

Emulsion Speed Rating Systems

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ABSTRACT: Early methods for determining and expressing film speeds were empirical. Hurter and Driffield's classic paper of 1890 described the "characteristic curve" and established the first rigorous criterion for film speed based on scientific principles.

Criteria used have been based on threshold, inertia, fixed density, minimum useful gradient, and fractional gradient. The various criteria and systems based on them, some of which preceded, but most of which followed from Hurter and Driffield's work, and which have been used for longer or shorter periods of time since then, are reviewed.

1. Introduction

Successful photography depends on, amongst other things, the emulsion receiving an exposure which will produce a negative or transparency in which the developed densities accurately represent the range of luminances existing in the original scene. If the range of scene luminances results in film illumination beyond a certain maximum range, highlights or shadows (or both) will lack detail. In order that the photographer can make an accurate estimate of the optimum exposure, a knowledge of a number of parameters of the photographic system is required. In particular, the range of scene luminances (often contracted into a single integrated value for the light reflected from the scene) must be measured, or a single measurement of the illumination of the scene—an incident light reading—must be made and the speed of the emulsion must be known. Other factors, such as flare, may be important and must then be taken into account. However, all that is required for most purposes is a measure of "the light" and a knowledge of the emulsion speed to allow a satisfactory exposure to be determined. The combined effects of these will result in a predictable range of densities being present in the developed image.

Under unchanging external conditions the illumination at any point of an emulsion will vary with the aperture of the camera lens, and the exposure (illumination \times time) will not vary if a correspond-

ing adjustment to the exposure time is made. Thus a single exposure estimation results in a range of possible camera aperture/exposure time combinations and it will be assumed that the photographer will decide which combination to use on other criteria than the arriving at an optimum exposure. In the absence of any information on emulsion speed the photographer can only use empirical assessment methods based on trial and error and, to a larger or smaller degree, his or her prior experience.

The measurement of scene illumination or range of luminances is beyond the scope of this paper which is only concerned with emulsion speed.

2. The situation prior to Hurter and Driffield

In the period towards the end of the nineteenth century film manufacturers were beginning to be able to produce emulsions with a reasonably small batch-to-batch variation in speed, and for this to result in published emulsion speed data required the establishment of criteria on which the speed of an emulsion could be determined. Warnerke¹ had devised a method based on the idea of just discernible density in 1880, but it was empirical and required the user to construct a device, effectively a simple sensitometer, to make use of it. There was no system for the assessment of emulsion speed based on scientific principles.

3. The innovations of Hurter and Driffield

The partnership of Ferdinand Hurter and Vero Charles Driffield was a powerful one. Their mutual interest in photography led to an early realization that there was little or no research being conducted on the "sensitiveness" of emulsions. Hurter's was the first attempt at a theoretical analysis of the complete photographic process and, together with Driffield's practical skills resulting from his engineering background, culminated in the classic paper of 31st May 1890—Photo-chemical investigations and a new method of determination of the sensitiveness of photographic plates.²

Hurter's mathematical analysis led him to produce a plot of density v. exposure, but he soon realized that a plot of density v. log (exposure) was a much more satisfactory way of representing the data. This was the first description of the characteristic curve as we know it today.

Hurter showed mathematically that the developed density, D , is related to:-

- the slope (γ) of the (straight line part of the) characteristic curve,
- the intensity (I) and time (t) of the exposure, and
- a quantity that he called the inertia (i) of the emulsion.

The expression for the characteristic curve derived by Hurter is³

$$D = \gamma \log_e [O - (O - 1)\beta^{(t/i)}] \quad (1)$$

where O is the 'opacity of the plate to chemically active rays before exposure', and β is given by $\log_e (-1/O)$.

If $1 < It/i < O$ this can be simplified⁴ to

$$D = \gamma \log_e (It/i) \quad (2)$$

Since It/i is a number and hence dimensionless, we note that i has the dimensions of exposure.

On plotting density, D , above base + fog ($B+F$) against the exposure ($I \times t$) on a logarithmic scale, the resulting line had the now familiar S-shape of the characteristic curve. The slope of the central straight line portion was the quantity γ of equations 1 and 2 above, and the intercept on the exposure axis gave the value of i , since, when $D=0$, equation 2 becomes

$$0 = \gamma \log_e (It/i) = \gamma (\log_e (It) - \log_e i)$$

Hence $i = It$ when $D=0$.

Hurter and Driffield also recognized that the characteristic curve illustrated the failure of a photographic emulsion to correctly represent scene luminances in regions of under- and over-exposure. Fig. 1 illustrates this.

It was clear that the greater the value of the inertia, i , the slower was the emulsion since it would be associated with a higher value for the exposure. A measurement of the inertia would thus allow the speed of the emulsion to be determined.

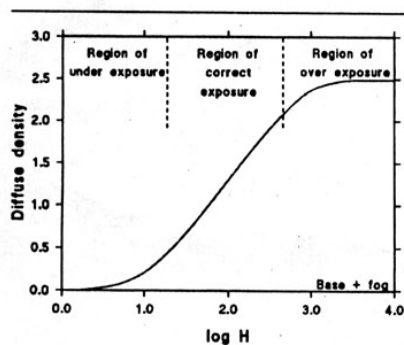


Fig. 1. H & D curve.

4. Emulsion speed rating criteria

In date order of their first introduction, criteria for the assessment of emulsion speed have included threshold (1880),¹ inertia (1890),² fixed density (1934),⁵ minimum useful gradient (1939)⁶ and fractional gradient (1943).⁷ Over the years these have enjoyed in turn more or less acceptance, with the more recent choice of criteria depending on whether monochrome or colour emulsions were being considered, and, in the case of colour materials, whether negative or reversal.

4.1 Threshold

Shadow areas in a photographic negative will lack detail if the exposure received in those areas is insufficient to give density on development. The minimum exposure can be considered as that which produces a just discernible density on the negative.

4.2 Inertia

In classical mechanics, the inertia of a body is what keeps it in its state of rest or uniform motion until acted on by a force. In photographic terms Hurter and Driffield regarded the property of an emulsion to require a minimum exposure to yield a density on development as a parallel to this, although the analogy should not be pushed too far. In practical terms it is the intercept of the straight line part of the characteristic curve with the line representing B+F on the density axis. The position of this point was found in limited experiments by Hurter and Driffield to be independent of the developer used and the development time. They concluded that it represented a value related to the speed of the emulsion alone. They did, however, concede that it might be possible to find a developer which would materially affect the speed of the emulsion.⁸

4.3 Fixed density

The idea of a just discernible density

depends on the judgement (and possibly the honesty) of the observer. By defining a chosen fixed minimum density as the basis for emulsion speed determination, this dependence is eliminated.

4.4 Minimum useful gradient

Differences in scene luminance may result in differences in developed density, but in the region of minimum exposure these differences in density may be very small. For shadow areas, those differences in scene luminance will appear on the print only if there is a reasonable difference in densities, that is, if the slope of the toe of the characteristic curve exceeds a reasonable minimum value. The minimum useful gradient criterion places the speed point where the gradient first reaches some agreed value.

4.5 Fractional gradient

A criterion based on minimum useful gradient is open to the criticism that emulsions of differing "gamma" will reach that gradient at different exposures, and would be regarded as being different in speed despite other sensitometric parameters contradicting this. If the speed point is defined as the point at which the slope of the characteristic curve first reaches a fixed fraction of the gradient, or average gradient, of the useful part of the characteristic curve, this objection is largely overcome.

5. Emulsion speed rating systems

Before the more important systems are described it may be useful at this point to clarify four points.

First, Hurter and Driffield's characteristic curve was a plot of density ($\log_{10} O$) against exposure plotted on a scale in which consecutive points differ by a factor of two. Modern practice is to plot both density and log exposure as base 10 logarithmic quantities, and with equal scales for both. This results in a slope (gamma) of 1 being represented by a line at 45° to the axes. This convention is used throughout the paper.

Second, Hurter and Driffield's theoretical studies were expressed in natural logarithms, whereas modern practice is to use base 10 logarithms for convenience. The difference in most instances is simply a constant multiplier.

Third, emulsion speeds may be given in two forms, arithmetic, in which succeeding film speed numbers double for a twofold speed increase, and logarithmic, in which the successive speed numbers increase by three for a doubling in speed. In most cases this is just two alternative ways of expressing the same quantity,

there being a simple relationship between the two values. Arithmetic speeds have the disadvantage of becoming large numbers as speed increases much more rapidly than is the case with logarithmic speeds, but have the advantage of being more readily understood. It is intuitively more acceptable to say that a film speed of 200 is twice as fast as one of speed 100 than it is to relate speeds of 24° and 21°, although the relationship is identical in the two cases.

Fourth, over the years the symbols used to represent the various parameters, (such as exposure, density, etc.) have been changed a number of times. For consistency in this paper the current internationally agreed symbol, H, will be used for exposure.

5.1 Monochrome emulsions

5.1.1 Systems based on threshold

In 1880 Warnerke¹ described a method for determining speed based on just discernible density. It involved the production of what today would be termed a step wedge consisting of a 5 × 5 array of sandwiches of from one to twenty five squares of pigmented paper. Each square was identified by a number imprinted on it in opaque ink. The emulsion under test was exposed for a fixed time, through this device, to the only standard light source available at the time, a candle. After development the negative was examined and the number on the square where density was just discernible gave a measure of the speed of the emulsion.

Disadvantages of this system, apart from the variability of the exposing source, are the difficulty of determining the step showing just discernible density, and the fact that the speed was being determined at a point not related to useful densities on the negative.

In Germany in 1894 Scheiner⁹ proposed a system in which the speed point was the point on the characteristic curve at which the density became just discernible. There was considerable room for personal interpretation of what this criterion meant, and in addition no development conditions were specified. This led to a situation in which manufacturers were able to make exaggerated claims for the speed of their materials by clever choice of development conditions and an optimistic view of the meaning of "just discernible". For a time users were confused by the changing film speeds quoted for unchanging emulsions!

5.1.2 Systems based on inertia

The first scientifically based system was, as already noted, that of Hurter and Driffield, and is the only one to have used the idea of the inertia point as the basis for

rating the speed of an emulsion. For the first time the exposure was expressed in a defined unit, the candle-metre-second, which allowed others to make measurements on their own equipment and to produce exposures relating directly to those of Hurter and Driffield.

Fig. 2 shows how the speed point is determined from the characteristic curve. If i is the exposure corresponding to the inertia point, the speed is defined¹⁰ as

$$\text{Speed} = 1/i$$

or, for "actinograph speed"¹¹

$$\text{Speed} = 34/i$$

to give more convenient numbers for emulsion speed.

Although the introduction of the H & D system was a big step forward, it became obvious that it had limitations. Some of these were inherent in the system, such as, for instance, the fact that as newer photographic materials were produced, the shapes of characteristic curves also changed and it became less easy to identify the slope of the straight line part of the curve. In many modern films there is no part of the curve that is straight. Other limitations were due to there being no specification for the developer or development conditions. Hurter and Driffield's emulsions showed little change in the inertia point with different developers, but newer developers produced families of characteristic curves in which the produced straight line part met at points below the log H axis or did not meet at a single point at all. It then became clear that it was unrealistic to continue to use the inertia criterion for speed determination.

5.1.3 Systems based on fixed density

The problems associated with the difficulty of establishing exactly where the threshold density appeared are overcome if the minimum density is specified. In 1934 the first national standard on emulsion speed determination was published

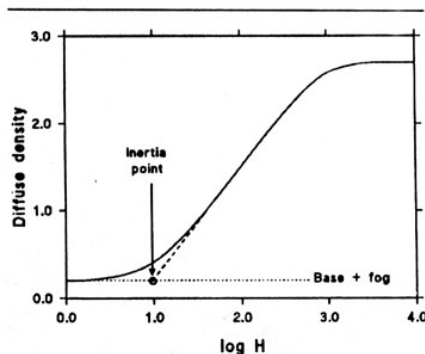


Fig. 2. Inertia speed point.

by the German standards organisation as a DIN (Deutsche Industrie Norm).⁵ In this, the point on the characteristic curve where the density first reaches 0.1 above B+F was specified as the speed point, Fig. 3. Speed is then defined as

$$\text{Speed} = \text{constant} - \log H_s$$

where H_s is the exposure at the speed point.

Even with the specification of the threshold density, lack of standardization of development conditions allowed manufacturers to inflate speeds by developing their emulsions with non-standard developers.

The British Standards Institute (BSI) adopted a similar standard in 1941¹² in which the development conditions were defined to be comparable to average photofinishing practice. The speed was determined in exactly the same way as for the DIN standard.

In the USSR the GOST¹³ standard was published in 1945 in which development conditions were specified and the exposure, H , determined at which the density reached 0.2 above B+F.

The speed was then defined as

$$\text{Speed} = 1/H$$

5.1.4 Systems based on minimum useful gradient

In the late 1930's Lloyd Jones worked on the problem of determining the minimum exposure required to produce a negative from which an excellent print could be made. He realized the importance of the toe gradient in the reproduction of shadow detail and proposed a system of speed measurement¹⁴ which placed the speed point at the exposure where the gradient of the characteristic curve first reaches a value of 0.2, as shown in Fig. 4. Later work showed that the minimum useful gradient depended on the grade of paper on which the print was to be made and this system was never accepted in practice. The work of Jones did however

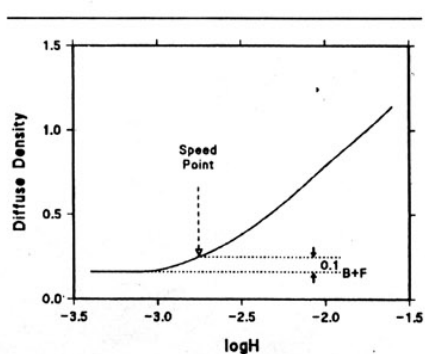


Fig. 3. Fixed density.

lead directly to the next system to be described.

5.1.5 Systems based on fractional gradient

Further work by Jones¹⁵ led to the system based on the observation that the minimum useful gradient depends on the overall contrast of the negative. Thus there is no fixed value for the minimum gradient, but it is defined as some fraction of the gradient of the characteristic curve over a typical subject luminance range. For daylight photography of exterior scenes this is about 30:1, corresponding to a log exposure range of 1.5.

The fraction decided on for the 1943 ASA standard was 0.3, with a fractional gradient (FG) given by

$$\text{FG} = 0.3 \times \bar{G} \quad (1.5)$$

where \bar{G} (1.5) is the average gradient over a logH range of 1.5

The speed point is then the point on the characteristic curve at which this fractional gradient is first reached, and is the lower logH value for the average gradient calculation. These two are not independent, and a certain amount of manipulation is required to finally arrive at the conditions of Fig. 5.

This criterion was found to give negatives from which an excellent print could

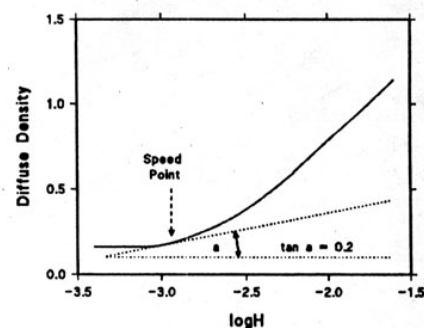


Fig. 4. Minimum useful gradient.

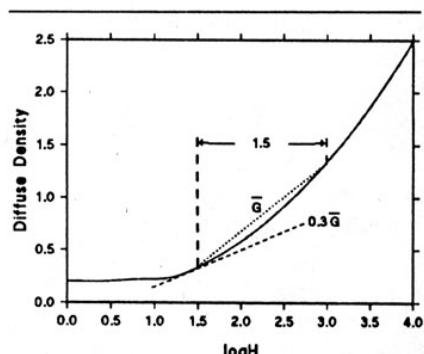


Fig. 5. Fractional gradient.

be made, and was adopted by the American Standards Association (ASA) in 1943¹⁶ and the British Standards Institution (BSI) in 1947.¹⁷

5.1.6 Current ISO standard

The 1941 British Standard on emulsion speed determination used the same fixed density criterion as the German DIN of 1934. This was changed for the 1947 British Standard to the fractional gradient system to bring it into line with the ASA standard. However, the method was somewhat cumbersome and in the early 1960's the American¹⁸ and British¹⁹ standards were altered to bring them into line with the German standard, since it was found that for modern materials the fixed density criterion at 0.1 above B+F gave good correlation with the fractional gradient criterion. For the first time British, American and German standards were equivalent. Later, with the increasing effort to produce international standards, the three national standards were made identical and the international version published as ISO 6:1974.²⁰ The corresponding British Standard is BS 1380: Part 1: 1973.²¹

This standard calls for a number of strips of the film under test to be identically exposed. They are then developed, in a developer appropriate for the film being tested, for different times. Characteristic curves, as shown in Fig. 6, are then plotted for each development time. For each curve, M is the point at a density of 0.1 above B+F, and N lies 1.3 log units from M in the direction of greater exposure. ΔD is the difference in the densities corresponding to points M and N. The development times are to be chosen so that values of ΔD above and below 0.8 are obtained. The values of ΔD are plotted against the values of $\log H_M$ and the value of $\log H$ corresponding to $\Delta D=0.8$ is read from the graph and designated $\log H'$.

The speed is now given by

$$\text{Speed} = 0.8/H'$$

The rounded arithmetic ISO speed is then found from a table. This ensures that

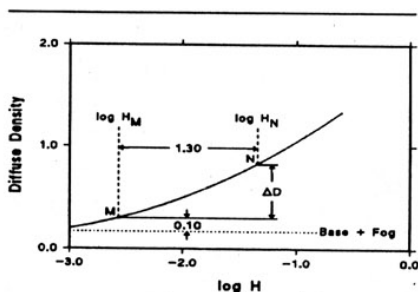


Fig. 6. Monochrome film.

only numbers in the series of preferred numbers, i.e. 6, 8, 10, ..., 2000, 2500, 3200 etc., occur.

5.2 Speed systems for colour films

The situation with colour films is complicated by the presence of layers sensitive to red, green and blue light. The overall speed of the film depends on the speeds of the three layers to the type of light source, daylight or artificial light, for which the film was designed. Under normal circumstances there will be little differences in the speeds of the three layers if the film is exposed with the correct source. For both colour reversal and colour negative materials similar exposure conditions are specified, using a substantially neutral stepped or continuous modulation, and processing is in accordance with the manufacturer's recommendations for each material. In the case of colour reversal materials assessment is by a single measurement of diffuse visual transmission density, whereas for colour negative materials it is by the measurement of blue, green and red diffuse integral densities. In both cases the characteristics of the measuring densitometer must conform to ISO 5.²² The speed determination methods for both types of film are described in the next two sections.

5.2.1 Colour reversal film

The characteristic curve, diffuse visual density v. $\log H$, of the film is plotted, and two points, T and S, identified on it. Point T is at a density of 0.2 above B+F. A tangent to the curve is drawn from point T, and the tangent point is designated S if it occurs at a density less than 2.0 above B+F. If the tangent point occurs at a density greater than 2.0 above B+F, point S is taken as the point on the curve where the density is equal to 2.0 above B+F. This is shown in Fig. 7. The $\log H$ values corresponding to the points T and S are labelled $\log H_T$ and $\log H_S$ respectively, and a further parameter, $\log H_M$ defined as

$$\log H_M = (\log H_S + \log H_T)/2$$

which is equivalent to

$$H_M = \sqrt{(H_S \times H_T)}$$

The exposure, H_M , represents the exposure used to determine ISO speed which is defined as

$$\text{Speed (S)} = 10/H_M \text{ (arithmetic)}$$

or

$$\begin{aligned} \text{Speed (S}^\circ) &= 1 + 10 \log(10/H_M) \\ &= 1 + 10 \log S \text{ (logarithmic)} \end{aligned}$$

As before, the rounded ISO speed, arithmetic or logarithmic, is read from a table.

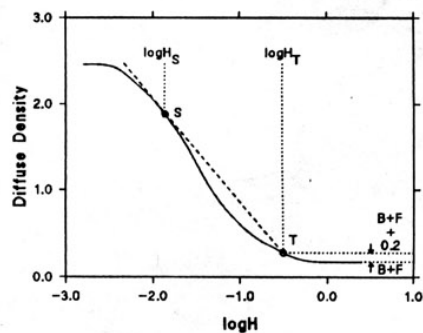


Fig. 7. Colour reversal film.

This is the basis of the international standard ISO 2240: 1982,²³ and its British equivalent BS 1380: Part 2: 1984.²⁴

5.2.2 Colour negative film

In this case the three characteristic curves corresponding to the three diffuse integral densities, red, green and blue, are plotted (Fig. 8), and the points $\log H_R$, $\log H_G$ and $\log H_B$ are identified where each of the curves reaches a density of 0.15 above B+F. A parameter $\log H_M$ is now defined. In an earlier standard it was the mean of the three $\log H$ values, but the current standard defines it as the mean of the $\log H$ value for the slowest layer and that for the green sensitive layer, i.e.

$$\log H_M = (\log H_G + \log H_{\text{slowest layer}})/2$$

which is equivalent to

$$H_M = \sqrt{(H_G \times H_{\text{slowest layer}})}$$

ISO speed is then given by

$$\text{Speed (S)} = \sqrt{2}/H_M \text{ (arithmetic)}$$

or

$$\text{Speed (S}^\circ) = 1 + \log(\sqrt{2}/H_M) \text{ (geometric)}$$

Again, the rounded ISO speed, arithmetic or logarithmic, is read from a table.

The relevant standards are ISO 5800: 1987²⁵ and BS 1380: Part 3: 1980.²⁶

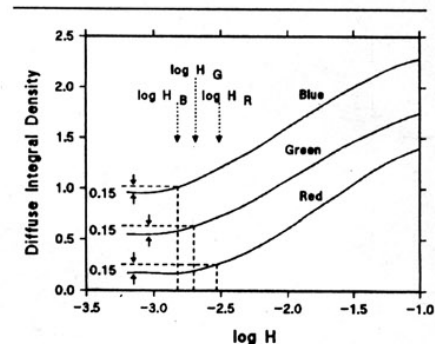


Fig. 8. Colour negative film.

TABLE 1

ILFORD Speed Group	A
ILFORD meter, BSI and Scheiner	17°
American Scheiner	12°
DIN/10	7°
British H & D	100
ASA, General Electric (GE) and Weston	4

6. Miscellaneous film speed systems

We have seen that before the advent of international standards rendered obsolete all other methods and systems for both the determination of film speeds and the manner in which speed is expressed, there had been a progression from Hurter and Drifffield's method through to the present situation. However, during that time there had also been a variety of other emulsion speed systems, many based on particular exposure meters such as the Weston series.²⁷ All surviving and subsequent exposure meters are calibrated to operate with the figures produced by the ISO standards, but in the late 1940's and early 1950's there was a considerable variety of values for emulsion speed in existence. At least one of these, the Ilford Speed Group system, gave letters for emulsion speeds, rather than numbers. The equivalents shown in Table 1 will serve to illustrate the diversity of values with which the photographer had to cope.²⁸

These were all equivalent values, the only point of identity between them being the doubling of arithmetic values, the incrementing by 3 of geometric values or moving to the next letter of the alphabet to express a doubling of speed.

7. Summary

Before Hurter and Drifffield's classic paper of May 1890 there was no scientifically based method for determining emulsion speed. Since that time a variety of criteria have been used, succeeding standards taking into account the most recent research into the reproduction of images by photographic means. Prior to 1979 Germany, the United States and Britain had their own standards, and other independent standards also existed. Since that date national standards have been produced in mutual co-operation and have

led to the production of the internationally accepted ISO standards which co-exist with the national standards. It seems unlikely that these standards will need replacing, particularly as they are agreed by all nations participating in ISO, but the standards committees of these nations keep the situation under review and new standards could be prepared if needed by significant changes in emulsion characteristics.

8. Acknowledgement

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