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Colour sensitometric parameters in colour film telerecording

by

C. B. B. WOOD
E. W. TAYLOR, M.A.
G. D. JUDD
(Research Department, BBC Engineering Division)

BRITISH BROADCASTING CORPORATION

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FOREWORD

THIS is one of a series of Engineering Monographs published by the British Broadcasting Corporation. About six are produced every year, each dealing with a technical subject within the field of television and sound broadcasting. Each Monograph describes work that has been done by the Engineering Division of the BBC and includes, where appropriate, a survey of earlier work on the same subject. From time to time the series may include selected reprints of articles by BBC authors that have appeared in technical journals. Papers dealing with general engineering developments in broadcasting may also be included occasionally.

This series should be of interest and value to engineers engaged in the fields of broadcasting and of telecommunications generally.

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COLOUR SENSITOMETRIC PARAMETERS IN COLOUR FILM TELERECORDING

SUMMARY

A description is given of a combination of the spectral characteristics of the cathode-ray tubes, absorption-type filters, and dichroic mirrors that is suitable for colour film telerecording purposes; the importance of minimizing flare in the optical system is discussed.

1. Introduction

The need for a reliable system of telerecording on colour film is generally recognized. Television programmes recorded on film have an advantage over other recordings in that they do not require standards-conversion when they are the subject of international exchange, while review or editing may be carried out easily by means that are universally available.

The BBC Research Department has developed an experimental three-tube display system which could in principle be used, in conjunction with a suitable film camera, to form a colour film telerecording apparatus. This display uses a combination of three separate cathode-ray tubes (one red emitting, one green emitting, and one blue emitting) since the brightness of a conventional shadow-mask colour cathode-ray tube is not satisfactory for colour telerecording purposes. Furthermore the required degree of colour saturation for a satisfactory colour film telerecording cannot be obtained by simple colour-photography of a phosphor-dot screen and it is necessary to introduce optical filtering of the light emitted by the display. This cannot easily be achieved unless access is available to each of the three colour-phosphors separately.

In making a colour film telerecording, the exposure conditions must be chosen so as to give:

(*a*) The best possible reproduction of saturated colours.
(*b*) A neutral reproduction of achromatic scenes over the whole light-input range.
(*c*) A satisfactory luminance contrast law.

The conditions that satisfy each of these requirements are to a large extent interdependent. Colour saturation in colour film telerecording is governed by the ability to cause the density of each colour-controlling dye in the positive film print to be related exclusively to the appropriate colour-separation signal supplied to the telerecording equipment. Cross-modulation between the red, green, and blue colour-separation signals can arise in the telerecording process because the spectral sensitivities of the three emulsion layers of the colour film overlap considerably, with the result that there are wavelengths of light to which two, or all three, layers respond to some extent. This means that the light from the telerecording display reaching the film must have a spectral characteristic so arranged that energy at these wavelengths has been suppressed. Even when this condition is accurately fulfilled, the resulting positive film print* cannot give pictures having accurate luminance values for highly saturated colours, either when optically projected or reproduced in a colour telecine machine, because of overlapping of the wavelength bands in which the colour-controlling dyes have significant absorption. Electronic masking techniques may, however, be used to reduce these inaccuracies in the case of telecine reproduction.

* This includes the 'master-positive' if reversal-type film stock is exposed as part of a 'reversal-reversal' process of exposure and printing.

The requirement of accurate control of the spectra of light corresponding to the three colour-separation signals determines the basic form of the picture-display equipment suitable for use in colour telerecording applications. Three separate cathode-ray tubes are used in the configuration shown in Fig. 1, the spectrum of the light from each tube being controlled by colour-shaping filters (F_R, F_G, F_B) before being combined by an arrangement of dichroic mirrors (M_R and M_B) and passed to the camera. The specification of the shaping filters and dichroic mirrors is discussed in detail in Section 2; the problems of obtaining accurate picture geometry, focus, and registration are outside the scope of this monograph.

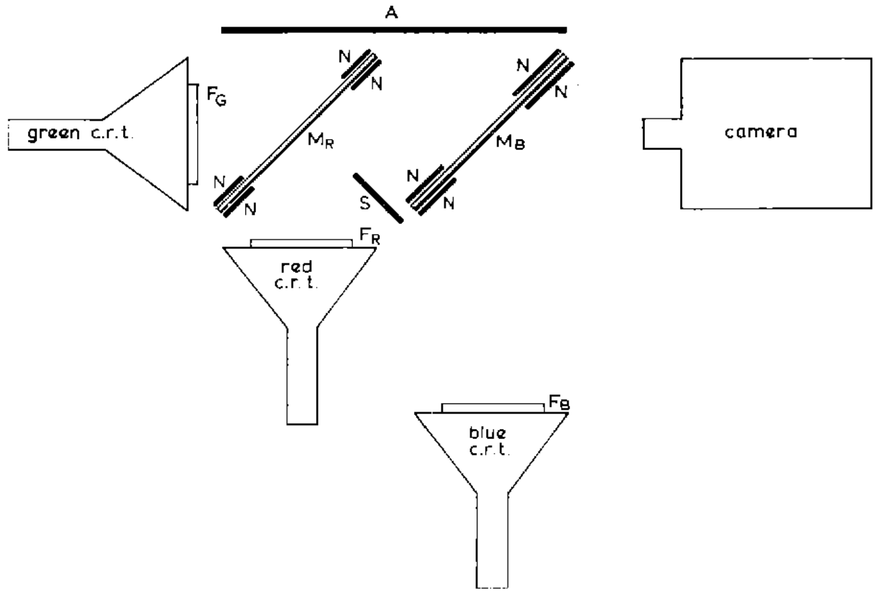
The neutral reproduction of achromatic scenes, and the achievement of a satisfactory contrast law (conditions (*b*) and (*c*) above) are obtained by control of the intensity of light from each of the displays. The characteristics of the film are such that there is 'exposure-inertia' at very low brightness levels, so that detail at very low brightness levels is not recorded; to avoid this the telerecording display is arranged to have a small but finite brightness in areas corresponding to black in the original picture. The intensity of this black-level brightness has to be accurately controlled in order to obtain correct 'tracking' between the three signals (i.e. the neutral reproduction of all luminance values between black and peak white) and it has been found that the necessary accuracy can only be achieved if the flare in the optical system is kept to a very low value; this aspect is discussed in Section 3.

2. Specification of Spectral Characteristics of Light for the Three Colour-Separation Displays*

2.1 *General*

The necessity of ensuring that each of the sensitive layers of the emulsion responds as far as possible only to the appropriate colour separation signal was mentioned in Section 1. When this condition is achieved, the film is used only to store the information in the colour television signal without itself contributing to the colour analysis of the scene; this is essential if the film is subsequently to be inter-

* The colorimetric design of the display was initially carried out by Mr C. B. B. Wood and Dr C. J. Dalton.



F_R, F_G, F_B—*Absorption-type shaping filters*
A, N, S—*Light-absorbing screens (see Section* 3.3)
M_R—*Red-reflecting dichroic mirror*
M_B—*Blue-reflecting dichroic mirror*

Fig. 1 — *Colour telerecording display equipment*

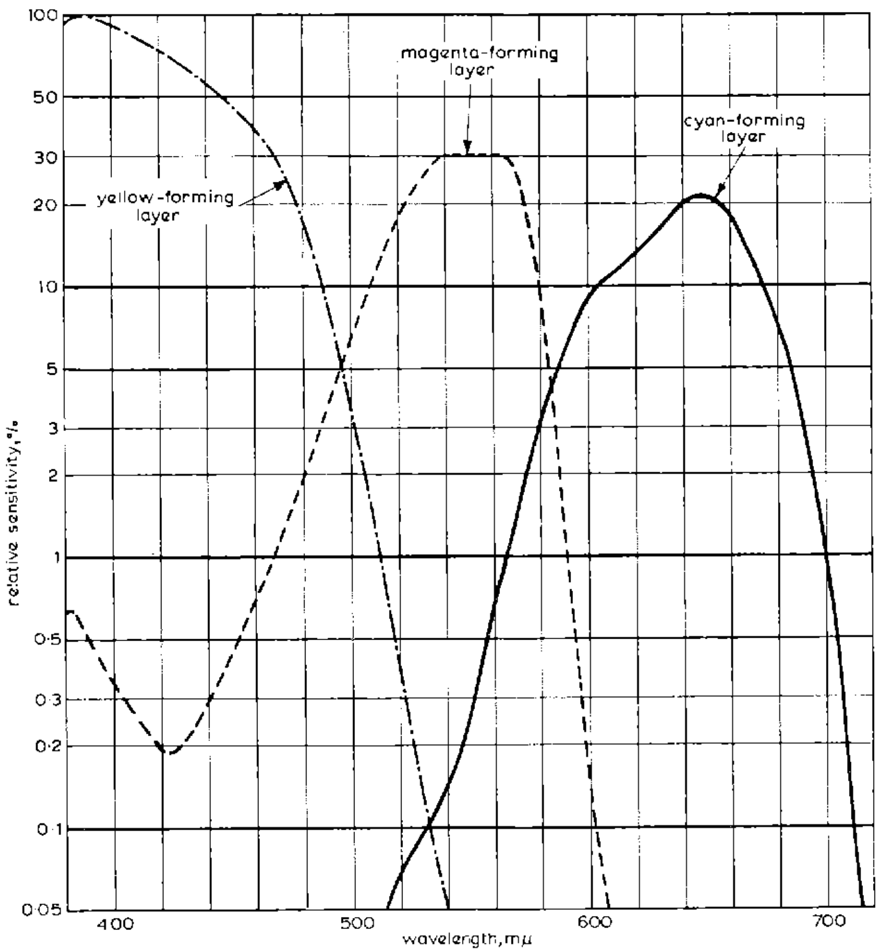


Fig. 2 — *Spectral sensitivities of a typical colour negative film* cut with camera pictures in a programme, since a colour film is unlikely to have the same colour-analysis characteristics as a camera.

Examination of available data on the spectral sensitivity of currently obtainable colour film emulsions shows a general similarity between them. Fig. 2 shows the spectral sensitivity curve for a typical colour negative film. This particular film stock is balanced for 3,200°K illumination; materials intended for exposure to 'daylight' (i.e., illumination of a higher colour temperature) have curves of similar shape, the principal distinction being a different relative balance between the sensitivities of the three layers. It can be seen that in order to expose the cyan-dye-forming layer without affecting the other two layers, the output of the red cathode-ray tube must not contain light of wavelength shorter than 610 mμ. It can also be seen that maximum sensitivity occurs at 650 mμ and falls off rapidly for wavelengths longer than 660 mμ; this is typical of most film stocks.

Similar consideration show that the yellow-dye-forming layers would have to be exposed to light of wavelength near to 430 mμ for minimum interaction with the other layers; whereas maximum sensitivity is achieved at 390 mμ. Consideration of Fig. 2 shows that it is impossible to expose the magenta-dye-forming layer of the film without affecting the other two layers of the emulsion to some extent: light of wavelength near to 530 mμ will give the greatest separation between the wanted and unwanted exposures of the film layers.

The sensitivity of the magenta- and cyan-dye-forming layers may increase for wavelengths in the ultra violet range (i.e., less than 400 mμ), not shown in detail in Fig. 2; such radiation should therefore be prevented from reaching the film.

A number of characteristics must be considered when selecting phosphors for use in colour film telerecording applications. A prime requirement is the presence of the appropriate spectral emission characteristic, and this will be discussed in Section 2.2. Other characteristics include:

(*a*) Sufficient light output to expose the film.
(*b*) Fine grain.
(*c*) Linear light output/beam current characteristic.
(*d*) Short afterglow.

The efficiency of the phosphor should be high enough to expose the film adequately at reasonable cathode-ray-tube beam currents after the necessary filtering of the spectral emission has been made. High beam currents may cause burning of the phosphor, necessitate the use of forced air cooling of the cathode-ray tube faceplate, and enlarge the spot size excessively, thus degrading the picture resolution and placing an excessive demand upon the cathode emission.

The grain of the phosphor should be fine enough not to degrade the picture either by 'static noise' or by lack of resolution.

It is very desirable that the light output of the cathode-ray tube should be proportional to the beam current over the whole range to be used. If this is not the case, the luminance characteristic of the reproduced colour-separation picture will be altered; if this effect occurs to different extents in the three channels the reproduced hue will depend on luminance level. This lack of 'tracking' may be compensated by non-linear electrical correction of the signals to the appropriate cathode-ray tubes but this involves additional circuit complexity which is best avoided. Furthermore, a non-linear relationship will cause the cathode-ray tube light output to depend upon focus and spot wobble in addition to beam current. These parameters are likely to vary across the tube face, thus causing spatial variations of hue in the colour display. It can thus be seen that phosphors with a non-linear characteristic should be avoided unless other considerations make their use unavoidable.

The exact values of the phosphor time constants are not of primary importance, but they should be kept as small as possible to avoid field shading effects or smears and coloured fringes following moving objects.

An extensive study of phosphor characteristics, followed by measurement of performance in sample tubes, resulted in the selection of a few possible phosphors for this application. Prototype colour telerecording tubes were then obtained and the final choice was made on the basis of all-round merit, taking into account the beam current required to expose the appropriate emulsion-layer of the film, freedom from cross modulation, linearity, spot size, granularity, and the other parameters already discussed.

2.2 *Spectral Emission of Selected Phosphors*

The phosphor selected for the red channel is yttrium vanadate, its spectral emission characteristic being shown

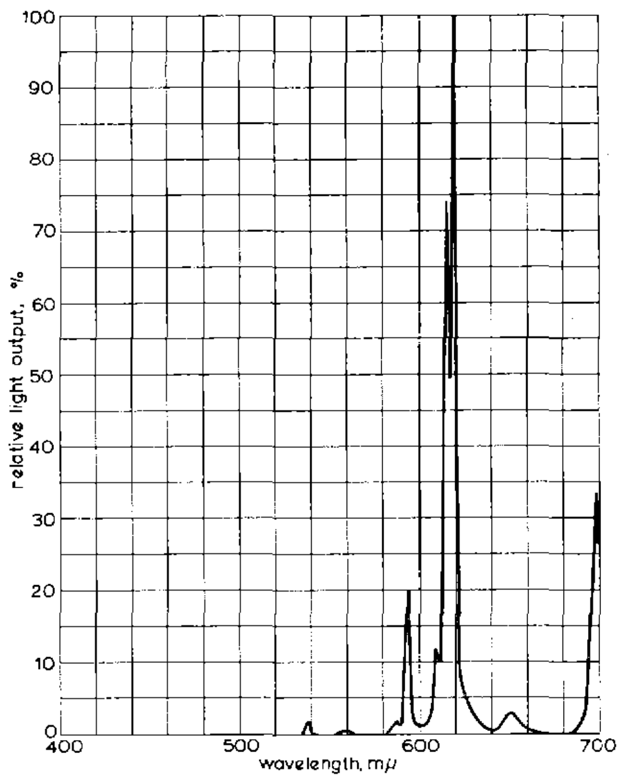


Fig. 3 — Spectral emission of the red phosphor

in Fig. 3. The peak output occurs from two closely spaced spectral lines at approximately 620 mμ; this is unfortunately of shorter wavelength than that desirable for maximum film sensitivity at 650 mμ but the linearity of this phosphor, compared with other red-emitting phosphors, makes it clearly the best choice. The output at 700 mμ is too long in wavelength to expose most emulsions, but the emission at wavelengths shorter than 610 mμ must be removed by filtering to avoid exposing the magenta-dye-forming layer.

The green channel uses a zinc ortho-silicate (willemite) phosphor* which has its peak emission at approximately 520 mμ (Fig. 4), a slightly shorter wavelength than the optimum for the film shown in Fig. 2. Light is emitted from 430 to 640 mμ and this must be restricted to a much narrower band (as described in Section 2.1) to minimize the exposure of the other two layers.

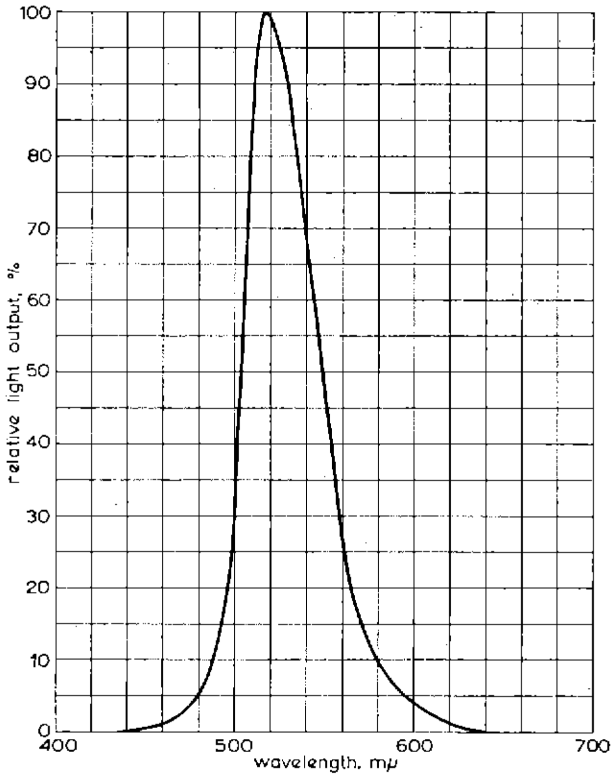


Fig. 4 — Spectral emission of the green phosphor

The silicate phosphor selected for the blue channel has its peak light output at 450 mμ (Fig. 5) as compared with the optimum value of 430 mμ for this peak. Light of longer wavelength than about 450 mμ must be removed by a suitable filter as must light of shorter wavelength than about 410 mμ.

* Under certain exposure conditions the relatively long time-constant of this phosphor may give rise to field shading effects: this is discussed in the Appendix. Available phosphors having shorter time-constants were found to have a non-linear light output/beam current characteristic.

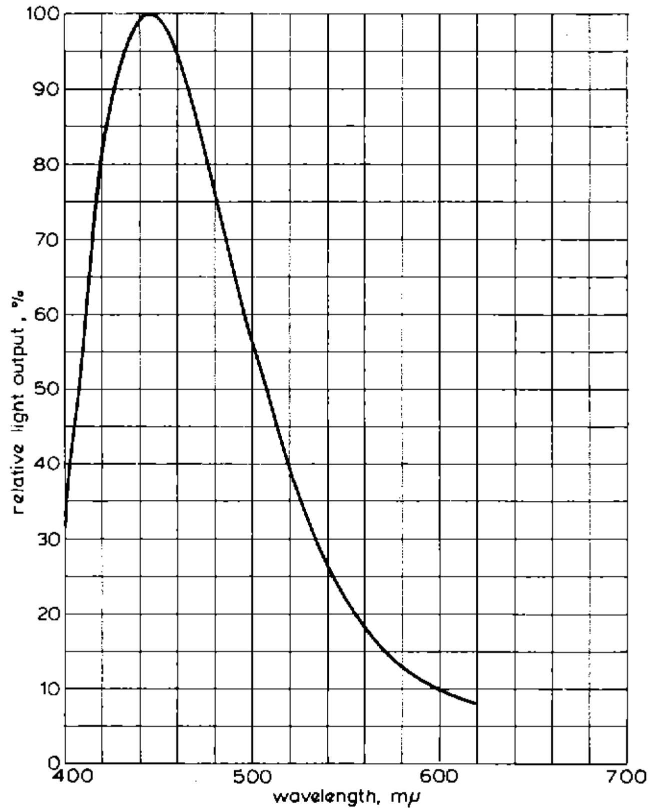


Fig. 5 — Spectral emission of the blue phosphor

2.3 *Specification of Filters*

The dichroic mirrors used to combine the light from the phosphors are also used as the principal means of controlling the light emitted in unwanted parts of the spectrum. Absorption type filters are used to give additional shaping of the light spectrum by suitable choice of their characteristics. Details of achieving this control are listed in Table 1 and the resulting spectrum modifications are shown in Figs 6–10.

The output from each channel after passing through the filters and mirrors is shown in Fig. 11; in this figure each peak has been normalized to 100 per cent. This light reaches the film after passing through the camera lens, which may have reduced transmission at the blue end of the spectrum. The spectral response of the camera lens used in the experiments is shown in Fig. 12.

The attenuation of light by the absorption filters in their transmission band may be used to advantage to reduce cathode-ray tube flare; this is discussed in Section 3.2. The use of an interference type shaping filter at normal incidence in the green channel was considered but had to be abandoned because of the resulting increase in veiling glare (see Section 3.3).

2.4 *Results Achieved with Specified Spectral Characteristics*

Tests have been carried out in which each cathode-ray tube in turn was illuminated, the other two tubes being

TABLE 1

Details of Spectral Shaping Filters and Dichroic Mirrors

Channel	*Wratten Absorption Filters*			*Dichroic Mirrors*	
	Number Used	*Type*	*Overall Transmission*	*Type*	*Transmission*
Red	1	29	Fig. 6	Red reflect Red and green transmit	Fig. 9(*a*) Fig. 10(*b*)
Green	1 1	12 44	Fig. 7	Green transmit Red and green transmit	Fig. 9(*b*) Fig. 10(*b*)
Blue	1	98	Fig. 8	Blue reflect	Fig. 10(*a*)

completely extinguished. Exposures on suitable film stocks were made with the beam current of the illuminated tube set to different values in order to produce 'wanted' dye densities* of different values. The densities of all three dye layers were measured† in each text exposure, and a typical case for Ektachrome MS reversal film in which the equivalent neutral densities of the deliberately exposed dye layers were 0·5 in each case are shown in Table 2.

TABLE 2

Equivalent Neutral Densities of Dye Layers Ektachrome MS Reversal Film

Illuminated channel	*Equivalent neutral densities of indicated dye layers*		
	Cyan	*Magenta*	*Yellow*
Red	0·5	3·0	3·4
Green	2·5	0·5	3·5
Blue	3·1	3·0	0·5

It can be seen that in the cases of the red and blue illuminated channels the difference achieved in equivalent neutral density between the deliberately exposed dye layer and the other dye layers was never less than 2·5. If the cross-coupling between the colour-separation signals in a telecine machine were due solely to these differences in dye-layer densities, the separation between the wanted and unwanted signals would be some 50 dB and would therefore be adequate. In the green channel, the separation between the equivalent neutral density values of the deliberately exposed (magenta) dye layer and the cyan layer is somewhat lower (2·0) than that of red and blue channels but even here the practical effect of this unwanted exposure is negligible. It should be noted that the maximum equivalent neutral density value that each dye layer is capable of achieving in the complete absence of incident light depends on the particular batch of film stock in use. The 'cross-coupling' density values shown in Table 2 approach these maximum values and the density differences between the deliberately and unintentionally exposed dye layers will therefore depend on the film batch.

* In this section the dye densities are expressed in terms of the 'equivalent neutral density'; that is, the density of the neutral image that could be formed by adding to the dye deposit under consideration sufficient quantities of the other two dyes.

† By Kodak Research Laboratories. Equivalent neutral density values were computed from these measurements.

3. Flare in the Telerecording Display

3.1 *General*

It is normal practice when making a black-and-white film telerecording to arrange for areas of the picture corresponding to black in the original scene to have a small but finite brightness on the telerecording display. By this means the exposure inertia of the film is overcome and the density in the positive film print corresponding to 'picture black' can be predetermined so that the negative/positive film process is used over the most suitable part of the exposure range. The effect of flare in the telerecording display is to increase the brightness of dark areas of the image by an amount depending on the picture content and thus reduce the brightness range of the recorded picture with consequent reduction of the quality of the recording, but acceptable results can nevertheless be obtained. In the same way, an increase of brightness will occur in the dark areas of each colour-separation image of a colour film telerecording display; differences in the magnitude of this effect in the three channels will result in the appearance of a colour-cast in the darker areas of the recorded picture and this can give rise to a very considerable reduction in quality. Where a saturated colour is predominant in the scene (for example, a large area of grass) differences in the average brightnesses of the three colour-separation images give rise to a coloured flare in shadow areas of the recorded picture.

It can be seen that the reduction of the flare in the telerecording display to the lowest possible value is essential if good recorded picture quality is to be maintained. Two separate sources of flare in the display may be distinguished:

(*a*) Flare in the faceplate of the cathode-ray tube.
(*b*) General 'veiling glare'.

These are discussed in the following sections.

3.2 *Cathode-Ray Tube Flare*

Flare in the faceplate of the cathode-ray tube gives rise to the 'halation' ring patterns formed round a small bright area on the cathode-ray tube phosphor, together with the integrated effect of such flare for large-field conditions. The most effective flare-reducing method is the provision of a light-absorbing medium between the phosphor and the first high-to-low refractive index boundary encountered by the light leaving the phosphor. In the present case, advantage may be taken of the 'in-band' absorption of the filters used for shaping the spectra from the three tubes (Figs 6, 7, and 8) by placing them in optical contact with the cathode-ray tube faceplate. This may be achieved by cementing the filters between two sheets of glass, and ensuring optical contact between the filter 'sandwich' and the flat cathode-ray tube faceplate by the use of a thin layer of liquid trapped between the two surfaces; the refractive index of all these components should be as nearly as possible equal to that of the tube faceplate.

An anti-reflexion coating applied to the high-to-low refractive index boundary (in the present case, the outer surface of the filter 'sandwich') gives a small but significant reduction in the amount of flare; the results described in Section 3.5 were obtained with filters treated in this way.

3.3 *Veiling Glare*

Veiling glare may arise because of reflexion (either specular or diffuse) of light on to the phosphor or film surfaces, and also by the scattering of light from out-of-focus imperfections in the mirrors or lens. It takes the form of a uniform illumination of the picture, the amount of this illumination depending on the average picture brightness; in this respect it differs from the cathode-ray tube flare described in the previous section, although in practice the overall effects of the two types of flare are very similar. The technique of placing the absorption-type shaping filters in optical contact with the cathode-ray tube faceplate eliminates the specular reflexions on to the phosphor that would otherwise be obtained from these filters; the use of sharp-cutting interference-type shaping filters appears to be impracticable because of the large amount of light that is reflected back on to the phosphor if such filters are used at normal incidence, together with the appearance of severe 'dichroic tilt' effects if the filters are tilted to avoid such reflexions.

The 'in-band' absorption of the shaping filters reduces the veiling glare caused by the reflexion of light on to the phosphor from other parts of the optical system or its supports. Light-absorbing screens should be arranged (for example at A in Fig. 1) to avoid the possibility of specular reflexion of light back on to the phosphors, either directly or by way of reflexion from the back surfaces of the dichroic mirrors; in this respect it is helpful to mask both sides of the dichroic mirrors with non-reflecting material (N in Fig. 1), leaving an aperture that is just sufficient to avoid vignetting in the recorded picture. The number of optical surfaces should be reduced to a minimum in order to lessen the probability of light scatter from blemishes and dust particles. The glass 'compensating plates' that are usually inserted in the light path that does not pass through either dichroic mirror (the blue channel in the present case) may for this reason be omitted; the resulting misregistration of the red image may be corrected by slight alteration of the scan geometry, as the display is viewed from a fixed point. The inclusion of all the absorption-type shaping filters in each channel into a single 'sandwich' assembly is also effective in reducing the number of optical boundaries. The scatter of light from the blue-reflecting mirror due to its illumination by the red-channel cathode-ray tube may be reduced by inserting a screen (S in Fig. 1) to prevent red light reaching this mirror except by way of the red-reflecting mirror.

3.4 *The Flare Performance of the Experimental Telerecording Display*

Measurements* were made of flare performance under

* These measurements were made using a prototype phosphor and shaping-filter combination in the blue channel which differed from the finally selected version described in Sections 2.2 and 2.3. Differences in the spectral characteristics of the two versions are relatively small and have no significant influence on the results shown in Table 3.

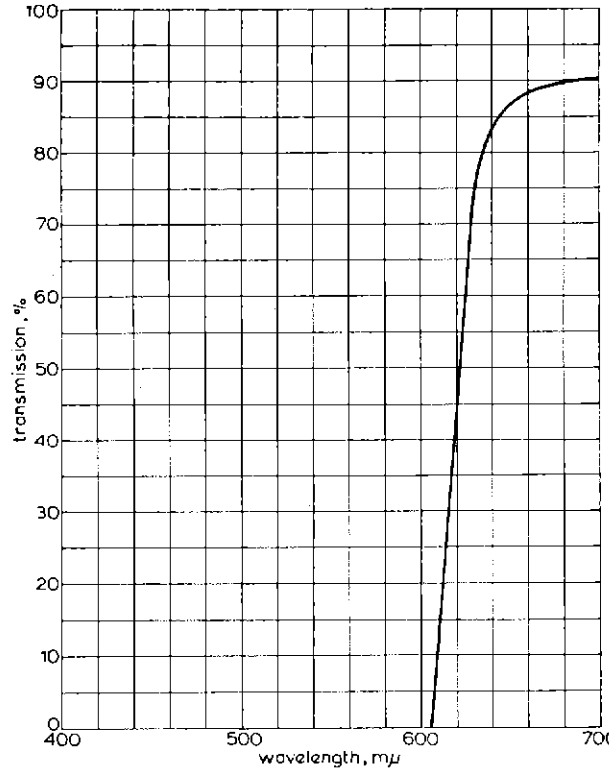


Fig. 6 — Spectral transmission of the absorption-type filter in the red channel

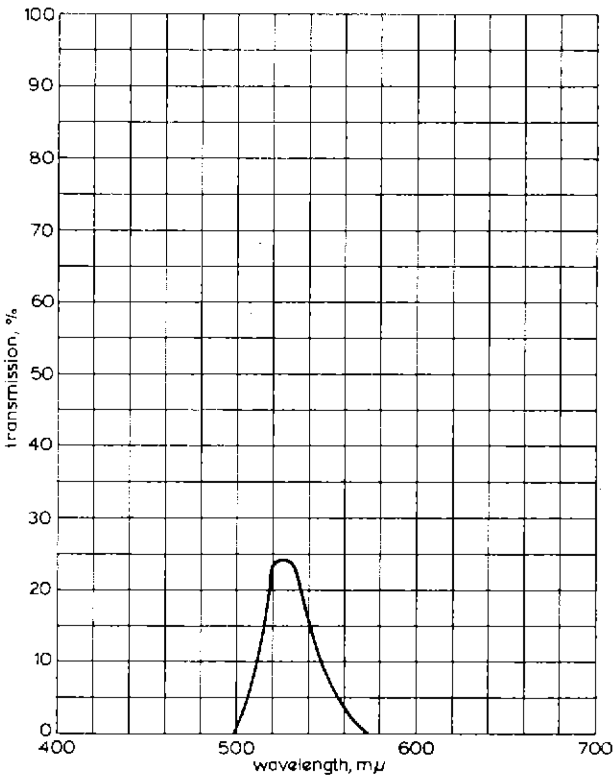


Fig. 7 — Spectral transmission of the absorption-type filter in the green channel

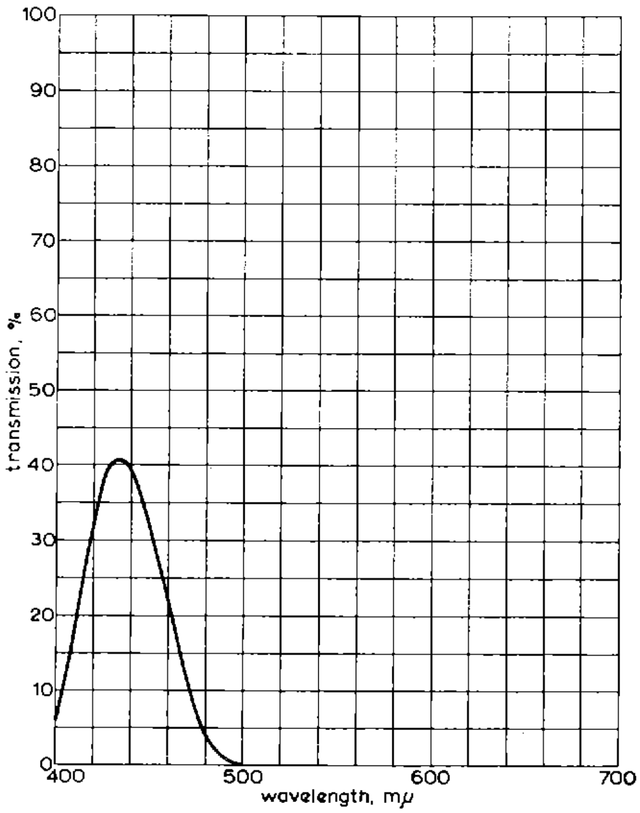


Fig. 8 — Spectral transmission of the absorption-type filter in the blue channel

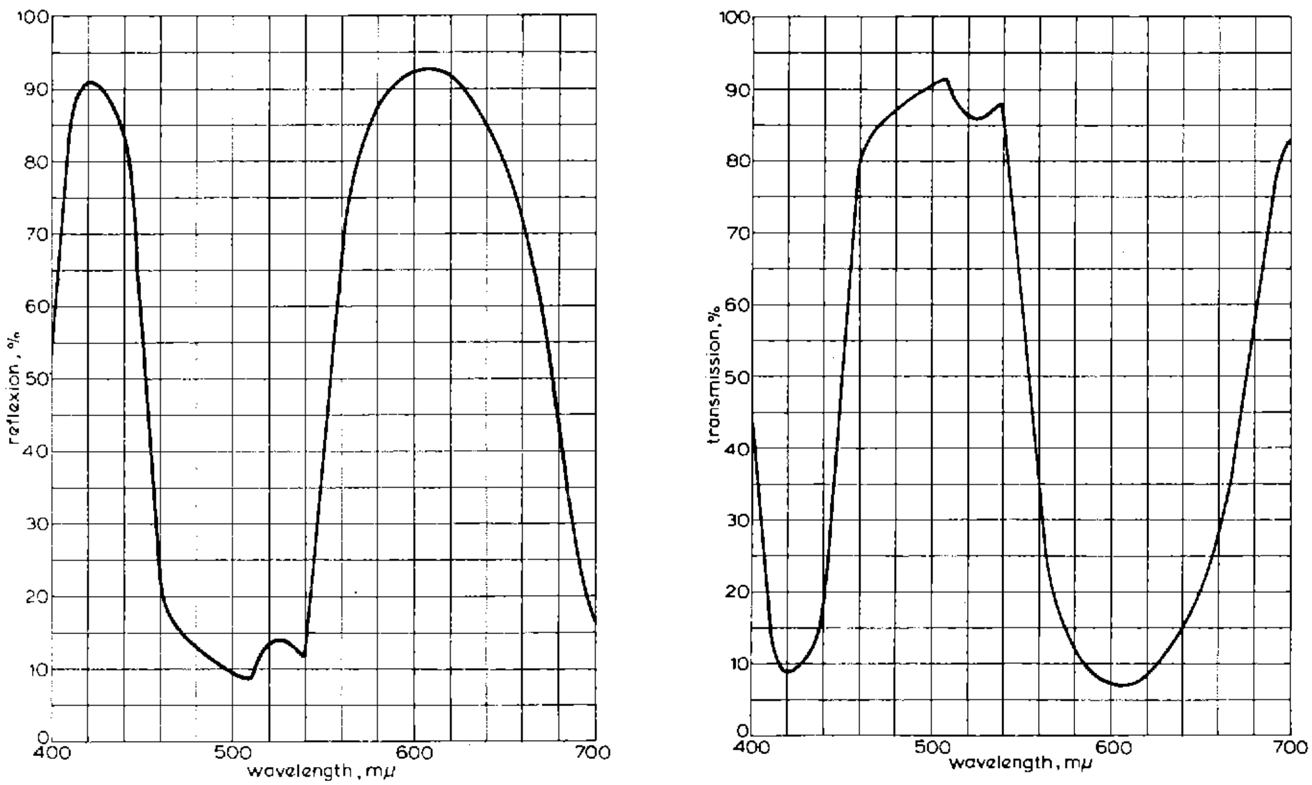


Fig. 9 — Spectral characteristics of the red-reflect dichroic mirror

Reflexion characteristics (b) Transmission characteristics

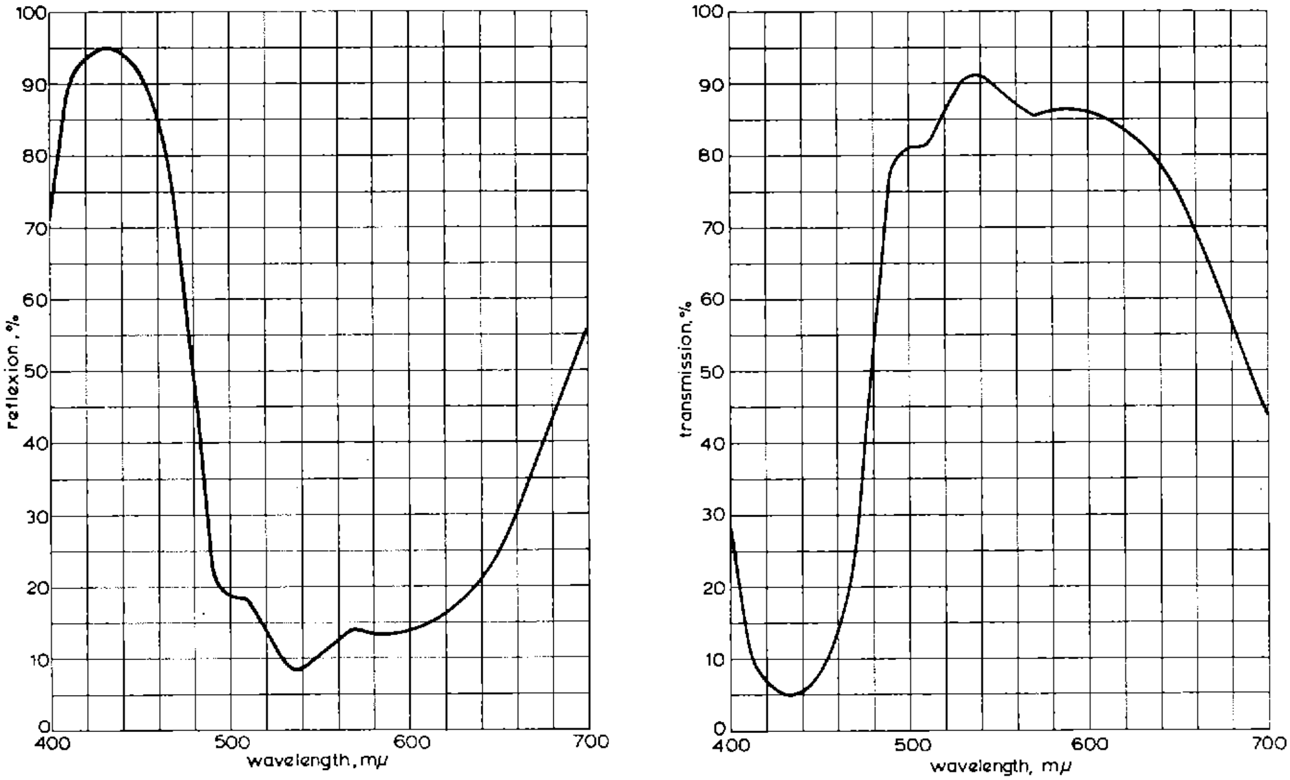


Fig. 10 — Spectral characteristics of the blue-reflect dichroic mirrors
(*a*) Reflexion characteristics
(*b*) Transmission characteristics

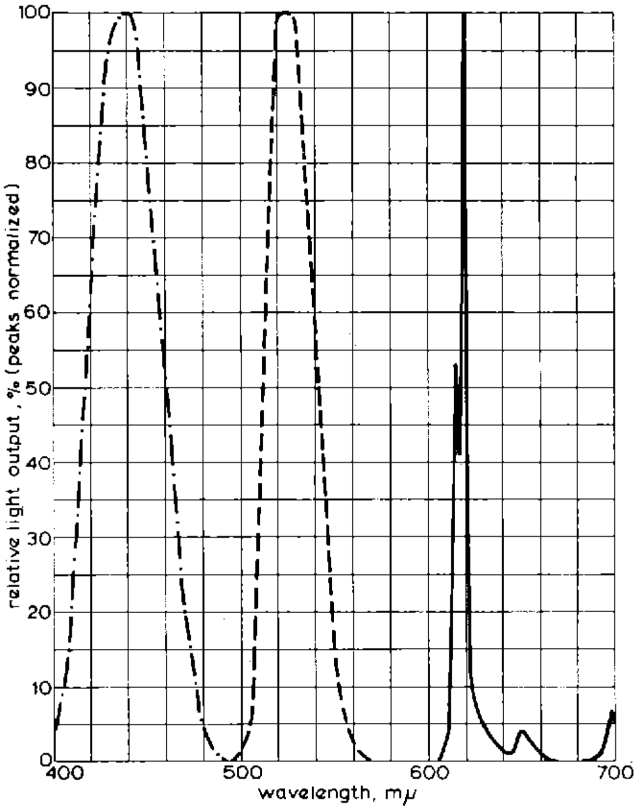


Fig. 11 — Spectral characteristics of the light from the three colour-separation channels
(*Each peak value has been normalized to equal* 100 *per cent*)

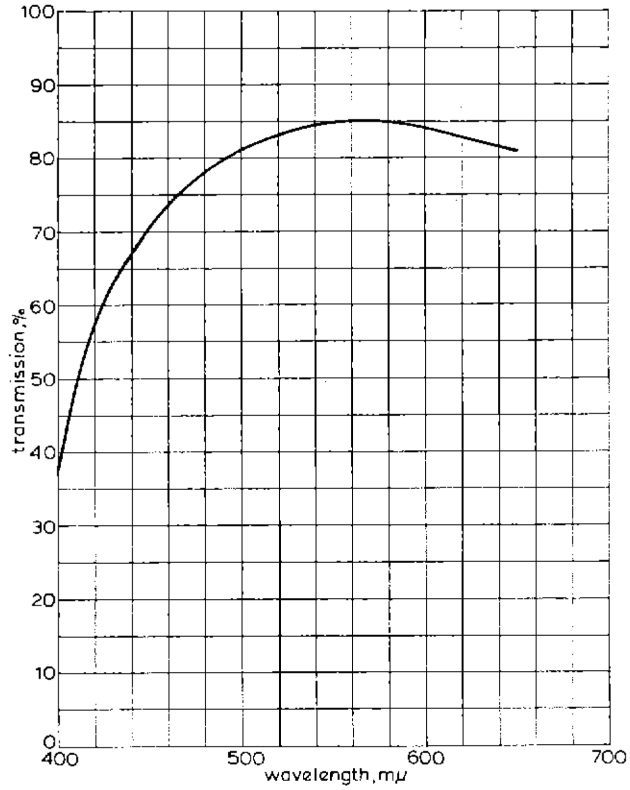


Fig. 12 — Spectral transmission of camera lens used for the film exposure tests

TABLE 3

Flare Figures of Telerecording Display for Various Measurement Conditions

Measurement conditions	Flare figure (%) for indicated channel including flare due to photometer or camera		
	Red	Green	Blue
Cathode-ray tubes alone	2·7	2·6	6·4
Cathode-ray tubes and absorption filters not in optical contact	3·6	3·6	7·7
Cathode-ray tubes and absorption filters in optical contact	1·7	1·4	1·6
Cathode-ray tubes: filters in optical contact: dichroic mirrors	2·1	1·7	2·1

various conditions using as a test picture a peak-white raster having a black square at its centre equal to 1/15 of the raster area. The brightnesses of the dark patch and the surrounding area of this picture were measured and the ratio of these two measurements, expressed as a percentage, was taken as the flare factor. A spot photometer* was used to make the brightness measurements. The flare of this photometer was 1 per cent when presented with a picture subtending the same angle as that obtained in the telerecording display. The flare performance of the camera and lens used in the film-exposure experiments was very similar, so the values shown in Table 3, which are measured results with no correction made for the photometer flare, can be taken as indicating directly the flare that would occur in practice in the complete optical system.

The faceplate of the blue tube had greater transmission than the faceplates of the tubes in the other two channels and the intrinsic flare of this tube was therefore the greatest. The increase in flare due to specular reflexions from shaping filters not in optical contact with the cathode-ray tube faceplates was on average about 1 per cent. The reduction in flare when the filters were placed in optical contact with the cathode-ray tube faceplates was particularly significant in the blue channel because of the poor flare performance of the blue-cathode-ray tube but a worthwhile amount of flare reduction was also produced in the other two channels. The addition of the dichroic mirrors to form the complete optical paths of each channel increased the flare figure by about 0·5 per cent.

3.5 *Correction for Flare in the Display*

By making an allowance for flare in the photometer used for the measurements, it can be seen from Table 3 that in any of the colour-separation channels only one-third of the total flare is contributed by the cathode-ray tubes, the remainder being due to 'veiling glare' from general scatter in the system. In a television camera, correction for veiling glare can be made by subtracting from the linear signal an amount proportional to the mean scene brightness but in optical systems such correction is usually not possible because of the inability to produce 'negative light'. In the present case, however, a correction may be achieved because the light output from the display is not zero in black picture areas. The presence of flare in the display can be compensated by a corresponding reduction in picture brightness up to the limit at which all the 'sit' brightness in black picture areas is due to flare and none to actual light output from those phosphor areas. The brightnesses of all areas of the picture as produced on the cathode-ray tube phosphor would by this technique be decreased by the same amount, the extent of this decrease being such that the flare in the display system would restore each brightness value to its intended magnitude.

A full realization of this technique would require the linearization of the incoming video signal (Fig. 13) and the subtraction of a potential proportional to the average value of the linear signal, followed by the gamma correction of this modified signal to suit the transfer charac-

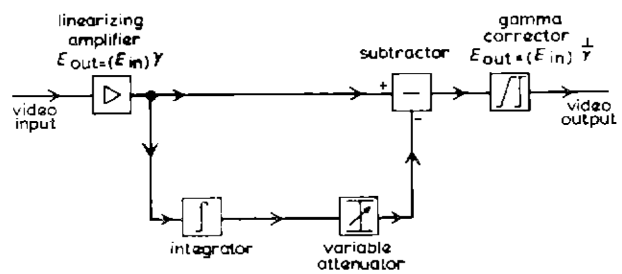


Fig. 13 — Illustration of a veiling-glare corrector

* The Spectra Brightness Spot Meter, manufactured by the Photo Research Corporation, Hollywood, California, U.S.A.

teristic of the display tube. It may, however, be possible to use a simplified arrangement in which the incoming signal is clamped so that the peak-brightness level is held constant, and is then subjected to a variable amount of black-stretching, the amount depending on the degree of flare-correction required and on the average brightness of the displayed picture.

It is possible to correct for the remaining cathode-ray tube flare by forming a diffuse negative (in the photographic sense) image which is then superimposed on the original display. Separate correction would, however, be required for each colour-separation channel, and the instrumental complexity would be considerable. In practice, the subjective effects of cathode-ray tube flare and veiling glare are very similar and it would probably be sufficient to compensate for all flare in the optical system by adjustment of the d.c. level as described above, since the amount of cathode-ray tube flare is less than one-third of the total. The subjective improvement of picture quality obtained by over-correcting for cathode-ray tube flare might, however, be beneficial in a colour telerecording display; to avoid the appearance of coloured haloes round bright objects in the scene, it would need to be applied as a luminance correction (i.e. equally to all three channels), the single correction signal being derived from a luminance signal formed by matrixing the colour-separation signals in the conventional manner.

4. Conclusions

The spectra of the light reaching a colour film from the red and blue colour-separation channels in a colour telerecording system may be chosen so that only the cyan and yellow dye layers respectively are effectively exposed, the exposure of the other two layers being very small in both cases. The degree of such unwanted exposure is greater in the green colour-separation channel, but acceptable sensitometric performance can nevertheless be obtained. The phosphors used in the three channels are acceptable as far as linearity, sensitivity, grain, and afterglow are concerned.

The reduction of cathode-ray tube flare is of great importance in the design of a colour telerecording display. It may be considerably reduced by placing the absorption-type filters in optical contact with the cathode-ray tube faceplates and when this is done, the predominant cause of flare is veiling glare in the camera lens and other optical components of the display, which may largely be compensated in a simple manner.

5. Acknowledgements

The authors wish to acknowledge the assistance and advice obtained from many sources. Thanks are due in particular to members of Kodak Research Department for their assistance in the processing and measurement of the test exposures, and to members of Ferranti Ltd for the provision of the cathode-ray tubes and phosphors.

6. Appendix

The Effect of Afterglow on Film Exposure

The effective exposure of the film in a telerecording process can be represented by the equation

$$E_\tau = \mathrm{k}\int_0^\tau B(t)\mathrm{d}t \qquad (1)$$

where E_τ is the exposure of the film.

$B(t)$ is the time-function describing the afterglow characteristic.

τ is the elapsed time between the excitation of the phosphor element by the scanning beam and the obscuration of this element from the film by the camera shutter.

k is a linear sensitivity factor.

In practice $B(t)$ may be a function that is not capable of exact integration: equation (1) is then solved by measuring the area (A_τ) under the afterglow characteristic curve between the ordinates at $t=0$ and $t=\tau$ (OABC, Fig. 14)

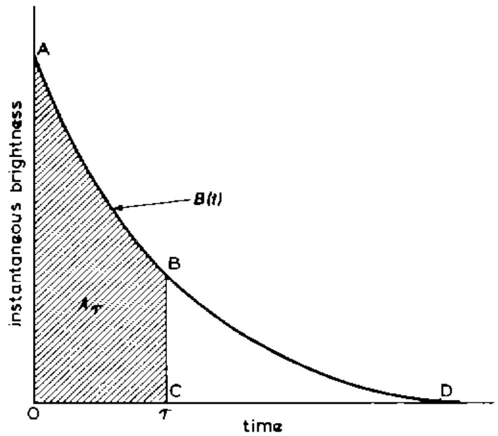


Fig. 14 — Determination of film exposure (see text)

and may therefore be rewritten

$$E_\tau = \mathrm{k}\, A_\tau \qquad (2)$$

The maximum exposure (E_{max}) is obtained when the light output from the phosphor has fallen to zero before the closing of the camera shutter: in this case

$$E_{max} = \mathrm{k}\, A_{max} \qquad (3)$$

where A_{max} is the area OABDCO in Fig. 14. The exposure of the film for any given value of τ relative to the maximum value (E_{rel}) is thus, from equations (2) and (3),

$$E_{rel} = \frac{E_\tau}{E_{max}} = \frac{A_\tau}{A_{max}} \qquad (4)$$

For the willemite phosphor used in the green channel of the telerecording display a relation between E_{rel} and τ is shown in Fig. 15. This relation is based on the manufac-

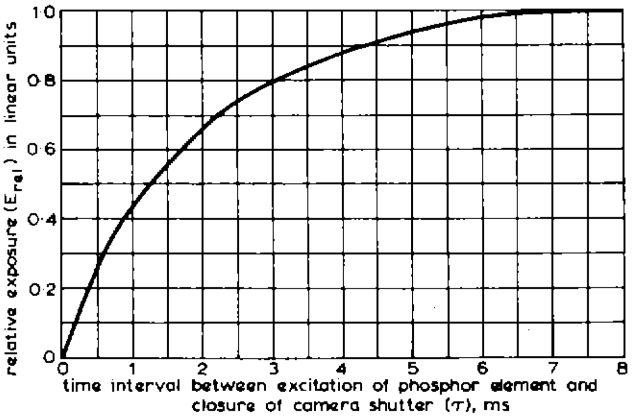


Fig. 15 — Relation between relative exposure and delay in closure of camera shutter

turer's published data on the phosphor time-constant: because this time-constant depends on the 'loading' of the phosphor (in terms of beam current per unit area) some departures may in practice occur from the curve shown in Fig. 15. It can be seen that for no exposure error to occur the time interval between the excitation of the phosphor and the closure of the shutter must exceed 7 ms: thus ideally the camera shutter should not close until 7 ms after the lowest line of the recorded scan is reached.* This implies that 13 ms would be available for film transport (i.e. 117 degrees out of the complete camera operating cycle of 360 degrees).

A shorter time-delay in closing the camera shutter will result in the appearance of a magenta 'cast' at the bottom of the recorded picture because of incomplete exposure of the green colour-separation signal. It can be seen from Fig. 15 that a delay of 4·4 ms would give rise to 10 per cent under exposure at the extreme bottom of the picture, the degree of under-exposure diminishing rapidly for picture areas further into the picture and falling to zero for areas 13 per cent above the bottom of the picture. In practice, the colour-cast produced by this degree of under-exposure is likely to be quite acceptable; under these conditions 15·6 ms or 140 degrees of the camera operating cycle would be available for film transport.

* It is assumed that the recording system used is such that during alternate periods of 1/50 second no picture information is displayed, thus permitting the use of a relatively slow-pulldown camera.

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