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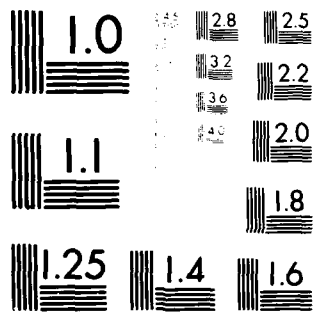
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MELBOURNE, VICTORIA**REPORT****MRL-R-767**

**A MEANS OF SPECIFYING INFRARED PROPERTIES OF CAMOUFLAGE
MATERIEL TO DEFEAT FALSE-COLOUR SURVEILLANCE**

David R. Skinner

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A MEANS OF SPECIFYING INFRARED PROPERTIES OF CAMOUFLAGE

MATERIEL TO DEFEAT FALSE-COLOUR SURVEILLANCE

1. INTRODUCTION

A common surveillance technique for the detection of camouflaged military matériel in a foliated environment is the use of false-colour photography (otherwise known as camouflage-detection photography) to detect any mis-match of near-infrared reflectance between a target and its background. Such a mis-match is likely because of the difficulties involved in mimicking the sharp rise in the reflectance spectrum of live green vegetation between 690 and 820 nm wavelengths. This rise is exemplified by Fig. 1, which shows the reflectance spectrum [1] of a single leaf (eucalyptus robusta - "mahogany gum"). Reflectance spectra for multiple-leaf specimens of foliage are much more difficult to obtain, but represent subdued versions of this, in that they have lower maxima and higher minima. False-colour photography provides a means of examining near-infrared reflectance by presenting an image in which colours are down-shifted in wavelength relative to those of the original subject, so that infrared is represented as red, red is represented as green, green is represented as blue, and blue and ultraviolet are suppressed by a yellow filter. This is shown schematically in Fig. 2.

A comparison of Figs. 1 and 2 leads immediately to the conclusion that the false-colour image of a leaf will appear purplish pink, since it will show a large red component derived from the infrared reflectance of the leaf, virtually no green as the leaf does not reflect much in the red, and a significant blue contribution from the visually obvious green. It is also obvious that a material matching the leaf for visual colour but deficient in near-infrared reflectance will be rendered too dark and too blue in a false-colour image. The sensitive colour discrimination of a normal trichromatic observer can thus be used to detect, in a false-colour image, materials that differ slightly from foliage only in near-infrared reflectance.

It would clearly be advantageous for the camoufleur to use materials that match foliage in reflectance over the entire wavelength range of probable surveillance. This is, however, likely to be difficult to achieve. A reasonable compromise would be to match foliage visually and in false-colour imagery. Because of the sharpness of the red-to-infrared rise in the

reflectance spectra, it appears likely that any material providing a good match for visual and false-colour imagery will also be difficult to detect with other forms of near-infrared surveillance.

This paper describes a simple method of specifying the near-infrared reflectance of materials for defeating false-colour surveillance, and presents experimental evidence that the method is valid.

2. THEORETICAL CONSIDERATIONS

In an ideally linear false-colour system, the contributions R, G and B of red, green and blue stimuli to the eye from an image would be :

$$R = \int_{\lambda} S_{IR,\lambda} E_{\lambda} \rho_{\lambda} d\lambda \quad (1)$$

$$G = \int_{\lambda} S_{R,\lambda} E_{\lambda} \rho_{\lambda} d\lambda \quad (2)$$

$$B = \int_{\lambda} S_{G,\lambda} E_{\lambda} \rho_{\lambda} d\lambda \quad (3)$$

where $S_{IR,\lambda}$, $S_{R,\lambda}$ and $S_{G,\lambda}$ represent the wavelength-varying sensitivities of the infrared, red and green-sensitive parts of the false-colour film, E_{λ} is the spectral irradiance of daylight and ρ_{λ} is the spectral diffuse reflectance of the subject of the photograph. The perceived chromaticness (combination of hue and chroma) of the image depends on the ratios R:G:B whilst the lightness depends on the level of the three stimuli [2]. The perceived lightness is of little interest in the definition of infrared properties, since this will be correct if the visual colour is suitable.

It is now proposed to define three weighted reflectances ρ_{IR} , ρ_R and ρ_G respectively for the infrared, red and green regions of the spectrum by :

$$\rho_{IR} = \frac{\int_{\lambda} S_{IR,\lambda} E_{\lambda} \rho_{\lambda} d\lambda}{\int_{\lambda} S_{IR,\lambda} E_{\lambda} d\lambda} \quad (4)$$

with similar equations for ρ_R and ρ_G . The stimuli R, G and B from the image are then :

$$R = K_{IR} \rho_{IR} \quad (5)$$

$$G = K_R \rho_R \quad (6)$$

$$B = K_G \rho_G \quad (7)$$

where K_{IR} , K_R and K_G are constants. It follows that the chromaticness of an image will depend only on the ratios $\rho_{IR}:\rho_R:\rho_G$. (This is closely analogous to the CIE recommendations [3] for defining surface colours under standard illuminants by weighting spectral reflectance). Since the ratio ρ_R/ρ_G is effectively specified by the condition that visual colours should match, it is concluded that a match in false-colour imagery can be specified purely by the ratio ρ_{IR}/ρ_R .

3. PRACTICAL CONSIDERATIONS

In order to reduce the required calculations to a finite number of steps, it is necessary to replace Eq. 4 by :

$$\rho_{IR} = \left(\sum_{\lambda} \rho_{\lambda} w_{IR,\lambda} \right) / F_{IR} \quad (8)$$

where $\sum_{\lambda}$ implies summation over a specified sequence of wavelengths, $w_{IR,\lambda}$ is a weighting factor proportional to the product $S_{IR,\lambda} E_{\lambda}$ and F_{IR} is written for $\sum_{\lambda} w_{IR,\lambda}$. There is, of course, an analogous expression for ρ_R , where the summation is over a different sequence of wavelengths.

The values of $S_{IR,\lambda}$ and $S_{R,\lambda}$ were estimated from published sensitivity curves [4] for Kodak Infrared Ektachrome, the only false-colour photographic film readily obtainable in Australia. The irradiance function E_{λ} was approximated by the figures of Moon [5], a fairly arbitrary choice from a number of published spectra. The products of these figures were scaled to give convenient values of $w_{IR,\lambda}$ and $w_{R,\lambda}$, both having maxima of 100. These figures are shown in Table 1.

A final practical consideration is the achievement of the best possible approximation to the ideal linear response assumed in the above analysis. Since the colorimetric process is close to linear, this problem reduces to that of finding the most suitable exposures for photographs using false-colour film. Unfortunately, there are no exposure meters (known to the author) for use with this type of film, and therefore it is necessary to "bracket" the exposure, that is, to produce a number of photographs having exposures less than, equal to and greater than a nominally correct value. A best photograph can then be chosen, using the criterion that there should

be a minimum loss of detail resulting from either burning-out of highlights or under-exposure of shadowed areas. This should maximise the area of the photograph for which the exposure is on the linear part of the characteristic curve of the film.

4. EXPERIMENTAL VALIDATION

Experimental validation was carried out using twelve samples [6] of poly(vinyl chloride) all having similar light olive-green visual colours, but differing appreciably in infrared reflectance. The weighted mean reflectances ρ_{IR} and ρ_R were computed according to Eq. 8 and Table 1 from measurements of diffuse spectral reflectance taken on a Cary 14 spectrophotometer. The ratio ρ_{IR}/ρ_R for each sample is shown in Table 2.

The samples were mounted on a card, and photographed against a background of temperate eucalyptus forest (at Mt. Macedon, Vic.) using Kodak IE 135-20 film. Photographs were taken using five exposures at one-stop intervals, centred on the value indicated by a standard (visual range) exposure meter set for 100 ASA film. The colours of the images of the samples, and of a section of background foliage, were compared, using a Spectra-Pritchard telephotometer, with a small area of purplish-pink paint (Berger "Scotch Heather") from which a diffuse reflectance spectrum had previously been obtained. The technique used was to illuminate the paint sample using a conventional 35-mm slide projector run from a stabilised power supply (without a slide in place) and to measure the R, G and B stimuli. The paint sample was replaced by a white screen, the false-colour slide was placed in the projector, and the stimuli were measured for the images of the plastics samples and of the background. There was a problem in converting these measurements to the conventional colour coordinates [3] x , y and $Y(\lambda)$, since the projector contained a quartz-halogen lamp having a correlated colour temperature intermediate between those of Standard Illuminants A and C. This problem was resolved by carrying out calculations in parallel based on both illuminants.

In order to compute differences in chromaticness, it was necessary to convert the measured colour coordinates to vectors capable of resolution into separate components of chroma, hue and lightness. The most suitable transformed system was considered to be the CIE 1976 ($L^* a^* b^*$) uniform colour space (CIELAB space) [7], which is designed for the comparison of surface colours. Chromatic difference can then be defined as $\sqrt{(\delta C^2 + \delta H^2)}$, where δC is the difference in chroma and δH the difference in hue. Chromatic differences were computed between the background and all twelve samples, using the alternative assumptions of Illuminant A and Illuminant C for the projector lamp. These computed values are shown in Table 2, from which it can be seen that the choice of assumption for illuminant is not at all critical.

It was known [8] that the diffuse reflectance at 850 nm wavelength is used as a quality-control check in the manufacture of camouflage materials, and therefore it was considered profitable to compare ρ_{IR}/ρ_R and ρ_{850} as

measures of predicted chromatic difference in false-colour imagery. The values of ρ_{850} for the samples are also shown in Table 2.

Figures 3 and 4 show the variation of chromatic difference with ρ_{850} and ρ_{IR}/ρ_R respectively, based on the assumption that the projector lamp approximates Illuminant A. Figures 5 and 6 show similar plots based on the assumption that the lamp approximates Illuminant C. The straight lines in Figs. 4 and 6 represent least-squares fits, in which ρ_{IR}/ρ_R is taken as the independent variable. Correlation coefficients were computed for all four plots, and it was established that the correlation of chromatic difference with ρ_{IR}/ρ_R was significant at the 0.001 level for both assumptions of illuminant, whereas the correlation with ρ_{850} was not significant at the 0.1 level for either.

It is not feasible to predict from Figs. 3 and 5 what value ρ_{850} should have for the best possible match with foliage, but it is clear from Figs. 4 and 6 that ρ_{IR}/ρ_R should have a value somewhat higher than 5.

5. CONCLUSIONS

An analysis of false-colour photography as an ideal linear system leads to the conclusion that the appearance of a false-colour image is determined entirely by three spectrally-weighted reflectances of the subject of the photograph. It further appears that, when two subjects are matched for visual colour, the match in false colour is determined simply by the ratio of two of these reflectances. A suitable set of spectral weighting functions has been derived from published data.

An experiment using twelve plastics samples of similar visual colour but different infrared reflectance has confirmed that differences in chromaticness between false-colour images of the samples and of eucalyptus foliage correlate with the infrared-to-red reflectance ratio at the 0.001 level of significance, indicating an ideal ratio a little over 5. This degree of correlation suggests that a good enough approximation can be achieved, in practice, to the ideally linear photographic process assumed in the analysis. There is no significant correlation when chromatic difference is plotted against a simple measure of infrared reflectance.

It is concluded that the proposed method of comparing weighted infrared and red reflectances is a valid technique for specifying infrared properties to defeat false-colour surveillance.

6. ACKNOWLEDGEMENTS

The author wishes to acknowledge the ready cooperation of Mr. G. Johansson of Barracudaverken AB and Mr. G. Lindqvist of Svenskfärg Industries in the supply of technical information and of material samples.

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T A B L E 1

WEIGHTING AND SCALING FACTORS FOR REFLECTANCE

Red		Infrared	
λ (nm)	$w_{R,\lambda}$	λ (nm)	$w_{IR,\lambda}$
570	13	650	44
580	17	660	49
590	22	670	54
600	27	680	64
610	38	690	69
620	57	700	92
630	81	710	100
640	96	720	77
650	100	730	80
660	92	740	79
670	53	750	62
680	16	760	38
		770	61
		780	55
		790	54
		800	50
		810	41
		820	46
		830	46
		840	41
		850	35
$F_R = 612$		$F_{IR} = 1237$	

T A B L E 2

MEASURED PROPERTIES OF PLASTIC SAMPLES

Sample No.	$\rho_{850}(\%)$	ρ_{IR}/ρ_R	$\sqrt{(\delta C^2 + \delta H^2)}^*$	
			Source A [†]	Source C [†]
1	69.1	3.06	23.0	22.0
2	73.5	3.29	17.9	17.1
3	60.2	4.46	9.6	8.9
4	54.5	1.89	41.7	41.3
5	55.1	2.15	34.7	34.5
6	83.8	3.38	23.0	22.1
7	86.1	3.73	20.4	19.7
8	62.2	2.94	26.6	26.4
9	73.3	2.95	22.4	21.8
10	70.2	3.18	24.2	23.6
11	65.0	3.22	23.4	22.8
12	65.9	3.52	21.3	20.8

* Chromatic difference between sample and foliage in false-colour photographs measured in CIELAB units.

† Assumption made for type of lamp in projector used with false-colour transparencies.

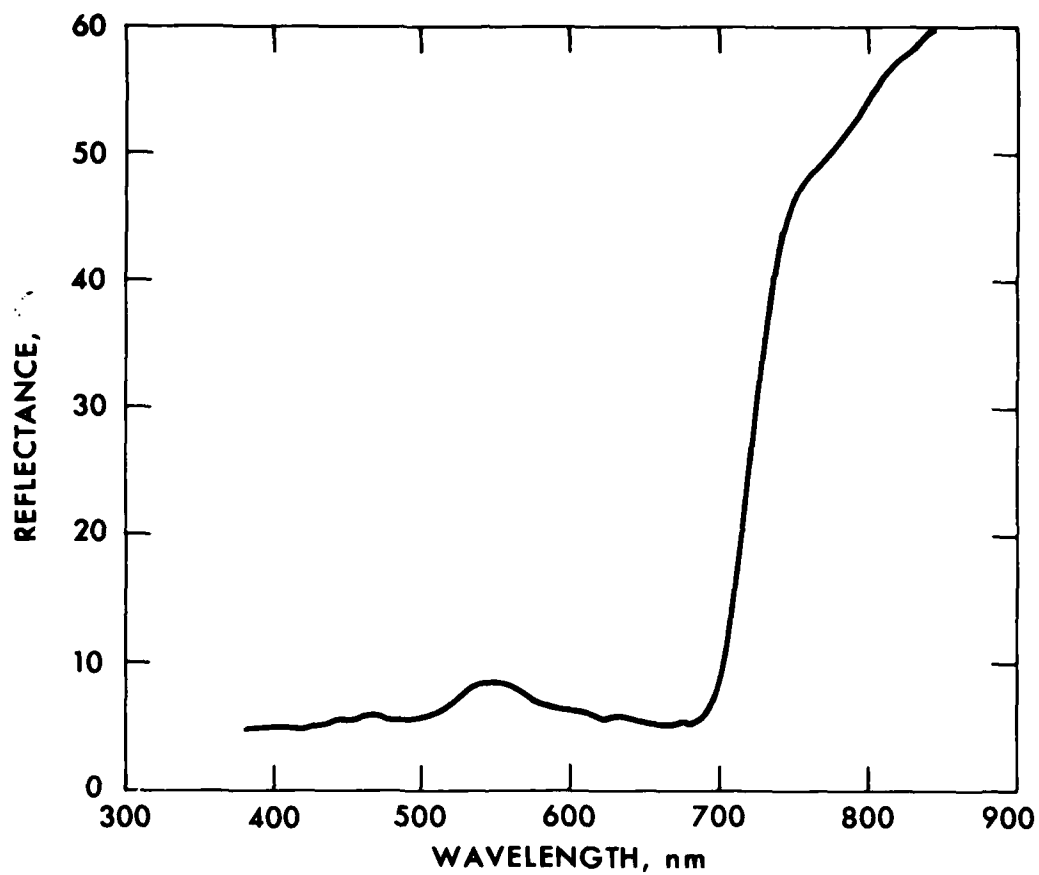


FIG. 1 - Variation of diffuse reflectance with wavelength for single leaf of eucalyptus robusta ("mahogany gum") - dark green specimen measured 3 hours after picking.

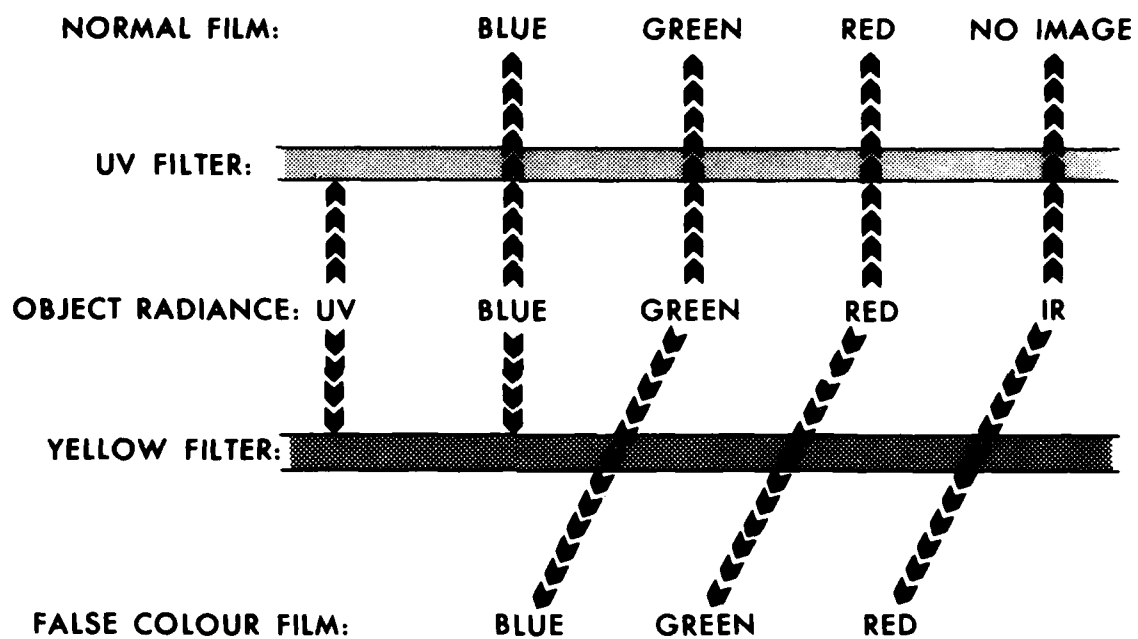


FIG. 2 - Schematic representation of the behaviour of normal-colour and false-colour film with appropriate filtration.

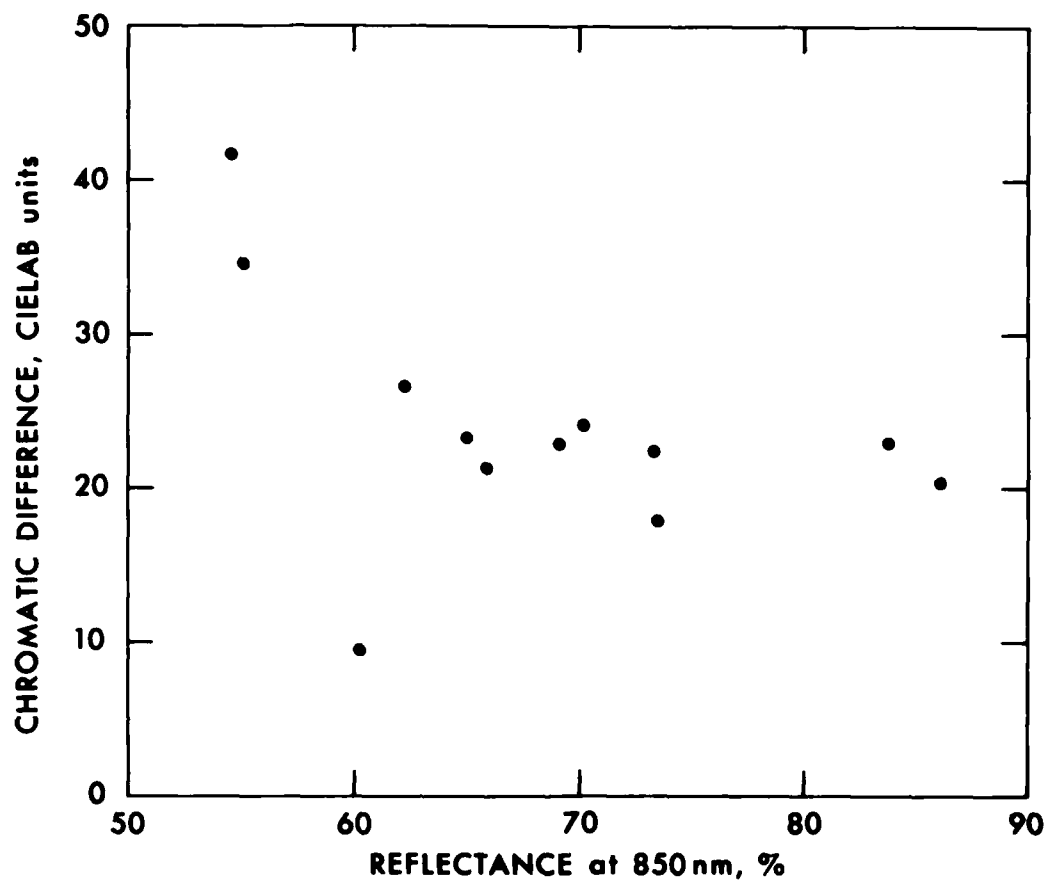


FIG. 3 - Comparison of chromatic difference with reflectance at 850 nm for plastics samples. Illuminant A assumed for projector lamp.

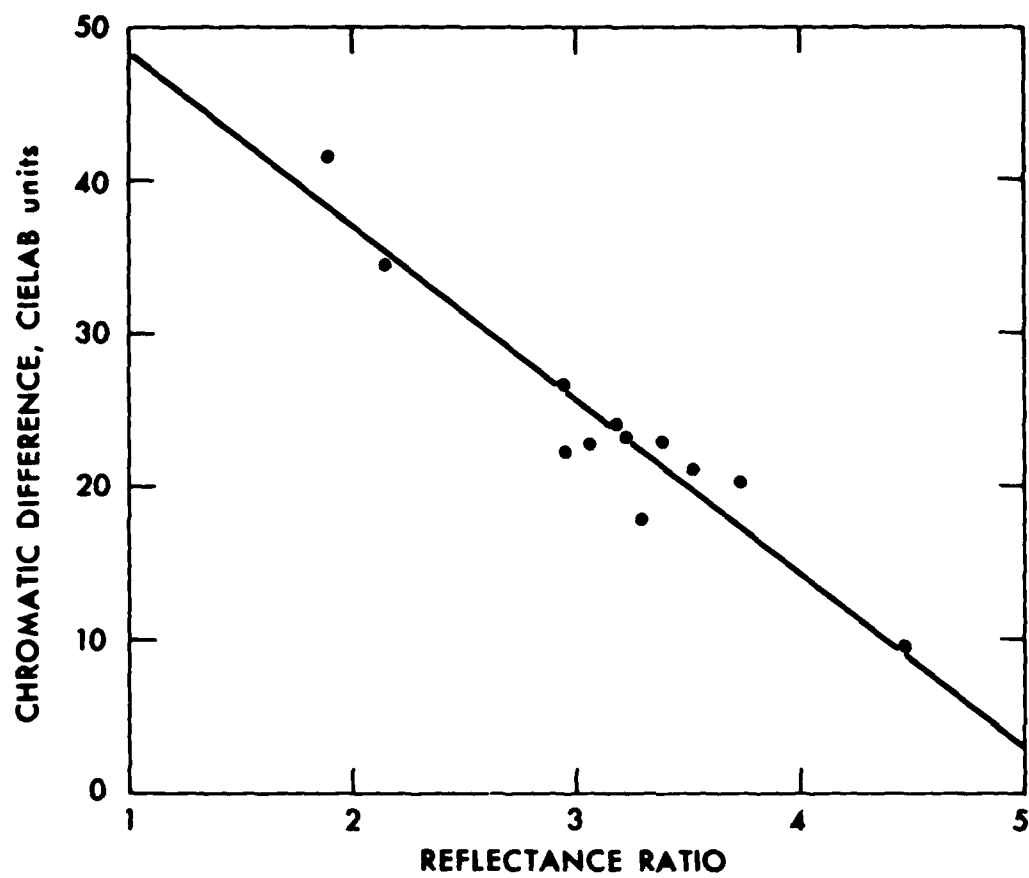


FIG. 4 - Comparison of chromatic difference with infrared/red reflectance ratio for plastics samples. Illuminant A assumed for projector lamp.

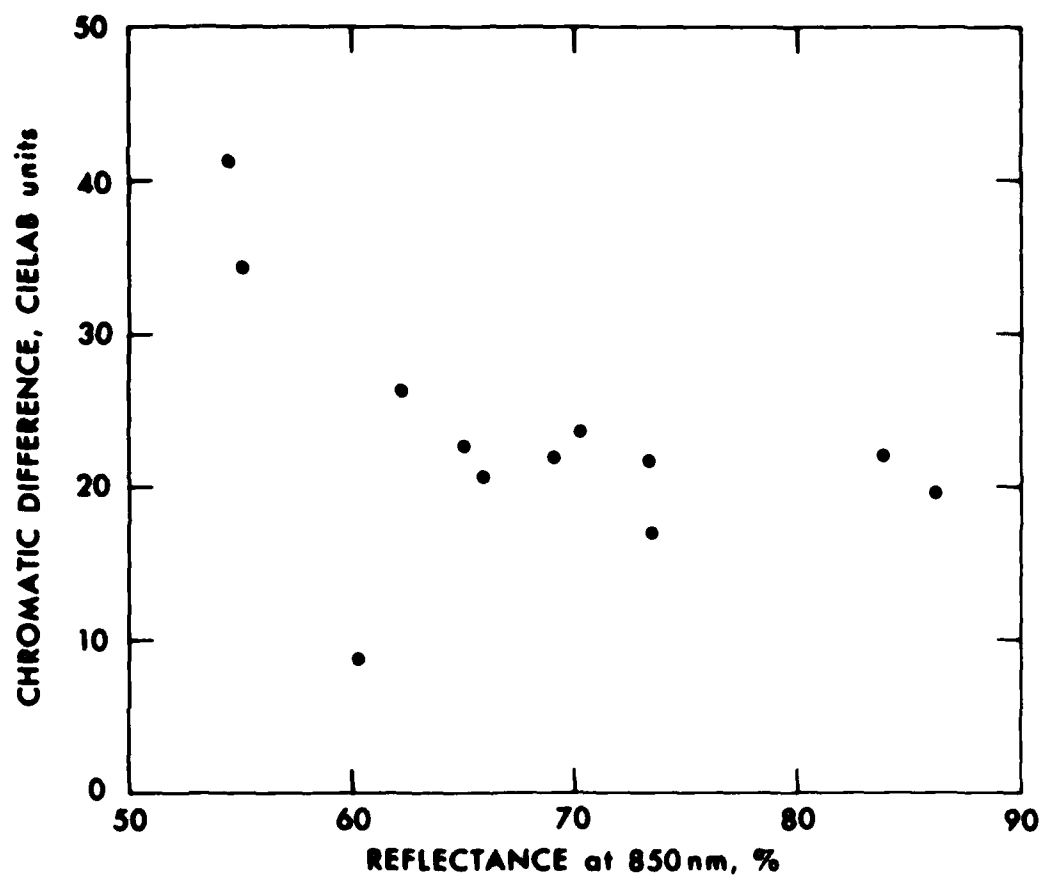


FIG. 5 - Comparison of chromatic difference with reflectance at 850 nm for plastics samples. Illuminant C assumed for projector lamp.

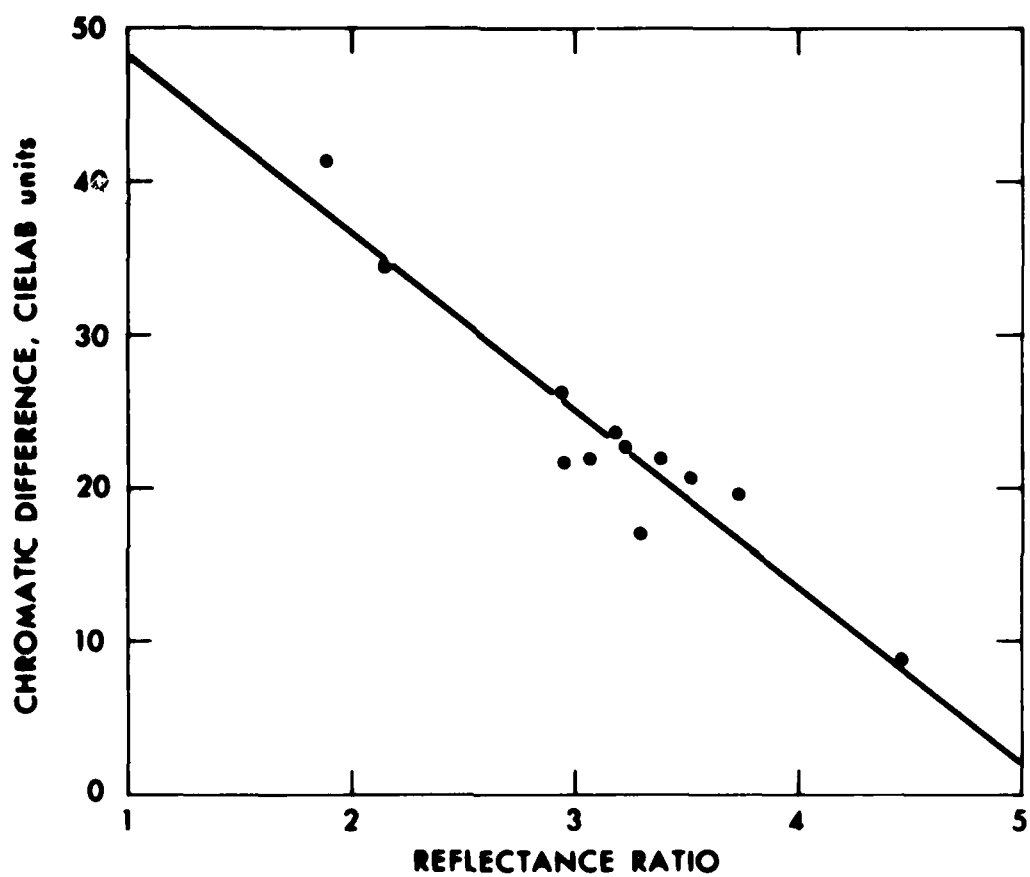


FIG. 6 - Comparison of chromatic difference with infrared/red reflectance ratio for plastics samples. Illuminant C assumed for projector lamp.

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