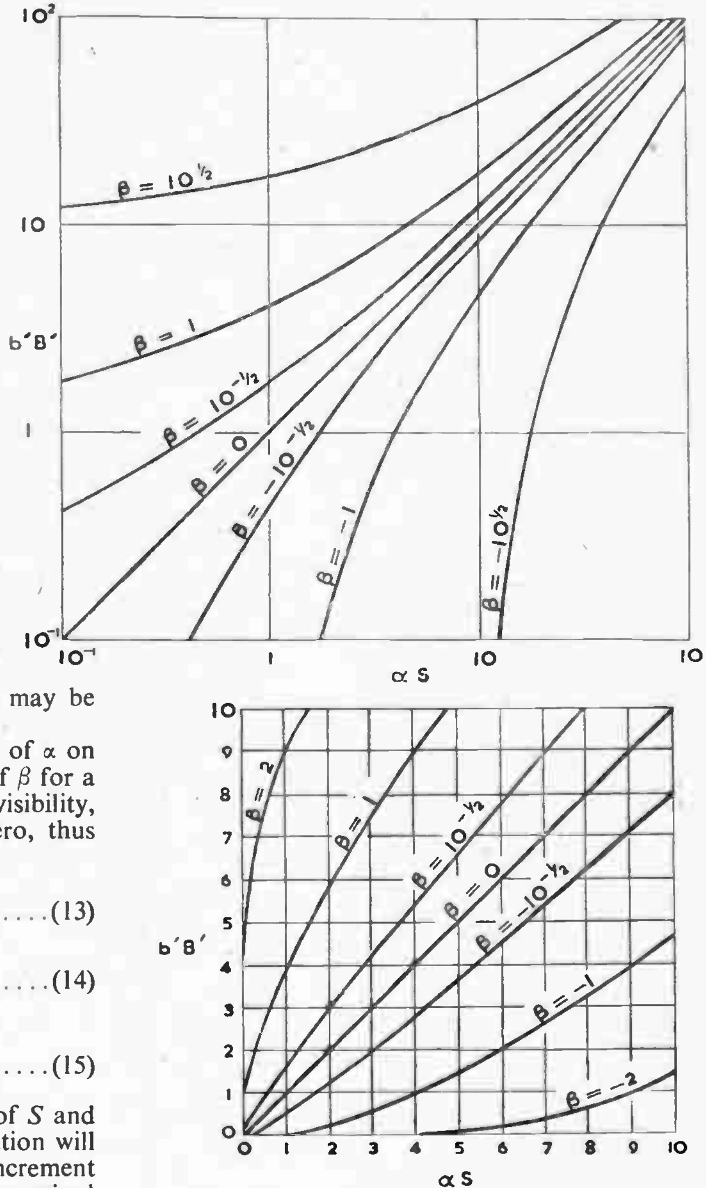


Fig. 27.—Log/Log and Linear/Linear plots of $b'B' = [(\alpha S)^{\frac{1}{2}} + \beta]^2$ *for various values of* β.

By suitable choice of α and β it is possible to make equation (12) tangential to any given transfer characteristic at any point. The value of α obtained for this point has been shown to be a measure of the improvement or otherwise in visibility in the reproduction, compared with the original. By substituting bB, the input brightness, for S in equation (12) it is obvious that $\alpha = 1$ corresponds to no change in visibility in the reproduction compared with the original. Values of $\alpha > 1$ will correspond to more being visible in the reproduction than the original, and $\alpha < 1$ to the reproduction showing less than the original. The values of α for various points on the transfer characteristics of the quarter-plate and 35-mm motion picture projection (Fig. 20(a) and (b)), have been determined by ting equation (12) tangentially to the transfer characteristics at these points, using a graphical method. The values of α derived in this way are shown plotted in Fig. 28, over the range of input brightnesses. It will be seen that on this basis of comparison the quarter-plate print gives much higher values than the 35-mm projection at the lower brightnesses, despite the fact that the latter has a brightness range of 45/1 in the reproduction compared with only 20/1 in the former. This is entirely in agreement with the observer data in Figs. 12 and 13. At the highlight end of the curves, Fig. 28 shows the quarter-plate print to be much inferior, but here it must be remembered that the special noise-limited conditions assumed in the above argument no longer apply. In this region the limiting resolution of the systems is more likely to be the dominant factor, and this is borne out by Figs. 12 and 13—again to the advantage of the quarter-plate reproduction. Technically, therefore, the quarter-plate photograph is shown to be a superior system of picture reproduction, striking an excellent compromise between the factors limiting its performance.

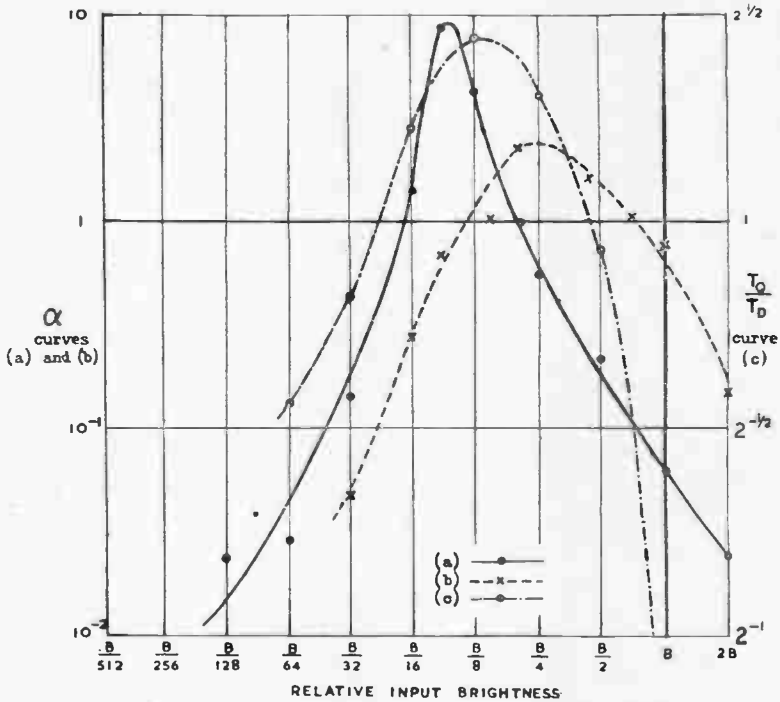


Fig. 28.—Values of α required to make $b'B' = [(\alpha S)^{\frac{1}{2}} + \beta]^2$ coincident with and tangential to the experimental curves given in Fig. 20, at every point, by putting $S = bB$.

(*a*) Quarter-plate print.

(*b*) 35 mm Motion Picture Projection.

(*c*) Ratio of Resolving Power of $\frac{\text{Quarter-Plate Print (Fig. 12}b\text{)}}{\text{Direct Viewing (Mean Figs. 10}b/11b\text{).}} = \frac{T_Q}{T_D}$ at $4 \times H$ and $C' = 0{\cdot}21$. (Average of three criteria.)

For comparison purposes, the ratio of the averaged resolving power of the quarter-plate reproduction and the direct viewing tests, for a viewing distance of $4 \times H$ (Figs. 12(b) and 10(b)) have been calculated for the range of input brightness, and plotted on an appropriate scale in Fig. 28. It will be seen that, at the lower brightnesses, although the units are different, the general agreement with the "α" curve for the quarter-plate (curve (a)) is very good.

In practice the eye is not asymptotic to a noise limit alone at low brightness. It also has a minimum brightness limit (Fig. 23). Some separate tests carried out on the observer team showed that this minimum was approximately $B/900$ for $C' = 0{\cdot}97$ and $T = 9$ and 18 test lines/picture height, other conditions being as in Figs. 10 and 11.

4.4. *Viewing Distance*

The importance of viewing distance on picture quality cannot be sufficiently stressed. As has already been stated, the difference between the original and the reproduction becomes progressively less as viewing distance is increased. At the other extreme, the effect of the observer's vision on quality becomes less important as viewing distance is reduced until, on close inspection, the limitation is almost entirely in the reproducing system. In attempting to define standards of reproduction, therefore, it is essential to agree a minimum viewing distance. It is then only necessary to satisfy the viewer at that distance—in fact it is wasteful to do more. Comparison of row (a) with row (b) in Fig. 13 shows how much fine detail present on a 35-mm film is lost to the viewer at a viewing distance of four times the picture height and, in fact, need never have been recorded as far as he is concerned. With the television systems shown in Figs. 14, 15, 18 and 19, however, there is hardly any difference between rows (a) and (b) largely due no doubt to the sharp frequency cut-off. For the same reason the three curves for the different criteria are bunched together at the maximum resolution point with the highest contrast test object, in the case of television, whereas they are practically parallel to each other for 35-mm film. Comparison of performance on the basis of limiting resolution at close inspection is therefore most unfair to a well-corrected television system.

The best seats (at the front of the circle) in a modern cinema are usually at about four times the picture height from the screen. The rearmost seats are, in the author's experience, never greater than, if as great as, eight times picture height away. By common consent, the figure of $4 \times H$ is becoming the generally accepted minimum for judging picture quality, and whilst it may be argued that this distance is greatly exceeded at present with domestic television viewing, it seems wise to make provision for the future when larger pictures will no doubt reduce it to this figure. Certainly there appears to be no reason for going below this value.

Both the direct viewing experiments (Figs. 10-11) show an important anomaly of vision associated with viewing distance. Assuming that visual acuity is independent on viewing distance and apparent size of test object, it would be expected that the resolving power of the eye expressed in test lines/picture height would be exactly halved in going from $4 \times H$ to $8 \times H$. Examination of the data shows that in fact it varies from nearly 2/1 at high contrast, low visibility down to $1\frac{1}{2}/1$ at low contrast, high visibility, i.e., acuity improves with increasing viewing distance. Freeman[19] observed a similar effect with the same order of magnitude for the viewing distances used in the present experiments. In an extensive series of carefully executed experiments he was unable to find an explanation. It is obviously of sufficient magnitude to be important in the present field of investigation. Picture size will have to be treated as a variable as well as relative viewing distance. The implication is that higher standards of reproduction are required for larger pictures, and it is consistent with the fact that small pictures, e.g., on a television camera monitor, usually "look good."

As has already been stressed, in the tests on reproducing systems the data for $4 \times H$ and $8 \times H$ is a combination of that of the system alone and the average observer's eye. A good approximation to the former is obtained from the $0 \times H$ tests on the system, and the latter is given for $4 \times H$ and $8 \times H$ in Fig. 10. It is useful to see if there is any simple relationship between them. Cawein[20] has suggested that the resolving power of systems in cascade may conform to the formula:—

$$\frac{1}{T_1^2} + \frac{1}{T_2^2} = \frac{1}{T_3^2} \qquad \text{.................(16)}$$

where T_1 and T_2 are the limiting resolution of two systems in cascade, and T_3 is the resultant (all expressed in test lines/picture height). If T_1 is taken as the performance of the eye at $4 \times H$ (Fig. 10(b)), T_2 as that of any of the reproducing systems at $0 \times H$, then T_3 is the calculated value for the same system viewed at $4 \times H$ according to the above equation. This can be compared with the actual experimental value (T_4), obtained from $4 \times H$ curves for the system. A number of such calculations have been carried out, and representative sets of results are shown in Fig. 29. It is important to remember that in equation (16) if either T_1 or T_2 is very small with respect to the other, it will dominate the equation and control the value of T_3. In Fig. 29, therefore, the ratio of the experimental to the calculated value (T_4/T_3) has been plotted against the ratio of T_2/T_1 in order to reveal this effect if present. The validity of the equation

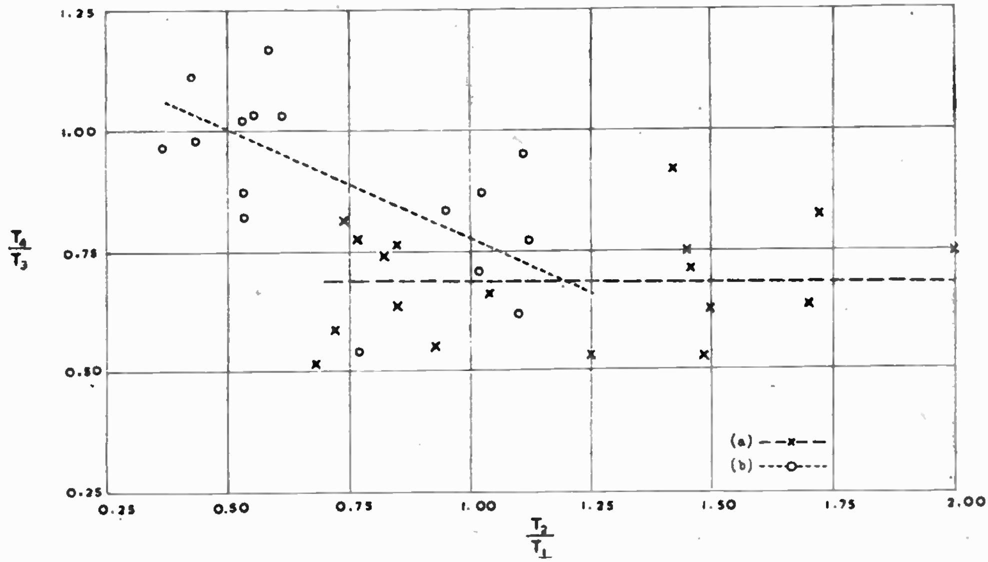


Fig. 29.—Comparison of experimental values of resolution for system plus observer at 4 × H (T_4) and values calculated (T_3) from system alone at 0 × H (T_2) and observer alone at 4 × H (T_1) using formula

$$\frac{1}{T_1^2} + \frac{1}{T_2^2} = \frac{1}{T_3^2}$$

(a) Data from 35-mm film projection.
(b) Data from 625-line Image Orthicon chain.

will only be established if $T_4/T_3 = 1$ in the region where T_2/T_1 is close to unity. From the results shown in Fig. 29, and others not plotted, there is little evidence in favour of equation (16), which is probably not surprising in view of the widely differing ways in which reproducing systems approach limiting resolution, e.g., the sharp cut-off in television and the gradual falling-off in photography.

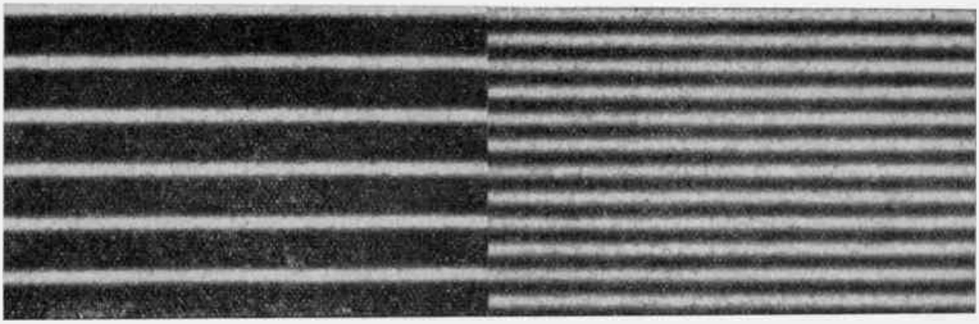
It does not seem possible at this stage, therefore, to calculate the performance of a system at a given viewing distance from the data for the system alone ($0 \times H$) and standardized data for the average observer at the same viewing distance. It appears necessary for the average observer to operate direct on the system at the required viewing distance. This is discussed further in Section 5.1.

4.5. *Spot Wobbling*

The revival of this scheme for direct television reproduction is largely due to the fact that the techniques involved have only recently reached the required degree of perfection. High focus quality and uniformity, coupled with vertical scanning linearity, are necessary in order that the "dual lines" shall superimpose accurately in successive fields of the interlace. Any degradation in these factors will result in inferior picture quality when spot wobbling is applied, with consequent condemnation of the idea. Properly engineered, however, it is very attractive and generally approved by the viewer. Photographs of a few lines each of single and interlaced fields on a receiver tube with and without spot wobbling are shown in Fig. 30.

The figures of 10 per cent loss in vertical, and 5 per cent gain in horizontal, resolution quoted in Section 3.5 are obviously inside the random variation limits of ±11 per cent relative accuracy determined in Section 4.1. From this it can be concluded that the application of the spot wobbling produces no significant degradation greater than 11 per cent resolution. This possibility seems a small price to pay for the advantages gained in reducing the visibility of line structure, etc.

It is somewhat surprising at first to find there is not a measurably greater reduction in vertical resolution. This may be due to any or all of the following:

(a)  (b)

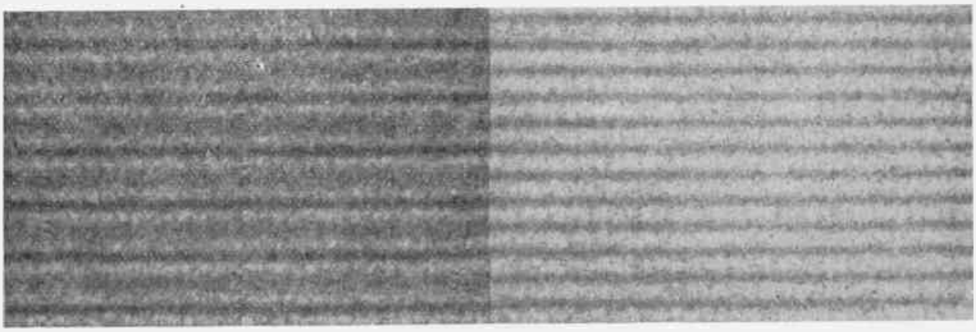
(c)  (d)

Fig. 30.—Photographs of single field and 2/1 interlaced fields with normal scanning and with superimposed spot oscillation.

(*a*) *Normal scanning. Single field.* (*b*) *Normal scanning. Interlaced fields.*
(*c*) *Vertical spot oscillation. Single field.* (*d*) *Vertical spot oscillation. Interlaced fields.*

(*a*) Vertical aperture size is increased only in the receiver.

(*b*) At 405-line (or greater) definition and at a viewing distance of $4 \times H$ (or greater) spot wobbling will have little or no effect on low contrast detail or on a high degree of visibility (e.g., C/V), since resolving power under these conditions is already approaching the limitation of the observer's eye.

(*c*) The addition of spot wobbling does not double the size of the vertical scanning aperture if spot diameter is decreased below normal line width at the same time.

The choice of the number of lines for a television system depends to some extent on the appearance of "lininess" in the received picture. With interlaced scanning the greatest degree of lininess visible is that due to a single field such as Fig. 30(a), which becomes apparent as soon as there is vertical motion of the observer's eye. This structure is almost exactly that of a high contrast resolution pattern used in the work under discussion. From Figs. 10-11(b) at $C' = 0{\cdot}97$, it is seen that such a pattern will only be completely invisible if it contains some 600 test lines/picture height. In the case of the television field under consideration it must contain at least 600 lines, therefore, to appear homogeneous at a viewing distance of $4 \times H$, or about half this number at $8 \times H$. The total number of lines in the picture (two fields) would therefore have to be 1,200 at $4 \times H$ or 600 at $8 \times H$. With the efficient application of spot wobbling the number of apparent lines in each field is doubled, as in Fig. 30(c), so that the above values could be halved. If (c) above is neglected, that is, the line width is not reduced, but made uniform, as in picture telegraphy, then the use of spot wobbling would permit further reduction in the above figures.

As spot wobbling was revived in connection with a special form of film recording (Section 3.5), it should be mentioned that it is not desirable to use it on the recording tube in any system where the complete set of interlaced lines is photographed on a single frame of film. In fact it is necessary to have a sharper scanning spot than is required for direct viewing in order to allow for the degradation in the photographic process. If spot wobbling is required to eliminate beating patterns on re-scanning, it is preferable to apply it to the flying-spot transmitter tube. This will, of course, probably necessitate the provision of an alternative degree of afterglow correction when this system of scanning is used.

4.6. *Colour*

In Section 3.1.1 it has been shown that, as far as the eye is concerned, there is nothing to choose in resolving power between a white or a tricolour red or green test object. For a tricolour blue, however, resolving power is decreased considerably. This is a well-known phenomenon, but it is useful to have the magnitude of the effect expressed in terms of the present method of measurement, as shown in Fig. 9. So far, only one value of contrast has been used in these experiments—$C' = 0{\cdot}44$—representing a brightness ratio between light and dark test lines of $r_p = 1{\cdot}78$. The results indicate that a reproducing system should be capable of showing the same amount of detail in a white, red, or green object, and, by assumption, any degree of desaturation of these colours, or of their mixture—yellow. With the blue object, however, a considerable reduction in the amount of detail should be tolerable if it is fully saturated in colour, with a gradual increase as it is desaturated or mixed with red or green. Advantage was taken of this in an early version of the R.C.A. simultaneous colour television system,[21] where definition in the blue channel was deliberately reduced to economize in video bandwidth.

The results shown in Fig. 9 are in full agreement with a similar investigation by A. V. Bedford[22] who used a different type of test object, but at high contrast only. He extended his range of test patterns to cover mixed coloured lines, showing that red/green acuity under certain conditions was just under half that of white/black, green/black or red/black. Green/blue and red/blue were of the same order of magnitude as blue/black, i.e., about one-quarter of white/black.

Some recent proposals for "band saving" in colour television, particularly in the U.S.A., are based on the idea that the eye cannot see fine detail in colour, and therefore it is only necessary to transmit the higher video frequencies in monochrome. Whilst this may be true, it is felt that the type of experiment so far discussed in this Section does not provide the necessary proof. To justify the scheme, it would be necessary to present the observer with coloured test objects and include naming the colour as part of the observer data. It would seem wise, therefore, to be conservative in estimating the amount of band saving which can be attained in systems where detail in large areas of a given colour is converted into black and white. There is, at least, one proposal which does not suffer from this defect. The whole problem of colour reproduction obviously needs further investigation before definite conclusions can be drawn. An investigation of the permissible degree of misregistration of primary images, for example, would be of great interest.

5. Conclusions

At this point it is necessary to stress an important issue regarding the appraisal of any form of reproducing system. No system of measurement, physical or subjective, can be taken as suitable for grading reproduction quality until experience has shown that it agrees with the *opinions* of those who regularly use or enjoy it. It is nonsensical to grade the performance of motor cars in terms of their maximum speed, when the user is interested in such factors as acceleration, comfort at cruising speed and miles per gallon. It is not claimed, therefore, that the present series of experiments has automatically produced a set of numbers which will set standards for, or grade the quality of, picture reproducing systems. This is only justified when good correlation is established between any of the data and actual observed reproduction quality.

The present investigation arose mainly because of the lack of agreement repeatedly encountered between simple and limiting resolution tests, step-wedge brightness measurements, and the actual picture quality observed. It was felt that more information would be of value, particularly regarding contrast and its simultaneous variation with brightness and resolution. The experiments have produced a method of determining the total amount of information reproduced, and a better understanding of certain factors affecting quality. For example, comparison of Figs. 13(b) and 10(b) shows that 35-mm motion picture projection produces a standard of reproduction which is approximately half that attainable by the eye alone. This indicates that the average observer is a lazy individual, who is content to run his visual pick-up equipment at "half-throttle" when enjoying a visit to the cinema. Other typical relationships which have already been discussed are the ability to exchange brightness for contrast in the reproduction (Section 4.3), and the interaction of the noise and resolution limits (Section 4.2).

An extensive examination of the data has been made, including numerous graphical and tabular cross-sections. Many useful correlations have been obtained, but the results are far too detailed for discussion here, except for a few of the more important issues.

5.1. *Test Methods for Evaluating Picture Quality*

No attempt was made during the experiments to use the observer team to carry out direct picture appraisal. Obviously it is necessary to have some degree of appraisal in order to examine the correlation of the data. The following, therefore, is a coarse gradation by the authors* of the picture qualities of the systems tested:

(1) *Quarter-Plate Print.*—Definition and tone gradation excellent. No sensation of brightness limitation except that the picture appeared less contrasty than the other systems.

(2) 35-*mm Motion Picture Projection.*—Adequate at normal viewing distance. Close inspection revealed lack of sharpness, graininess, etc. At maximum viewing distance (8 × *H*) reproduction was entirely adequate.

(3) 405-*line Flying-Spot C.R.T. Film Scanner viewed on* 20-*in Aluminized Monitor C.R.T.*—Adequate at normal viewing distance; no apparent loss of quality compared with (2)—in fact, tone rendering in shadows was slightly better. Line structure and stroboscopic interlace effects were very noticeable. On close inspection the latter became much worse, and picture noise became visible. At 8 × *H* all these defects disappeared, except line break-up.

(4) *As* (3) *with the addition of* 10 *Mc/s Spot Wobbling.*—No obvious loss of sharpness compared with (3), except occasionally on an object moving vertically at line crawling speed. The annoyance of line structure and interlacing effects was reduced below the threshold of irritation at normal viewing distance. Generally preferred to (3).

(5) 625-*line Image Orthicon Camera* (*Type* 5655) *on* 15-*in Monitor C.R.T.*—Sharp by a conventional resolution chart, but the picture lacked crispness and was noisy. On a switch-over comparison, the difference between the 4 and 6 Mc/s channels could be detected at normal viewing distance (4 × *H*), but unless the change-over was made abruptly it was impossible to differentiate between the two on programme material.

Summarizing these comments, the quarter-plate print was obviously the best quality picture. The 35-mm film projection and the two variations of the 405-line film scanner were next in a group by themselves. The 625-line Image Orthicon picture was placed last. The step between it and the 35-mm film group was considered to be much less than that between the latter and the quarter-plate print.

Now consider the relation between these comments and the experimental results. On the basis of the transfer characteristics shown in Fig. 20, the order of performance can be graded in terms of the output brightness range r'_t. This puts the 405-line telecine picture first, then the 625-line image orthicon, 35-mm film projection, and the quarter-plate print very obviously last.

On the basis of Figs. 12-19 a very wide choice of method can be made. The classical system has always been to use a high contrast highlight-brightness test object, close inspection of the reproduction, and limiting resolution (N/J criterion). This represents only a single point on one of the seven or more three-dimensional surfaces of the type illustrated in Fig. 23, which are available for each system from the present experimental data. It would appear to be too much to expect that a single measurement made under specified conditions would suffice to define a system performance. Detailed examination of the data does indicate, however, a large

* See Section 4.1, paragraph 3, second sentence.

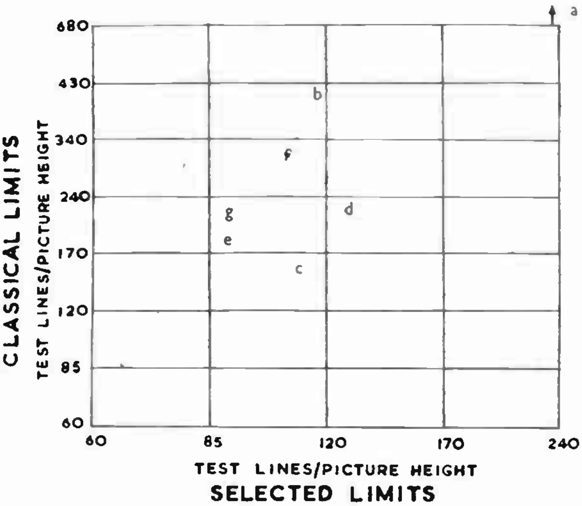


Fig. 31.—Comparison of the Limits of Resolution under "Classical" and "Selected" conditions of test.

Classical Conditions—Viewing Distance 0 × *H*; *Visibility Criterion* N/J; *Contrast C′* = 0·97; *Brightness B.*

Selected conditions—Viewing Distance 4 × *H*; *Visibility Criterion* J/V; *Contrast C′* = 0·21; *Brightness B*/4.

(*a*) *Quarter-plate print.* (*Classical Limit* > 680) (*Fig.* 12)
(*b*) 35-*mm Motion Picture* (*Fig.* 13)
(*c*) 405-*line Telecine. Horizontal Test Lines* (*Fig.* 14)
(*d*) 405-*line Telecine. Vertical Test Lines* (*Fig.* 15)
(*e*) 625-*line Image Orthicon. Horizontal Test Lines.* (*Fig.* 18)
(*f*) 625-*line Image Orthicon.* 6 *Mc/s. Vertical Test Lines* (*Section* 3·6)
(*g*) 625-*line Image Orthicon.* 4·5 *Mc/s. Vertical Test Lines* (*Fig.* 19)

zone where the order of performance of the systems is the same as the authors' gradation above. The centre of this zone is represented by a low contrast test object, viewed at normal viewing distance (4 × *H*) in the reproduction, at a brightness of *B*/4. Practically all the results show a resolution maximum for each curve in the region of this brightness, which incidentally corresponds to the brightness of the object of principal interest according to measurements made by motion picture engineers.[8] The use of low contrast test objects is receiving increasing attention from the photographers, and is supported by the discussion in Section 4.2, if noise limitation is considered important. Rose[16] says: "In the judgment of picture quality, the eye attaches little weight to the picture elements in the neighbourhood of limiting resolution," which may be interpreted as supporting the use of normal viewing distance instead of limiting resolution by close inspection (0 × *H*) as in the classical test.

The selected conditions of test just described are shown plotted against the classical conditions for the various systems in Fig. 31, and it is instructive to compare the order of merit from the two different sets of criteria with that from the transfer characteristics and from the authors' appraisal, as shown in Table 2. Further investigation may show that one or two "selected" tests may prove more reliable than the classical limiting resolution test.

The particular selected test just discussed introduces a serious practical difficulty for the engineer who wishes to use it. It requires a team of observers to carry it out. An important requirement, therefore, is the development of an "Electronic Observer", along the lines of the "Physical Eye" already achieved by the photometrists. This raises some interesting points for consideration, not the least of which are the way in which the average eye assesses different brightness distributions in a reproduced resolution test pattern and the degree to which the eye

TABLE 2
Order of Merit of System Performance

System	Classical Limits (Fig. 31)	Selected Limits (Fig. 31)	Output Brightness Range r_t' (Fig. 20)	Authors' Appraisal
Quarter-Plate Print	1	1	4	1
35-mm Motion Picture ..	2	2/3	3	2/3
405-line Telecine	4	2/3	1	2/3
625-line Image Orthicon ..	3	4	2	4

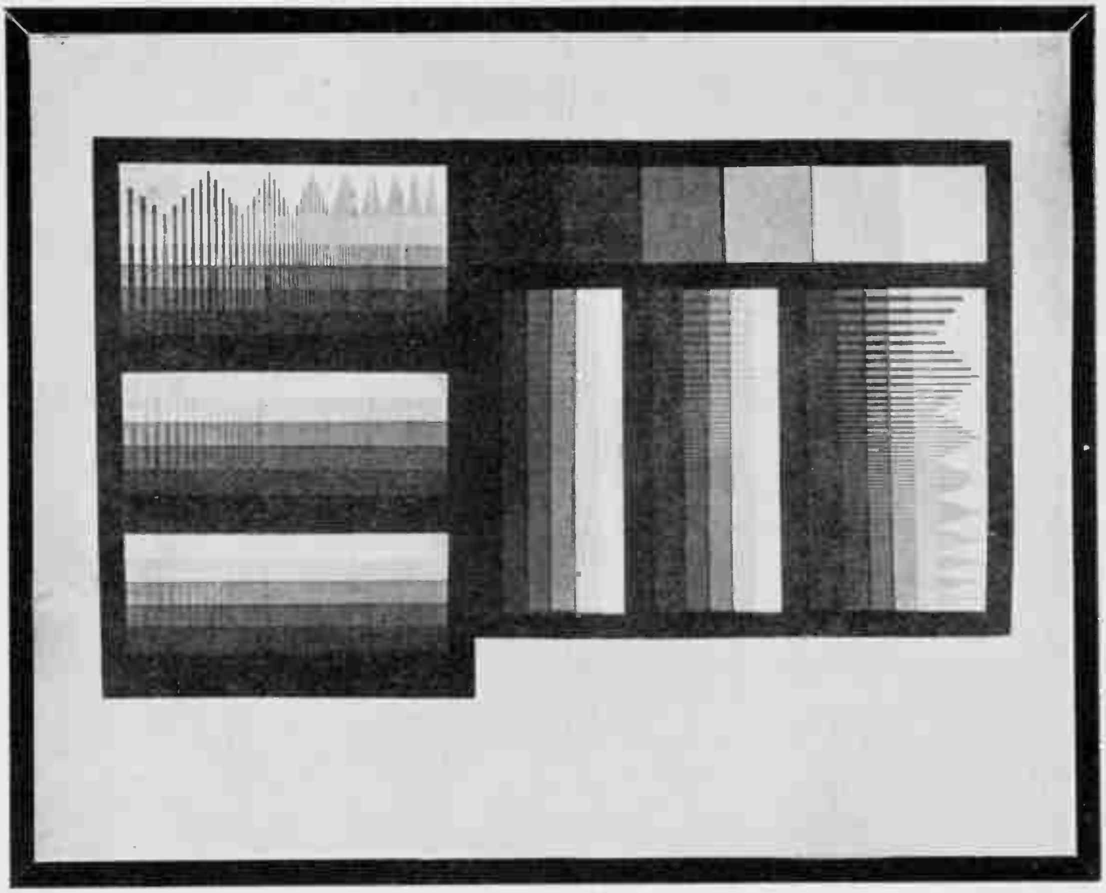


Fig. 32.—Single test object incorporating the combined variable brightness, resolution and contrast over the range used in the individual test patterns (Figs. 4, 5).

can follow picture unsteadiness. Undoubtedly useful relative data can be obtained by a single observer making observations under "selected" conditions, provided he has no abnormality of vision. There now appears to be a requirement for agreement and standardization of observer data of the type shown in Figs. 10-11, which would seem to be a matter ultimately for the C.I.E. Additional information is also required in terms of "just perceptible steps" in order that the different regions of the brightness/resolution/contrast space may be properly scaled for comparison. This may have considerable bearing on band saving technique in future television systems. It is already obvious from Figs. 10-11 that the eye does not require the transmission of maximum detail at low brightness and contrast.

A single test chart which covers the complete range of all the test patterns used in the present experiments is shown in Fig. 32. Such a chart has most of the disadvantages discussed in Section 1. For example, it relies on uniform response over the picture area and it has a very unsatisfactory adapting field, the adjacent brightnesses of the pattern creating local adapting conditions for each other. However, it has proved useful for rough preliminary checks indicating, for example, the range of the variables required for more careful exploration with the individual test patterns (Figs. 4-5). Used indiscriminately it can be most misleading, however, and its inclusion here is mainly as a warning to the uninitiated of what not to do!

Before leaving the question of test procedure, it is necessary to remember that whatever choice is made, it is always possible to find a system which will give false readings of quality. For example, a television system with excessive H.F. peaking will reproduce a resolution chart producing the same basic frequency as that of the peak with great clarity. There will be obvious defects in normal picture reproduction however. Such spurious effects have to be carefully interpreted—mainly by the application of commonsense.

5.2. *Television Standards*

The following is an illustration of a method of applying the type of data obtained from these experiments to the determination of television standards for adequate "home" or "theatre" viewing, on purely technical grounds. There seems to be no hope of settling such an issue entirely on this basis, which neglects the very important economic and political aspects of the problem. Nevertheless it is essential that the technical factors should be clearly understood.

As has been stated, it is not possible to deduce absolute quality from measurements without introducing the characteristics of the observer to calibrate them. It is, however, possible to compare qualities in terms of measurements. It is proposed, therefore, to attempt (once more) to equate the quality of 35-mm motion picture reproduction to a hypothetical television picture and evaluate its standards.

It will be generally agreed that some of, if not the best television picture quality so far demonstrated, irrespective of scanning standards, etc., is from 35-mm flying spot telecine equipment. It is suggested, therefore, that for a system using spot wobbling, comparison of the data in Figs. 16-17 with Fig. 13 will not be in any way unfair to the conclusions regarding the television system.

Comparison of Figs. 13(*b*), 16(*b*) and (*c*), and 17(*b*) and (*c*), shows that at a viewing distance of $4 \times H$ the 405-line television system is generally worse than 35-mm film, and at $8 \times H$ it is better, if it is assumed that the picture seen at the greater distance is half of a picture of twice the height—i.e., viewed at $4 \times H$. It is possible by interpolation to find a viewing distance for the television picture which will give equivalent performance to the film at any given value of contrast and brightness. A correction has to be made for the anomaly of vision discussed in 4.4 by which visual acuity varies with actual viewing distance. The results of such a calculation, including the estimated correction, are shown in Table 3, for a number of selected conditions. A brightness of $B/4$ has been chosen throughout for the same reason as in Fig. 31.

It will be seen from Table 3 that so long as only low contrast is considered ($C' = 0{\cdot}44$ or less) a maximum of 580 lines and 5 Mc/s is sufficient to give equality with 35-mm motion picture standards at a viewing distance of $4 \times H$.

TABLE 3

Viewing Distance		Contrast C'	0·97			0·44			0·21		
		Visibility Criterion	N/J	J/V	V/C	N/J	J/V	V/C	N/J	J/V	V/C
$4 \times H$	Equivalent total number of scanning lines		810	820	705	565	465	430	520	515	585
	Equivalent video bandwidth Mc/s		7·9	9·7	6·6	5·2	3·1	3·1	2·9	3·7	—
$8 \times H$	Equivalent total number of scanning lines		520	460	430	415	375	355	380	375	415
	Equivalent video bandwidth.. Mc/s		3·7	3·2	2·7	2·5	2·4	2·4	2·2	2·2	—

If this is increased to 8 × H then 400 lines and 2·5 Mc/s is sufficient. It was shown in Section 4.5 that approximately 600 and 300 lines were sufficient to render line structure defects invisible at these two viewing distances. In round numbers, therefore, with spot wobbling, 600 lines and 5 Mc/s at 4 × H, and 400 lines and 2·5 Mc/s at 8 × H, would be capable of reproducing all the low contrast detail resolvable with 35-mm film projection.

In considering the above statement, it is important to remember the following points:—

(1) The extrapolation of a 405-line system to a higher standard of definition implies a corresponding improvement in signal/noise and reduction in camera and receiver scanning spot sizes. These, in turn, may necessitate an improved design of camera tube (which may not be attainable), an increase in studio illumination, and an increase in radio transmitter power.

(2) The data given in Table 3 are based on a single negative/positive process for the film, whereas in practice a dupe negative is always prepared for printing the release prints, thus introducing further photographic degradation; the television system used was a closed-circuit system, not involving a radio link. Final engineering standards must be based on practical conditions, so that the above figures should be taken as representative of the region in which such practical tests should be carried out.

(3) Table 3 shows that reproduction of maximum contrast detail requires about 800 lines, 9 Mc/s at 4 × H. More evidence is required that the low contrast criterion is sufficient.

(4) The limits of $\pm 13\frac{1}{2}$ per cent. for the absolute accuracy of the data evaluated in Section 4.1 apply to Table 3.

(5) The choice of television standards, particularly the number of lines, sets the maximum standard attainable when perfection of all system components is achieved.

The relation between choice of television standards and the requirements of television recording (tele-film) is an important issue. There is progressive deterioration of quality in every process of reproduction however small, so that the production of a satisfactory standard of play-back necessitates the generation of a signal which is initially sufficiently superior. This point is well illustrated by Fig. 13, which shows the progressive deterioration of a 35-mm film picture in the order negative, positive, projection, viewing. Complete tests on some experimental film recording systems have been made, but the results have so far been very disappointing. It would be an advantage to start with a television picture of an extra high standard for recording which could be converted down to the normal standards for transmission by some such device as a "Graphechon." Alternatively, it would be preferable to record programmes direct on film with a normal film camera at the same time as they are televised. A combined television/film camera with a common lens turret could be used, suitable cue marks being photographed on the film to facilitate editing. When the same line scanning standard is used for recording and play-back, some form of "photo-electric groove" would be an advantage, so that each individual line of the original recording can be played back without the limitations arising from misregistration on re-scanning, mentioned at the end of Section 4.5. In this case, it would only be necessary to increase the frequency band and reduce the camera scanning aperture in order to take advantage of the above suggestion to generate a higher quality picture for recording purposes. No change in scanning standards would then be required.

5.3. *Programme of Further Investigation*

The results so far obtained are encouraging, and some suggestions for extending the scope of the work have already been discussed. These include the establishment of a "Standard C.I.E. observer"; investigation at lower contrasts and at various picture sizes; determination of just perceptible steps for the variables of depth of focus requirements.

In addition the performance of other systems such as substandard film, large screen television, new television cameras, film recording and colour, need attention. The effect of various types of noise on television pictures requires more fundamental consideration. Electrically generated test patterns would permit individual components of a television system to be tested. The work on edge and corner resolution requires completion.

6. Acknowledgments.

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7. References

1. E. W. Engstrom. "A Study of Television Image Characteristics." Part I. *Proc. Inst. Radio Engrs*, **21**, Dec. 1933, p. 631. Part II. **23**, April 1935, p. 295.
   L. C. Jesty and G. T. Winch. "Television Images. An Analysis of their Essential Qualities." *Trans. Illum. Engng Soc.*, **2**, August 1937.
   M. W. Baldwin, Jr. "The Subjective Sharpness of Simulated Television Images." *Proc. Inst. Radio Engrs*, **28**, No. 10, Oct. 1940, p. 458.
   L. H. Bedford. "Picture Definition." *J. Brit. Kine. Soc.*, **7**, Jan./March 1944, p. 14.
   R. Pinoir. "Le Pouvoir Resolvant Photographique." Centre de Perfectionnement Technique Cours Conferences, Fascicule 1397, March 1945. (Presses Documentaires—Paris.)
   R. E. Graham and F. W. Reynolds. "A Simple Optical Method for the Synthesis and Evaluation of Television Images." *Proc. Inst. Radio Engrs*, **34**, Jan. 1946, p. 18.
   J. L. Delvaux. "Valeurs Numeriques de la Definition des Filmes Cinematographiques—Comparison avec la Television." *Onde élect.*, **28**, Oct. 1948, p. 369.
2. "The Fundamental Research Problems of Telecommunications." (H.M. Stationery Office for D.S.I.R., 1948.)
3. Otto H. Schade. "Electro-optical Characteristics of Television Systems." *R.C.A. Rev.*, **9**, Nos. 1, 2, 3, 4, March, June, Sept., Dec., 1948.
4. E. W. H. Selwyn and J. L. Tearle. "The Performance of Aircraft Camera Lenses." *Proc. Phys. Soc.*, **58**, 1946, p. 493.
5. P. W. Cobb and F. K. Moss. "The Four Variables of the Visual Threshold." *J. Franklin Inst.*, **205**, June 1928, p. 831.
6. Irvine C. Gardner. "A Test of Lens Resolution for the Photographer." U.S. Dept. of Commerce, Nat. Bureau of Standards Publication C428, Dec. 27th, 1940.
   L. C. Martin. "Introduction to Applied Optics," Vol. I, pp. 166-169. (Pitman. 1936.)
7. E. W. H. Selwyn. "The Photographic and Visual Resolving Power of Lenses." *Photogr. J.*, **88B**, 1948, pp. 6-12, 46-56.
8. "Report of Projection Screen Brightness Committee" (Table IV). *J. Soc. Mot. Pict. Engrs*, **27**, No. 2, August 1936, p. 27.
9. Prentice Reeves. "Rate of Pupillary Dilation and Contraction." *Psychological Rev.*, **25**, 1918, p. 330.
   M. Abribat. "Les Contrastes de Brilliances dans la Nature et dans ses Representations." Reunion d'l'Institut d'Optique, April 1935.
10. "Recommended Screen Brightness for the Projection of 35-mm Film." British Standard 1404, 1947.
11. L. C. Jesty, *Nature*, **163**, June 18th, 1949, p. 960.
12. K. Henney and B. Dudley. "Handbook of Photography," Chapter 23—Motion Picture Photography—Carl Dreher. (McGraw-Hill. 1939.)
13. Cie. des Compteurs. British Patent No. 428,926.
14. Cinema-Television, Ltd., and L. C. Jesty. British Patent No. 638,443.
15. D. G. Fink. "Television Standards and Practice." N.T.S.C., pp. 232-3. (McGraw-Hill, 1943.)
16. A. Rose. "A Unified Approach to the Performance of Photographic Film, Television Pick-up Tubes and the Human Eye." *J. Soc. Mot. Pict. Engrs*, **47**, No. 4, Oct. 1946, p. 273.
17. A. Rose. "The Relative Sensitivities of Television Pick up Tubes, Photographic Film and the Human Eye." *Proc. Inst. Radio Engrs*, **30**, June 1942, p. 293.
    A. Rose. "Television Tubes and the Problem of Vision. *Advances in Electronics*, *Vol.* 1, edited by L. Marton. p. 131. Acad. Press Inc., N.Y.
18. L. H. Bedford. "Television Camera Tubes." *Wireless Engineer*, **28**, Jan. 1951, p. 4.
19. Ellis Freeman. "Anomalies of Visual Acuity in Relation to Stimulus Distance." *J. Opt. Soc. Amer.*, **22**, May 1932, p. 285.
20. M. Cawein. "Television Resolution as a Function of Line Structure." *Proc. Inst. Radio Engrs*, **33**, Dec. 1945, p. 855.
21. R. D. Kell, G. C. Sziklai, R. C. Ballard, A. C. Schroeder, K. R. Wendt, and G. L. Fredendall. "An Experimental Simultaneous Colour Television System." *Proc. Inst. Radio Engrs*, **35**, Sept. 1947, p. 861.
22. A. V. Bedford. "Mixed Highs in Colour Television." *Proc. Inst. Radio Engrs*, **38**, Sept. 1950, p. 1003.

TWELVE YEARS' PROGRESS IN THE DESIGN OF DOMESTIC BROADCAST SOUND RECEIVERS*

by

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A Paper presented at the Third Session of the 1951 Radio Convention on July 25th at University College, Southampton.

SUMMARY

The progress made in the design of domestic broadcast sound receivers since the beginning of the war and the effect of war-time developments on their present design is described. The likely impact of television broadcasting in relation to the future of sound receivers is mentioned. It is also shown design that the rapidly rising cost of production has led to a vigorous attack on the problems of providing the purchaser with the best value for his money.

1. Introduction

The basic circuit design of the domestic broadcast receiver became stabilized during the middle 'thirties. The only major advance in circuit design in the period under review is that of the introduction of negative feed-back. This is frequently used to reduce harmonic distortion and the noise and hum generated in the amplifier, to modify the frequency response and to produce effective loud-speaker damping. During the following pre-war years, designers turned their attention to the provision of novel supplementary devices such as tuning indicators, various forms of pre-set tuning devices and elaborate cabinets and tuning scales. The post-war period has seen a reversal of this tendency, since the rapidly rising costs of raw materials and wages have forced designers into a more realistic approach to the economics of design in order to give the customer the best value for his money. As a result, most of the supplementary features have been omitted.

As a result of the necessity of producing small, lightweight equipment for use in aircraft during the war, many valves and components have become smaller and this has made it possible to design a series of personal and small portable receivers which give a remarkably good performance. Many components are now capable of satisfactory performance and reasonable life even in the most adverse climatic conditions and this has had considerable effect upon the tropical market. On the other hand, many materials have become very difficult to obtain and new or substitute materials, some better and some worse than the original, have been employed in the manufacture of receivers.

The design of a receiver involves a knowledge of the following matters:—

(*a*) The data upon which the design is to be based.

(*b*) The intended market, i.e. location and price range.

(*c*) The components and materials which are available for use in making the finished product, and

(*d*) The manufacturing methods and machinery to be employed in its manufacture.

Of the above items,

(*a*) The data is generally the responsibility of the Sales Department, although the details are usually decided upon with the advice of the designer.

(*b*) The market is also the responsibility of the Sales Department.

(*c*) The designer must be familiar with the components and materials which are available since the design must be based upon their use, and

(*d*) The designer cannot successfully design a receiver unless he knows the capabilities and limitations of the factory in which it is to be made.

Only these items coming within the headings (*b*) and (*c*) will be discussed in this paper.

2. Progress in Component Design

2.1. *Valves*

Progress in the field of valve design has been most evident in a reduction in size (miniaturization) and in the introduction of the all-glass technique.

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The majority of the valves now used in broadcast receivers employ the miniature B7G and B 9A (NOVAL) bases. These bases are considerably smaller than the octal and loctal bases which were in general use before, and at the beginning of, the war. This has permitted the use of much smaller chassis which results in shorter connecting leads. This, together with the fact that glass is now used for the manufacture of valve bases and that the internal connections in the valves are much shorter, has reduced the losses in R.F. amplifiers and permitted increased gain to be obtained with improved stability.

Furthermore, the use of glass bases has considerably reduced the heating time, so that the frequency of an oscillator reaches its final value more rapidly. As a result, the frequency drift during the first half-hour of an average receiver operating at a wave-length of, say, 13 metres has been reduced to about one-fourth.

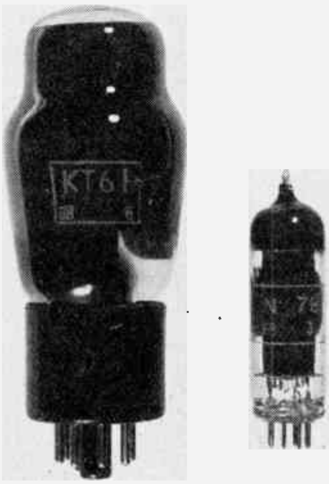

Fig. 1.—Two valves giving similar gain and output power: KT61–Octal base; N.78–B7G base

Perhaps one of the most outstanding miniaturized valves is the Marconi-Osram type N.78. This is an output pentode in a long bulb with a B7G base and which has a slope of 10 mA/V and an anode plus screen dissipation of 11·5 W. Fig. 1 shows two valves giving similar power output. These valves are the KT.61 on an octal base, and the N.78 on a B7G base.

The heating current required for a.c/d.c. valves has, in most cases, been reduced to 100 mA and this has not only reduced the mains consumption, but has greatly reduced the heat generated inside the cabinet. The amount of heat generated in a small radio cabinet has always proved a difficult problem.

2.2. *Resistors*

The normal composition type of resistor has been reduced in size. New resistors having a high degree of temperature-resistance stability have been developed and the price of these is now approximately equal to that of the composition type where tolerances of ± 5 per cent. or less are necessary. As a result, high-stability resistors are often used in place of the composition type because of their improved performance.

2.3. *R.F. and I.F. Tuning Coils and R.F. Transformers*

The use of dust cores, either in the closed or open form, has become nearly universal in the design of R.F. and I.F. tuning coils and R.F. transformers. The dust core aids in miniaturization, it economizes in wire and provides an ease of adjustment which is ideally suitable for mass production. Variable inductances and silvered-mica capacitors provide far better stability than do fixed inductances tuned by mica compression type, trimmer capacitors. Use is now being made of waxed, enamelled, Litz wire instead of silk covered Litz wire for winding I.F. transformers. This gives a more compact coil and greatly reduces the cost.

2.4. *Dry Batteries*

The most interesting development in batteries is that of the layer-pack battery. Although this method of construction, which is based on that of the Zamboni cell, is limited to cells of small capacity, it has permitted a very real economy in the volume of H.T. batteries. This type of cell also has the great advantage of an extremely long shelf life, even in tropical countries. It has now become popular practice to combine the H.T. and L.T. batteries in one case, for convenience and ease of replacement—but technical disadvantages result. These are (*a*) different shelf life of batteries and (*b*) life of one seldom equals the other. Fig. 2 shows two H.T. batteries of equal potential and capacity; one using cylindrical cells and the other the layer-pack construction. Weights are approximately equal, but the layer-pack battery is 50 per cent. of the volume of the cylindrical cell type.

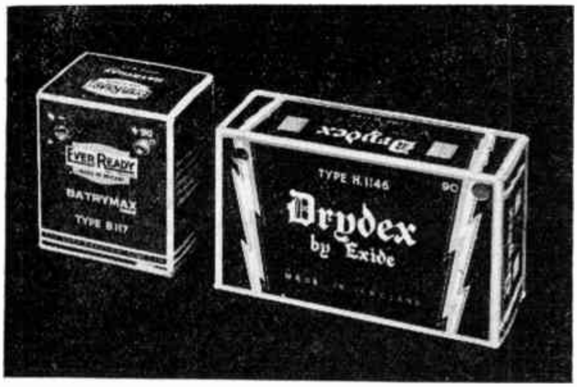

Fig. 2.—Two batteries of equal potential and capacity: layer-pack and cylindrical type cells

2.5. *Carbon Track Volume and Tone Control*

Miniature carbon track potentiometers have been developed and their life under tropical conditions has been greatly increased. Carbonized paper potentiometers are being replaced by those having moulded composition tracks. New materials have been used for the collector rings and brushes in order to reduce the contact potential. Special types of non-oxidizing lubricants, which will withstand tropical conditions, have been produced and these reduce the amount of noise generated in the potentiometer.

2.6. *Capacitors*

2.6.1. Electrolytic Capacitors

The original wet form of the electrolytic capacitor has been superseded by those having a jelly electrolyte as a result of which they may be mounted at any angle. The use of new materials, e.g. etched foil, sprayed gauze and finally tantalum, has enabled the dimensions to be materially reduced and the ripple current rating and reliability have been greatly improved. The economic possibility of obtaining large capacitances has made possible the use of resistance-capacitance mains smoothing filters and this has resulted in the use of permanent-magnet loudspeakers, since it is no longer necessary to use the field winding as a smoothing inductance. The practice of combining many capacitors in one case has been abandoned and this is an advantage in servicing, in reducing the number of types and the cost of replacement. Fig. 3 shows the relative sizes of various electrolytic capacitors.

2.6.2. Variable Air Capacitors

New production techniques in the manufacture of variable air capacitors have enabled the spacing between the plates to be reduced from 0·01 to 0·007in., with the same tolerance in the capacitance and without increasing the effects of microphony. Ceramic insulators have been almost universally adopted with better stability and power factor; this is especially noticeable when the capacitance is at a minimum value.

2.6.3. Tubular Paper Capacitors

The use of metallized paper has resulted in capacitors of small size and high capacitance. This method of construction saves up to 40 per cent. in volume compared with the earlier interleaved paper and foil type.

The use of aluminium cases and Neoprene end caps has greatly improved the life and reliability of tubular capacitors under tropical conditions.

2.6.4. Silvered Mica Capacitors

The deposition of silver on both sides of a sheet of mica results in a very stable capacitor. This method of construction is now in general use when high stability is essential. The silvered mica capacitor has a temperature stability of approximately ± 60 parts per million per degree

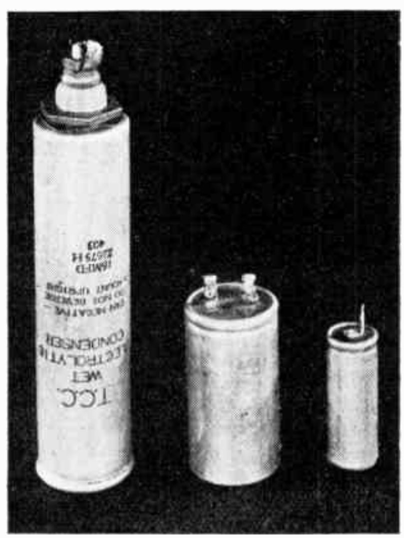

Fig. 3.—Three electrolytic capacitors of equivalent capacity (16 μF). L. to R.—450-V wet type, 450-V jelly with etched foil construction, 350-V jelly and sprayed gauze construction

centigrade compared with approximately ±200 for stacked mica capacitors.

2.6.5. Ceramic Capacitors

The development of new dielectric materials has resulted in small high-capacitance capacitors which can be produced cheaply and in large quantities. These capacitors may have either negative or positive temperature coefficients and, by proper choice of capacitance and temperature coefficient of a number of capacitors, the frequency drift, due to temperature variation, of a tuned circuit may be reduced almost to zero. Unfortunately, those ceramics which are used for the higher capacitances result in poor stability and low power factor. It is possible that, in the future, capacitors made with these ceramics may supersede electrolytic capacitors in mains-smoothing circuits.

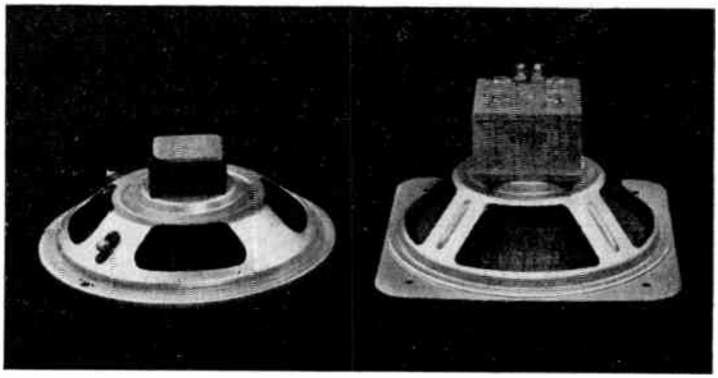

Fig. 4.—Two 6½-in. loudspeakers of equal sensitivity: modern magnet steel and pre-war steel

2.7. *Iron-Core Transformers and Chokes*

New impregnation processes, giving greatly improved reliability under tropical conditions, have been developed and these are particularly effective in the case of multi-turn, fine-wire transformers.

Iron dust cores are becoming more widely used for audio frequency transformers and chokes on account of their reduced losses and cost of assembly. Two examples of these cores are "Caslam" and "Ferroxcube."

2.8. *Loudspeakers*

The introduction of new magnet steels such as Ticonal and Alnico No. 3 save at least 50 per cent. in the weight of a loudspeaker magnet, so that a lighter type of framework may be used. Because of their convenient shape and improved high-frequency distribution properties, elliptical loudspeakers are now often used. Progress in the development of materials for the manufacture of cones and improved manufacturing processes result in a wider and flatter frequency response and in improved performance under tropical conditions. Fig. 4 shows two 6½-in. diameter permanent magnet loudspeakers, having a flux density in the gap of 8,000 gauss. Of these, that on the left uses modern magnet steel.

2.9. *Pick-Ups*

The weight of a pick-up upon a gramophone record used to be 100-130 grams. It is now unusual for the weight to exceed 40 grams, while 8 to 15 grams is not uncommon. The reduction in weight results in greatly reduced needle and record wear and more faithful reproduction. Chrome-steel needles which will play about 100 records, and sapphire needles which will play at least 2,000 records, have now replaced ordinary steel needles.

Both moving-iron and moving-coil pick-ups are used, but the Rochelle Salt crystal pick-up is also becoming popular because its reliability under conditions of high humidity has been much improved by new sealing methods. Crystal pick-ups are much more efficient than the other types since they give greater output and frequency range for a given tracking weight. For example, a modern crystal pick-up will give 0·5 V with a response which is flat up to 10 kc/s when the playing weight is 15 grams. This compares with a moving-iron pick-up which gives 0·3 V over the same frequency range with a weight of 35 grams.

Rochelle Salt crystals are not suitable for use at temperatures higher than about 40 deg C especially in conditions of high humidity. On the other hand, Barium Titanate ceramic may be used since pick-ups made in this ceramic are suitable for temperatures up to 100 deg C and they will operate in conditions of high humidity. Their sensitivity is rather less than that of Rochelle Salt but is adequate. Although certain production problems are as yet unsolved, Barium Titanate crystals appear to have a great future.

The frequency range of pick-ups has been greatly extended by reducing the inertia of the moving parts and the use of a cantilever needle arrangement greatly reduces the amount of buzz and harmonic distortion.

For long-playing records, the use of crystal pick-ups is almost universal because of their higher output. Moreover, the natural frequency response of a crystal pick-up is ideal since it is the inverse of the L.P. recording characteristic. The weight is usually 6-10 grams for "Vinylite" or similar record materials.

2.10. *Cabinets*

2.10.1. Wooden Cabinets

Cabinet manufacturing methods have gained considerably owing to the development of wooden aircraft (e.g. the "Mosquito") during the war. In particular, the development of synthetic resin glues has provided several advantages. These glues are often used, even where their remarkable water-resisting qualities are not essential, because their high degree of thermal activity enables them to be cured quickly with various heating methods, e.g. R.F. eddy current heating which provides rapid curing of the glue. Where moisture-resisting qualities are essential, as in tropical countries, the advantage is obvious. Moreover, the strength of the resultant cabinet is greater and the not inconsiderable handling time in clamping and removal of clamps is avoided.

2.10.2. Coverings for Wooden Cabinets

New leather-cloth materials having a vinyl instead of a cellulose nitrate base are now available for covering the wooden cabinets of portable sets. These materials provide more attractive colours and greater resistance to abrasion.

2.10.3. Plastic Cabinets

Methods of producing large cabinets from phenolic thermosetting materials have been evolved. For example, a television console receiver has been marketed in a moulded bakelite cabinet.

Urea materials (Beetle) have in the past been found to be unsatisfactory, except for small parts, owing to their dimensional instability. However, careful design of the moulding to allow for dimensional changes has made it possible to use these materials and to take advantage of their wide range of attractive colours.

With the development of large injection-moulding machines, many cabinets are now made of thermo-plastic materials, e.g. polystyrene, cellulose acetate and cellulose acetate-butyrate. These materials offer a wide range of colour and effect. Polystyrene does not suffer from dimensional instability and is not water-absorbent. The mechanical properties of polystyrene have been improved and it is now the most suitable material for this purpose. The injection-moulding technique has many advantages over bakelite moulding owing to its speed, low tool cost and overall economy.

2.11. *Chassis Materials*

Many attempts have been made to use aluminium for the manufacture of chassis, but practical difficulties have caused manufacturers to use steel as much as possible.

The advantages in favour of steel are:—

1. It is comparatively easy to press it to a rigid shape
2. It is easily protected by plating and good electrical connections can easily be made after the plating process
3. Its magnetic screening properties are often required, and
4. It is cheap

The advantages of aluminium are:—

1. The weight of aluminium is about one-third of that of steel
2. Its electrical resistance is low, and
3. No finishing or plating is necessary

The disadvantages of aluminium are:—

1. Good electrical connections cannot easily be made, and
2. It is difficult to make a rigid chassis unless the material is nearly three times as thick as the steel required for a chassis of the same size and strength.

2.11.1. Chassis Metal Finishes

Cadmium plating has been improved in appearance and forms the best protection for steel chassis. Passivated tin-zinc plating is another process which gives adequate protection. If desired, these finishes may be covered with a lacquer, and aluminium flakes may be used as a pigment. These lacquers give additional protection and provide a pleasing appearance. No finish is required on aluminium chassis.

2.12. *Fret Materials*

Loudspeaker frets of attractive appearance are being made by the injection-moulding method. Cotton twine, covered with brightly-coloured plastic material, is now woven into fabrics of new and attractive design. The use of expanded metal continues, and dyed, anodized, aluminium wire or strip is also employed.

3. Progress in Receiver Design

The advances in component design and the provision of new and improved materials have had considerable effect upon receiver design. Receivers have become smaller except where the size of the loudspeaker or æsthetic considerations prevent it and, even in these cases, the chassis is often smaller. This reduction in dimensions generally results in a reduction in cost, although this is often masked by the present increases in the cost of labour and materials.

The more important factors in the design of various types of receiver will now be discussed.

3.1. *Personal and Portable Receivers*

A personal, battery-operated receiver, whose weight, complete with dry batteries having a 30-hour life, is only 4 lb, has been designed. This is shown in Fig. 5.

Fig. 5.—A personal battery-operated receiver—external view (Home version)

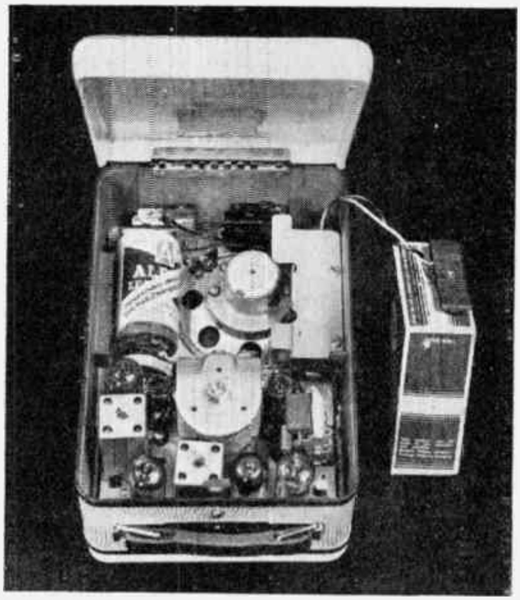

Fig. 6.—A personal battery-operated receiver—internal view (Export version)

A die-cast zinc-alloy case is employed to hold the receiver. The die-cast case is covered with leatherette and is in the shape of a box without top or bottom, the latter being in the form of cream coloured polystyrene injection mouldings. A normal 4-valve superheterodyne circuit is employed and a 3-in. loudspeaker, whose magnet has a high flux-density, is used; a frame aerial is fitted in the lid. Fig. 6 shows a view of the inside of this receiver which consumes 8mA at 67 V and 0·25 A at 1·5 V.

A.C./D.C., battery, portable receivers are being made in increasing quantities since they have the advantage of greater economy when they can be connected to the mains, while retaining the possibility of operation when no mains supplies are available. Fig. 7 shows a view of a receiver of this type with the chassis inverted. The receiver contains separate H.T. and L.T. batteries having 50 hours' life and which, together with the batteries and the mains supply unit, weight only 9 lb. A normal, 4-valve, superheterodyne circuit is employed and a metal rectifier is fitted for use when the receiver is operated from the supply mains. All necessary precautions are taken to protect the user from the danger of shock if the chassis should be live. Fig. 8 shows the circuit of this receiver.

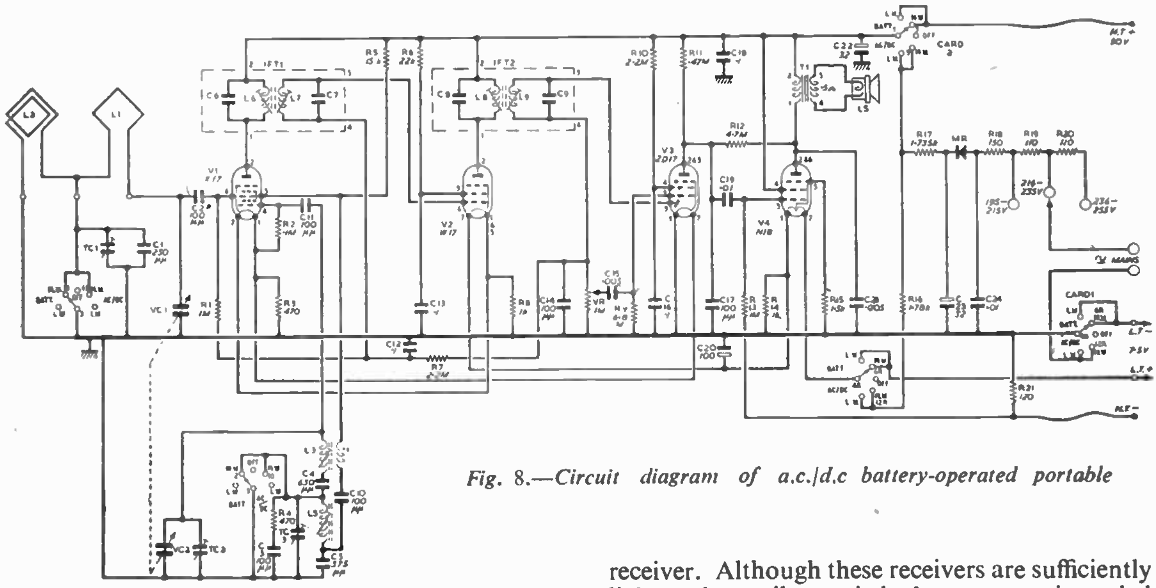

Fig. 8.—Circuit diagram of a.c./d.c battery-operated portable receiver.

3.2. *Transportable Mains Receivers*

Another form of receiver, which has been developed during the period under review, is a small mains transportable receiver which is intended to be used in the home as a second receiver. Although these receivers are sufficiently light to be easily carried, they are not intended to be used in the open air and, for this reason battery operation is not provided. These receivers generally operate from a.c. or d.c. supply mains and the cabinet is usually made from some form of plastic material. The use of miniature components permits these receivers to be very small and the reduction in size is also assisted because the small modern valve generally has a reduced current consumption, with the result that the amount of power which has to be dissipated within the cabinet is reduced.

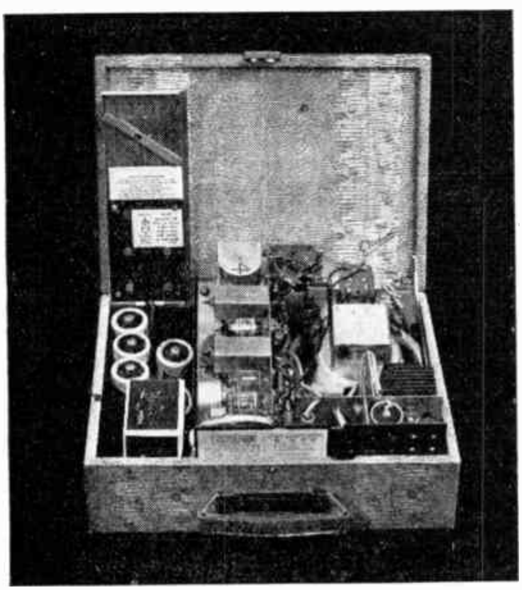

Fig. 7.—A.C/D.C battery-operated portable receiver.

A new type of moulded cabinet, which is shaped rather like a tea-cosy and arranged to drop over the chassis, is finding favour because of the improved appearance of the back of the receiver.

With some receivers, capacitor plates are used as aerials, but, in general, an internal tuned frame aerial is employed, since the signal/noise ratio is thereby improved. Fig. 9 shows the appearance of a receiver of this type and Fig. 10 shows the internal construction of the chassis and cabinet.

3.3. *Car Receivers*

A very large market now exists for car receivers in all parts of the world. The development of miniature tropical components has enabled the size of these receivers to be reduced and their reliability has been greatly increased.

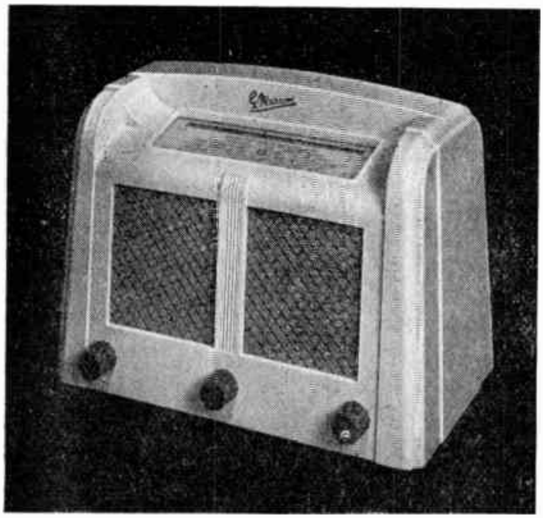

Fig. 9.—A.C./D.C. transportable receiver.

As the amount of space between the dashboard and the engine bulkhead on the average English car is very small, it has become common practice to divide the receivers into two units, which can be fitted separately or bolted together. The loudspeaker is usually fitted in the roof immediately above the windscreen.

A telescopic type of aerial, which is fitted to the roof or wing of the car, is in general use while aerials which are fitted under the car have become less popular. Permeability tuning is usually adopted, especially where no short-wave band is employed. Where short-wave reception is provided, band-spreading is usually adopted. Since the effective height of the aerial is very small, most receivers are fitted with a radio-frequency amplifier stage.

One of the most difficult problems in the design of a car receiver is that of power supplies. The receiver has to be capable of satisfactory operation with potentials varying between 11 and 15·5 V. This large variation depends upon the condition of the car battery and upon whether it is being charged or not.

Probably the least reliable part of a car receiver is the vibrator which has a life of about 1,000 hours. Some of the receivers make use of self-rectifying vibrators while others use ordinary vibrators and valve rectifiers. In the large installations only, e.g. in coaches where a number of loudspeakers have to be operated, it is usual to employ motor-generators, operating from the coach battery, as a source of power. These larger installations often include a microphone to permit the driver to make announcements to his passengers.

3.4. *Battery-Operated Table Receivers*

The development of the "grid" system has greatly reduced the popularity of the battery-operated table receiver for the home market, although receivers fitted with vibrators which operate from a 6-V car accumulator are still popular in certain export territories.

3.5. *Mains-Operated Table Receivers*

Table receivers operating from the a.c. mains, now usually enclosed in wooden cabinets, are still the most popular form of radio receiver. The increases in labour and material cost since the war have resulted in simplification of the design and many non-essential features have been omitted. For example, precise tuning indicators, elaborate multi-station pre-set tuning arrangements and motor tuning have been omitted or replaced by a simple form of switch which provides the choice of three stations together with normal manual tuning.

For receivers which are to be sold on the home market, R.F. amplifiers are generally omitted, but, for export purposes where high sensitivity and signal/noise ratio are required, these amplifiers have been retained. In some cases, in order to reduce the cost, the R.F. amplifier is aperiodic instead of being tuned. Also, for export

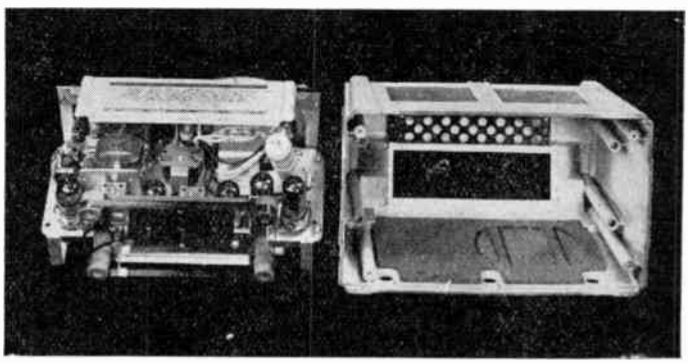

Fig. 10.—A.C./D.C. transportable receiver. (*Expanded internal view*)

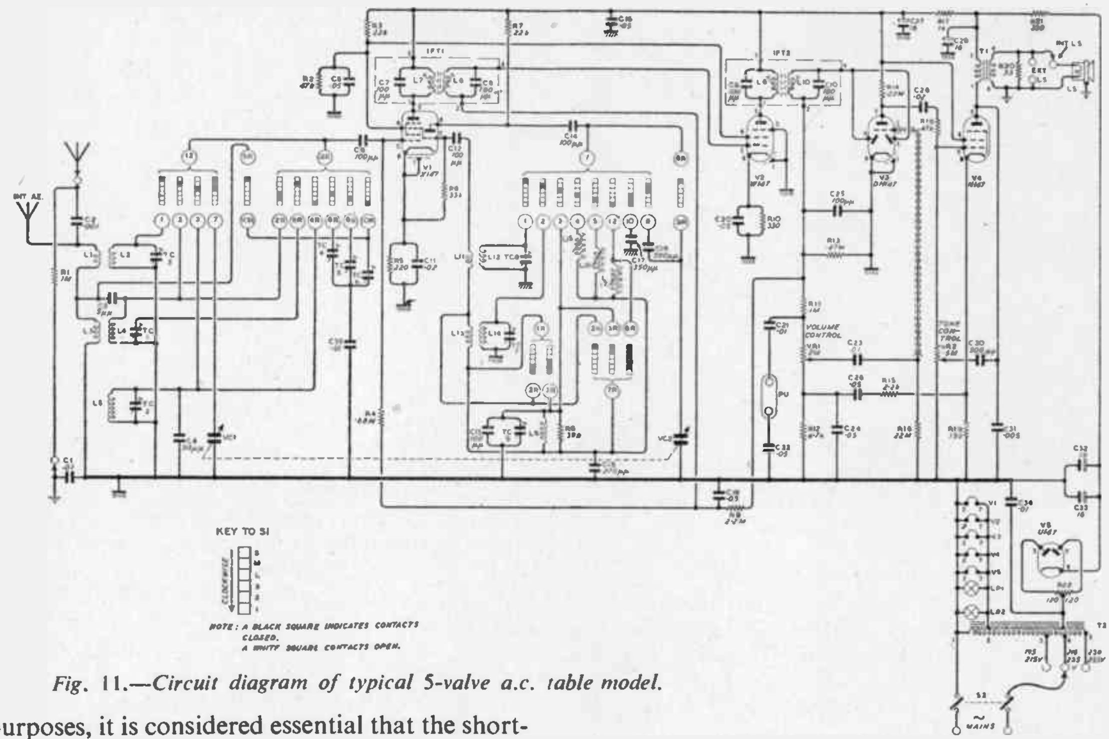

Fig. 11.—Circuit diagram of typical 5-valve a.c. table model.

purposes, it is considered essential that the short-wave bands should be provided with a band-spread device.

Some further changes which have been introduced in order to reduce the cost are outlined below:—

1. The mains transformer has in some cases been replaced by an auto transformer, and although this also reduces the weight, it has the disadvantage that the chassis becomes live.
2. Inductance-capacitance smoothing is being replaced by resistance-capacitance smoothing since resistors are much cheaper and lighter in weight than inductances and occupy a smaller space. Moreover, high values of electrolytic capacitors can now be obtained for the same price as earlier capacitors of lower capacitance.
3. Permanent magnet loudspeakers are now in general use instead of electro-magnetic speakers, because the improvement in strength and quality of magnets made from modern magnet steels, together with their reduced cost, dimensions and weight makes it economical to use them.
4. Directly-heated rectifier valves have been replaced by indirectly-heated valves because the potential which may be applied between the cathode and the heater has been increased as the result of development work. This permits the rectifier valve to be heated by current supplied from the transformer winding which heats all the other valves in the receiver, this saving a separate heater winding on the mains transformer. In addition, the new valves have the advantage that their relative long heating time results in their not coming into operation until the remainder of the valves in the receiver are already hot, with the result that large potential surges do not appear. This has the effect of permitting the use of electrolytic smoothing capacitors of lower voltage-rating and hence of smaller dimensions.
5. The rotary type of wave-change switch has been substituted for those of the push-button type because they are cheaper and more reliable.

6. The output transformers are generally of smaller dimensions than before and the resultant loss of bass response is compensated by the use of frequency-conscious negative feedback circuits.

In addition to the above changes, which have been introduced in order to reduce the cost and to provide various other advantages, certain other changes have been made with a view to improving the quality of the sound output from these receivers. Various forms of filter network have been introduced in order to vary the frequency response as the output level is altered, in order to compensate for the changing frequency response of the human ear with different volume levels. For satisfactory operation of this arrangement the receiver must have a very good automatic gain control to give a constant level of output at a given setting of the volume control, from signals of widely different field strengths. On more expensive receivers in which the bass frequency response is better than that on the cheaper models, it is doubtful whether any advantages are gained by employing this device. Fig. 11 shows the circuit diagram of a modern receiver in which most of these modifications are incorporated.

Flywheel tuning drive mechanism and linear scales are more popular than those of other types.

3.6. *Console Receivers*

Since the war, the console radio receiver without a gramophone or television has failed to find a market.

3.7. *Radio-Gramophones*

A considerable amount of progress has been made in the quality of record reproduction. This improvement is partly due to advances in circuit design, but it is also greatly influenced by improved recordings and by the use of low surface-noise materials for the manufacture of the records and the improved design of electrical pick-ups. The improvement of pick-ups has already been discussed. The improvement in record pressings and pick-ups has permitted the upper limit of high-frequency response to be increased from about 4 kc/s to 10 and even 15 or 20 kc/s in special reproducers. Although these upper frequencies are often outside the audible range their presence greatly improves the quality of reproduction of transients. Fig. 12 shows the circuit diagram of a modern export version of a radio-gramophone.

Record-changing mechanisms have become much more simple and reliable, but the advent of long-playing records may reverse this position if the American practice of using three different turn-table speeds is adopted. The advisability of using long-playing records in conjunction with a record-changing mechanism is open to question on the grounds that a single record plays for about half an hour.

3.8. *F.M. Receivers*

The commencement of the B.B.C. transmission experiments to determine the relative advantages of F.M. and A.M. for short-wave broadcast reception has resulted in the production of F.M. and A.M. receiver prototypes by a number of manufacturers. Because of the increased number of valves and the extremely small market, the selling price of these receivers is necessarily greater than that of the normal five-valve table receiver. It is unlikely that receivers of this type will be put into large-scale production until the B.B.C. has completed its experiments and announced its future policy. It will also be necessary for the B.B.C. to provide a suitable chain of transmitting stations before any large public demand is likely to arise.

4. Safety Precautions

The problem of the protection of the user from the risk of fire or shock has, in the past, proved to be a considerable embarrassment to radio receiver designers. This embarrassment arose owing to the varying stringency of the requirements which were insisted upon by various countries. In particular, the safety requirements which had to be made in the case of receivers which were exported to Denmark and Sweden were much more severe than those for most other countries, some of which had no regulations of any kind.

Since the war, a Commission (International Electrotechnical Commission), which included Great Britain and many other European nations, has attempted to establish a common code of practice with regard to the safety of radio receivers. As a result of these meetings, various regulations have been issued in the countries concerned, and the British Standards Institution is now revising B.S. 415 "Safety requirements for electric mains-operated radio and television receivers" in order to include most of the requirements agreed upon by the Commission. Some of

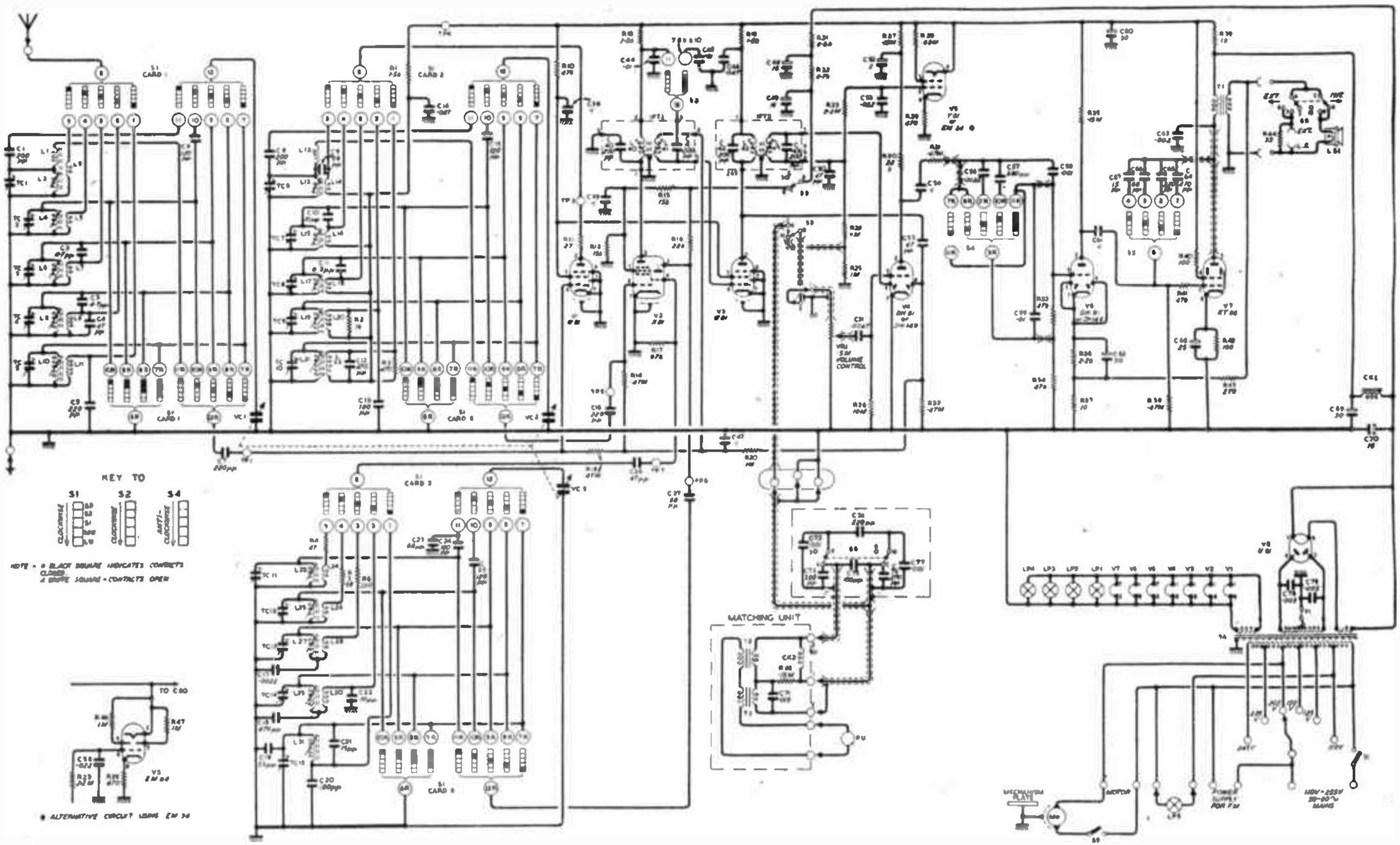

Fig. 12.—Circuit diagram of modern radio gramophone with bandspread S.W. tuning

the requirements which will be included in B.S. 415, but which have not previously been incorporated in British receivers are being added by some manufacturers, but it is doubtful whether the Radio Industry will, as a whole, immediately accept all the provisions of the new B.S. 415 on account of the additional cost involved. The major changes which will be required by B.S. 415 include complete protection by internal fuses which are so arranged that they will blow in the event of the failure of any component which might result in over-heating of the receiver and much more drastic precautions to protect the user from the risk of shock.

5. Conclusions

The outstanding factors which have resulted in changes in the design of broadcast receivers during the past twelve years have been:—

1. The development of miniature components.
2. The improvement in the ability of components to withstand tropical conditions.
3. The development of new materials, in particular of plastics and of magnet steels.
4. The changes which have been made in order to combat the rapidly increasing costs of production, and
5. The changes which have been made to improve the quality of reproduction.

Although the sale of battery-operated table receivers has practically ceased, this market has been replaced by a very large demand for personal, transportable and car receivers. In addition, the market for console receivers containing a radio receiver only has ceased to exist since the war, and they now always include a gramophone and/or a television receiver. It is possible that the rapid expanding demand for television receivers may result in a large reduction in the demand for table radio receivers and that the future market for radio receivers is likely to consist solely of personal, mains, and/or battery-operated portable receivers, mains transportable receivers, and radio-gramophones. It is even possible that the radio receiver of the future will be a television receiver, probably combined with a radio receiver and/or gramophone, and that table radio receivers may be sold in such reduced quantities that they occupy the same sort of special position as did a television receiver before the war.

6. Acknowledgments

The author wishes to thank Messrs. D. F. Spear and F. H. Bayley for advice on components and plastics respectively. He also wishes to thank E.M.I. Engineering Development, Ltd., for permission to publish this paper.

DISCUSSION

F. R. Yardley (*Associate Member*): Regarding the design of dry batteries for use in portable domestic A.M. sound receivers, can Mr. Lett say whether consideration has been given to the design of a battery pack of higher capacity to give a longer life than those which are at present in use.

M. Exwood (*Associate Member*): The author mentions unsatisfactory experience with Urea materials for the manufacture of cabinets and I should be grateful if he would give more details as to the difficulties experienced.

F. T. Lett (*in reply*): Limitations in space, weight and cost are the deciding factors in making such a choice, and I think that the present value is a good compromise. It must be remembered that although the layer pack construction of H.T. batteries nearly halves their volume, it does not in fact save weight for a given potential and capacity. It also costs more than the cylindrical cell type.

Urea (Beetle) moulding materials are much less stable than bakelite and require a very tight control of the moulding process both as regards temperature and curing time, otherwise they become brittle. Also, because their water absorption factor is higher than bakelite they are dimensionally more unstable after moulding. Mould ejection is also a problem unless the tool is chromium plated.

GRADUATESHIP EXAMINATION NOVEMBER 1951

SECOND PASS LIST

This list contains the results of the remaining oversea candidates and completes the results for the November 1951 examination. The first list was published in the February Journal (page 134). A total of 439 candidates entered for the examination.

Eligible for Transfer or Election to Graduateship or Higher Grade of Membership

The following candidates have passed the entire examination, or having previously been exempt from part of the examination have now passed the remaining subjects.

AVINOR, Michael. (S) *Tel Aviv.*
BAHL, Dilbagh Rai. (S) *Jubbulpore.*
DATE, Vishnu Purushottam. (S) *Poona.*
KAIWAR, Badri Nath. (S) *Madras.*
RISHI, Parshottam Lal. (S) *New Delhi.*
SASTRY, Kuruganti Venkateswara. (S) *Bangalore.*
SUBRAMANIAM, Rangaiyar Trivandrum. (S) *Bombay.*
TEMBE, Sakharam Bhaskar. (S) *Bombay.*
TIKARE, Narayan Dattatraya. (S) *Poona.*
VARGHESE, Jacob. *Dehra Dun.*

The Following Candidates Passed Part I

ELKAN, Sally Albert. (S) *Jerusalem.*
MEHTA, Trilok Nath. (S) *New Delhi.*
NEELY, Terence Joseph. *Grahamstown, S. Africa.*
STUUT, Frederik Derk. (S) *Perth.*
SUBRAMANIAN, K. Venkata. (S) *Madras.*

The Following Candidates Passed Part II

CHOPRA, Krishan Singh. (S) *Dehra Dun.*
DANIEL, Henry Asir. (S) *Poona.*
JAHANGOIR, Mohd Afza. (S) *Peshawar.*
MEHDI, Ch. Ghulam. (S) *Rawalpindi.*
SUBRAMANIAM, Vaithiyalingom. (S) *Bihar.*

The Following Candidates Passed Part IIIb

MEENAKSHISUNDARAM, T. S. (S) *Pepivakulum, India.*
SETHURAMAN, R. (S) *Madras.*

The Following Candidates Passed Part IV

BALAGANGADHARA, Rao T. K. (S) *North Arcot.*
DUTTA, Rajendra Nath. (S) *Dehra Dun.*

The Following Candidates Passed Parts I and II

RAMCHANDRA, Rao A. V. (S) *Bangalore.*
PADMANABHA, Iyer Rama Iyer. (S) *Jubbulpore.*

The Following Candidate Passed Parts II and IIIb

JOSHI, Prabhakar Shanker. (S) *Nagpur.*

The Following Candidates Passed Part IIIa

AGRAWAL, Purushottam Narayan. (S) *Kanpur.*
AMAR, Nath. (S) *Delhi.*
ANAND, Jagdish Parkash. (S) *New Delhi.*
BHASIN, Rajinder Nath. (S) *Lucknow.*
BHATTI, Dharam Singh. (S) *Nagpur.*
DHAR, Trikoli Nath. (S) *Jubbulpore.*
GURBAJ, Singh Moti. (S) *Ambala.*
HARI, Das E. N. (S) *Travancore.*
MADAN, Lal. (S) *Delhi.*
MISRO, Achyuta. (S) *Cuttack.*
MOHAPATRA, Purna Chandra. (S) *Cuttack.*
NARAYANA, Anur K (S) *Bangalore.*
PADUKONE, Narendranath Shripad. (S) *Madhya, Bharat State.*
PARANJAPE, Bhalchandra Narayan. (S) *Bombay.*
RAI, Ram Mohan. (S) *Jubbulpore.*
RANJIT SINGH CHIMNI, Sardar. (S) *Dehra Dun.*
RIDGEWELL, Richard Nye. (S) *Karachi.*
SHARMA, Gulzari Lal. (S) *Amritsar.*
SRINIVASAN, Bangalore S. (S) *Bangalore.*
UTGI, Vishnu Vithal. (S) *Poona.*

The Following Candidate Passed Parts I and IIIa

MANJE, Gowda Nelagahally S. (S) *Bangalore.*

The Following Candidates Passed Parts II and IIIa

KRISHNAMACHARYULU, Maringanti S. K. (S) *Begumpet, India.*
MORGAN, Raymond Grosvenor. (S) *Westland, New Zealand.*
RAMAMOORTHY, M. S. (S) *Bombay.*

(S) denotes a Registered Student

UNDERWATER TELEVISION

The applications of television for purposes other than entertainment are increasing rapidly and one of the most dramatic in recent months has been in the discovery of the submarine *Affray* by means of an underwater television camera. It is understood that Marconi's Wireless Telegraph Co., Ltd., has been investigating this application further and believes that it holds considerable promise.

It is interesting to learn that only comparatively minor modifications have been necessary to enable the cameras to work successfully under water. Remote controls for focusing and adjustment of the lens aperture are of course required. The assembly is provided with fully adjustable lighting and there is an inclinometer which shows the angle of the unit when submerged. There is also a water indicator to give warning of moisture in the pressure casing. Later refinements will probably include a compass to show the orientation of the unit.

The depth at which the *Affray* was found was 280 ft. and future developments envisage operation at depths greater than 1,000 ft.; a pressure casing and cable glands are being developed for this requirement. It is found that under certain conditions artificial lighting is unnecessary down to 80 ft. and experiments to date seem to show that tungsten lighting is superior to sodium or mercury vapour.

APPLICANTS FOR MEMBERSHIP

New proposals were considered by the Membership Committee at a meeting held on March 26th, 1952, as follows: 15 proposals for direct election to Graduateship or higher grade of membership and 13 proposals for transfer to Graduateship or higher grade of membership. In addition 21 applications for Studentship registration were considered. This list also contains the names of 12 applicants who have subsequently agreed to accept a lower grade than that for which they originally applied.

The following are the names of those who have been properly proposed and appear qualified. In accordance with a resolution of Council and in the absence of any objections being lodged, these elections will be confirmed 14 days from the circulation of this list. Any objections received will be submitted to the next meeting of the Council, with whom the final decision rests.

Direct Election to Associate Member

BHARUCHA, Phiroze Darabshaw, B.A. *Bombay.*
CROWLEY, Harry Reginald. *Plymouth.*
REEN, Peter John. *Newcastle-upon-Tyne.*

Transfer from Associate to Associate Member

GAMMON, Michael Morley Johnston, B.Sc., B.Eng.(Hons.). *Kingston-on-Thames.*

Direct Election to Associate

BUCKLEY, Frederick Ernest. *Beckenham, Kent.*
FISHMAN, David H. *Haifa, Israel.*
HAGGART, Robert Ian Donaldson. *West Horsley, Surrey.*
HANDS, David William Stanhope.* *Eastbourne.*
MATHIESEN, Eric Frithjof. *Voortrekkerhoogte, South Africa.*
NICKEL, Frank Joseph. *Barnton, Midlothian.*
SEN, Amiya Kumar. *Assam, India.*

Transfer from Associate to Graduate

GEORGE, George Naguib. *Heliopolis, Egypt.*
LANGTON, Charles Hazelhurst. *Stalybridge, Cheshire.*
WALTER, Norman Archibald. *Portsmouth.*

Transfer from Student to Associate

ROTHENBERG, Herman. *Johannesburg.*

Direct Election to Graduate

ELLAMS, George, Flight Lieutenant. *Ramsgate.*
LA JOIE, Marc Jean-Baptiste. *Vacoas, Mauritius.*
LAWTON, William Alfred, Flying Officer. *Exeter.*
MEADOWS, Clement Arthur, B.Sc.(Eng.). *London, W.13.*
WILLIAMS, David Lloyd McNeil. *Lowestoft, Suffolk.*

*Reinstatement.

Transfer from Student to Graduate

BRIDGER, Stanley. *Twickenham, Middlesex.*
CHADWICK, Sidney. *Nottingham.*
CLARKSON, Graham Albert. *Corsham, Wiltshire.*
DENNING, Frederick Richard. *Weston-super-Mare.*
MEEK, Charles. *Wallasey, Cheshire.*
MORRIS, Charles William George. *London, S.E.16.*
RAMASWAMI, Subramanian. *Bombay.*
REID, John Michael. *London, N.21.*
WALSH, Michael William. *Tralee, Ireland.*
WHITE, Colin James. *London, S.E.12.*
WYNN, Peter. *Teddington, Middlesex.*

Studentship Registrations

AHMAD, Saiyed Amin. *Karachi.*
BALARAM, Krishnaswami, B.Sc. *Bangalore.*
DAVIS, Ronald Joseph. *West Bromwich, Staffordshire.*
DUGGAL, Saroop Singh. *Poona.*
FERGUSON, Andrew Carson Lackey. *Glasgow.*
GEORGE, Arthur Henry. *Southampton.*
IZZARD, Malcolm Ian. *Pietermaritzburg, South Africa.*
JAYAKAREN, Israel, Captain. *Madras.*
KALSI, Mohindar Singh. *Jullundur, East Punjab.*
KHAN, Mohd. Ashraf, B.Sc. *Gujrat, Pakistan.*
KHAN, Zahid Ali, B.Sc. *Karachi.*
NAYARATNAM, Stephen Thuriappah. *Pahang, Malaya.*
PANDEY, Kailash Narain, B.Sc. *Allahabad, India.*
RAMANAND, Voleti Sita, B.Sc. *Rajamundry, India.*
RANADE, Sateesh Triuikram. *Poona.*
SAXENA, Bhagwati Prasad. *Bareilly, India.*
SENIOR, Eric. *Halifax, Yorkshire.*
SHERMAN, James Peter. *London, S.E.9.*
UPPAL, Jagtar Singh. *Poona.*
VAN WINCKEL, Maurice Gustave Antoine. *Cape Town.*
WALDER, Peter Jesse Charles. *Singapore.*

REMOTE CONTROL OF HIGH-POWER TRANSMITTERS

The new high-power (150-kW) Third Programme transmitter at Daventry, which came into service in April last year on 464 m, has been working unattended since January 13th. This is a notable achievement, since it is the first high-power transmitter to be operated by remote control.

The B.B.C. has been operating several low-power stations in this way for some time past, but the unattended operation of high-power equipment is a much more difficult problem and its solution represents an important step towards easing the present-day shortage of skilled manpower. Normally at least two engineers per shift would be needed to operate a high-power broadcasting transmitter, but by making possible the remote control of the station from another point, already and necessarily staffed, the technical staff can be released for duties elsewhere.

The new transmitter, which is capable of a full output of 200 kW, is operated with a maximum power of 150 kW in order to conform with the Copenhagen Plan. It was designed by Marconi's Wireless Telegraph Company to be suitable for remote operation and it is built as two identical units, the outputs of which are combined in a specially designed circuit, so arranged that no transference of power takes place between the two sections.

The operation of applying the various power supplies to the transmitter is carried out automatically in the correct order and at the appropriate time intervals, by the operation of a single "start" button at the remote control point. This button switches on the air blowers for cooling the valves, followed by the valve filaments and other supplies in their correct sequence until, with the application of the main H.T., both halves of the transmitter are working.

This sequence of events is relay-controlled, a system of interlocks ensuring that the supplies and services are applied in the correct order and that, furthermore, any fault or failure of supply will arrest the progress of the operation. As each operation is completed a lamp on an indicator panel in the transmitter building is illuminated. On manual operation this shows how far the chain is completed and also helps to locate faults when the station is on remote control since indication is clearly given as to what sections of the transmitter are working correctly.

When all the operations have been completed and the transmitter is on the air, indicator lamps at the remote points are illuminated. If these lamps fail to light within approximately 2 minutes of the operation of the "start" button it denotes that some fault has developed.

Two automatic monitors developed by the Designs Department of the B.B.C. continuously monitor each half of the transmitter. In the event of the automatic monitor on either half "noticing" a programme fault it automatically shuts down that half of the transmitter with which it is associated. At the same time, to prevent a complete shutdown of the station as the result of a comparatively minor fault, the monitor on the faulty unit removes the shutdown control from its counterpart on the healthy section, substituting an alarm circuit. A third automatic monitor checks the transmission from the aerial. To prevent the service being interrupted through a failure of the monitor itself, an ingenious arrangement is incorporated which enables it to check its own circuits before shutting down the transmitter.

Since the monitor operates by comparing the programme as received with the programme as radiated it is essential that a momentary shutdown of the transmitter due, say, to the operation of the lightning protection gear, shall not be regarded as a programme fault. The automatic protection of the transmitter itself incorporates a number of devices which, on the occurrence of a fault, will remove the main H.T., wait a few seconds and then restore it. If the fault persists the main H.T. is again removed and restored. After the third attempt the transmitter automatically closes down and gives an alarm. During the three attempts to restore normal conditions the operation of the monitor is automatically suppressed. In the event of the breaks in programme being due to some other cause, however, the suppression would not take place and the monitor itself would close down the transmitter.

It seems fitting that this important development should be at Daventry with its long history as a B.B.C. transmitting station where much pioneering work in broadcast engineering has been done. It was from here, over 26 years ago, that the first high-power long-wave broadcasting transmitter in the world (5XX) commenced its transmissions.