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Sources of Error in and Calibration of the *f*-Number of Photographic Lenses

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In problems of photography, where the accuracy of lens marking is critical in determining the proper exposure, the various errors to which these markings are subject is of considerable interest. The present report gives the magnitude of such errors that were found to exist in a representative group of 20 lenses having focal lengths that range from 0.5 to 47.5 in. In addition, the results of calibration of these lenses by a photometric method that permits compensation of light losses resulting from absorption, reflection, and scattering are given. Values of lens transmittance for these lenses are shown. A method of plotting results of nominal, true, and calibrated *f*-numbers is given that permits quick evaluation of the magnitude of the over-all error in terms of fractions of a stop.

I. Introduction

With the advance of photographic technology, a need has developed for more precise information on the light-transmitting characteristics of photographic objectives. In particular, a specific need exists for a more accurate means of marking or calibrating the lenses that employ a variable stop for adjusting the lens speed. The usual method, at present, of calibrating a lens is to inscribe a scale of *f*-numbers on the diaphragm control. These *f*-numbers are based upon certain geometric properties of the lens, and neglecting errors of marking, provide a satisfactory means of varying the speed of the particular lens by definite integral steps. Unfortunately this system of marking takes no cognizance of differences in light-transmitting properties that occur among different types of lenses and, in addition, those differences that result between lenses of the same type when the surfaces of one have been treated to reduce reflection losses.

This problem has been under vigorous attack for the past 10 years and numerous methods [1 to 12][1] have been devised for the rating of lens speed with respect to some standard. These methods differ in such matters as type of light source, comparison lens or standard aperture, and type of light-registering device. The theoretical aspects of the problem have been discussed by McRae [9] and by Gardner [1, 2], who proposed several possible methods for calibration of a lens. In the present article, one of the methods described by Gardner is verified experimentally. The experimental technique is described, and the variations in performance for 20 lenses, having focal lengths that range from 0.5 to 47.5 in., are shown. Attention is given to sources of error in the existing marked *f*-number. Lastly, a process is described for determining the transmittance of a lens from data obtained in the course of calibration.

II. Apparatus and Method of Measurement

The apparatus consists essentially of a broad uniform source of white light, a sensitive light-measuring device, and a holder that can be used interchangeably for either mounting the lens under test or one of a series of standard diaphragms each of which has a centrally located circular opening of known diameter. The arrangements of these elements is the same as that suggested by Gardner [1,2]. The relative lens speed is determined by a comparison of the quantity of light flux transmitted by a lens with that transmitted by a circular opening. By making an appropriate series of measurements and by proper interpretation of their significance, the lens can be calibrated in terms of an "ideal" lens having 100-percent transmittance.

[1] Figures in brackets indicate the literature references at the end of this paper.

1. Procedure for a Lens

A lens in mounted in the holder, and its axis is alined with the center of the broad uniform source and the center of the small circular opening in the baffle covering the sensitive element of the light-measuring device. The front of the lens faces the light source, and the distance separating the rear nodal point of the lens and the baffle covering the light sensitive element is adjusted to equality, with the equivalent focal length, F, of the lens. The opening in the baffle does not usually exceed 1 mm, except for some lenses of very long focal length, in which cases it is kept under $0.01F$. All parts of the equipment are shielded so that only light from the source that passes through the lens can reach the light-sensitive element.

Readings of the light meter are taken at each of the marked stop openings. To minimize error arising from back lash, readings are taken both for the condition of the setting at the marked f-number being made with the diaphragm ring of the lens moving in the closing direction and with the diaphragm ring moving in the opening direction.[2] The readings from these two sets of observations are averaged, and this value is taken as the accepted reading of the light meter at a given marked stop opening.

2. Procedure for the standard diaphragms

The lens is replaced by one of the series of standard diaphragms, which have centrally located circular openings with known diameters. The reading of the light meter is taken, and the distance D, from the diaphragm to the baffle covering the light-sensitive element is measured. This operation is repeated for several of the standard diaphragms so selected that readings of the light meter are obtained throughout the same range of readings that were observed for the various marked apertures of the lens. The brightness of the source and the sensitivity of the light meter are kept unchanged throughout both parts of the experiment. To insure constancy of brightness of the source, a constant voltage transformer is used to maintain a constant voltage for the lamps that illuminate the broad uniform source. To minimize error, two sets of data are taken for both the lens and the series of standard diaphragms, so intermingled that random fluctuations in the brightness of the light source and in the sensitivity of the light meter can be neglected.

Ideally, the diameters of the standard diaphragm openings should be so chosen that the same series of f-numbers are present in both phases of the experiment. Too, the distance, D, should equal the equivalent focal length, F, of the lens. In practice, however, it has proved to be more convenient to let D differ from F and to place more reliance upon the ratio, D/A, where A is the diameter of the circular opening in a standard diaphragm. When a wide variety of lenses are being calibrated, as is the case in this experiment, it is simpler to compute the f-number of the standard diaphragm from the ratio, D/A, and to determine the performance of the conventional series of f-numbers from the curve of light meter reading versus f-number than to attempt to reproduce the conventional set of f-numbers by appropriate selection of values of D and A.

The f-number for a lens is defined by the equation

$$f\text{-number} = \frac{1}{2 \sin \alpha}, \tag{1}$$

where α is the angle between the axis and the extreme ray of the circular conical bundle transmitted by the lens. In the case of the standard diaphragm, the relation connecting the measured quantities D and A is

$$\frac{D}{A} = \frac{1}{2 \tan \alpha}. \tag{2}$$

Accordingly, the values of the f-numbers for the standard diaphragms can readily be computed from the known values of D/A. A sufficiently accurate determination of the f-number can be made with the aid of a curve, such as is shown in figure 1. To produce this curve, the values of the quantity, f-number $-D/A$, are plotted as a function of D/A. Hence, for a given value of D/A, the increment that must be added thereto to yield the f-number can be easily read from the graph. For values of D/A greater than 15, the values of D/A and f-number are equal for all practical purposes, since their difference is less than 0.1 percent.

[2] Ten lenses (10, and 12 to 20, incl.) were calibrated in this manner. The remaining 10 lenses were calibrated with the diaphragm ring moving in the closing direction only in accordance with the recommendation contained in Report No. 6 of the Subcommittee on Lens Calibration of the Society of Motion Picture Engineers on Nov. 6, 1947.

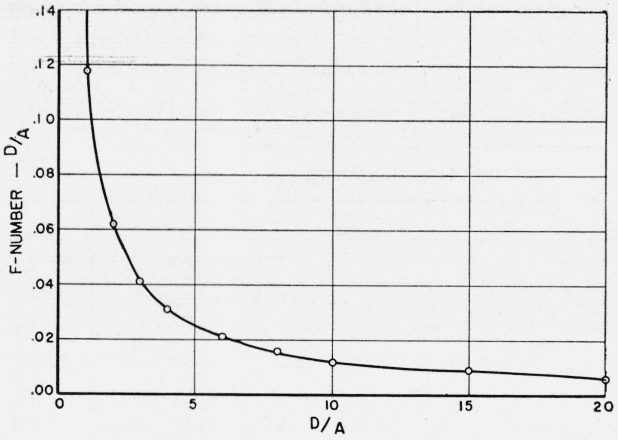

FIGURE 1. *Calibration curve for computing f-number of standard diaphragms when the value of D/A is known.*

III. Results of Measurement

When the values of the scale deflections of the light meter are plotted against the *f*-numbers of the standard diaphragms on logarithmic paper, the resulting curve is a straight line with a slope nearly equal to 2. The fact that the slope is not exactly 2 may be attributed to a slight departure from linearity of the response of the light meter to varying amounts of light indicated on the receiver. This curve, shown as curve 1 in figure 2, shows the relation between the scale deflections

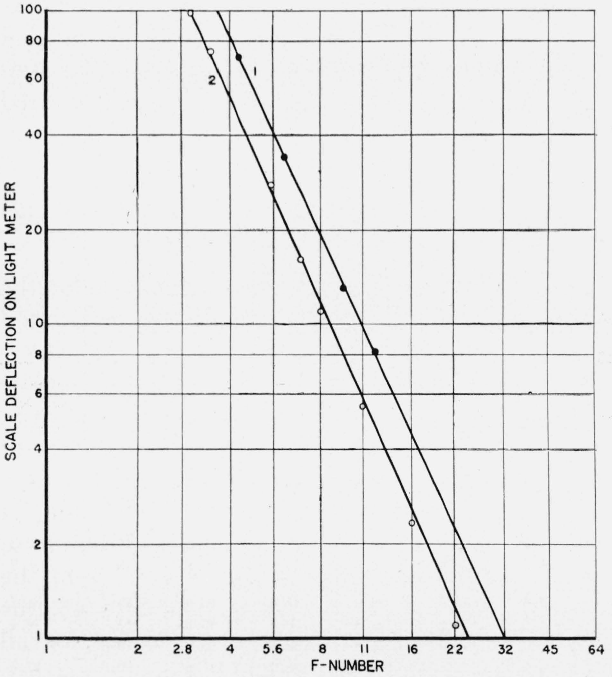

FIGURE 2. *Scale deflection on light meter versus f-number.* Curve 1 is for, the standard diaphrams. Curve 2 is for the lens under test.

of the light meter and the *f*-numbers of an ideal lens.

In a like manner, the values of the scale deflection of the light meter are plotted against the *f*-numbers of the actual lens on the same curve sheet. The resulting curve, designated curve 2 in figure 2, is a straight line parallel to curve 1, but displaced laterally therefrom. This displacement shows in a striking manner the effect of light losses in the actual lens. A fairly close approximation of the relative light transmission of the actual lens at a given *f*-number can be made at once, as it is simply the ratio of the ordinates of curve 1 and curve 2 for the given *f*-number.

It must be mentioned that while curve 1 is always a straight line, this is a consequence of its accurately determined *f*-numbers. On the other hand, the *f*-numbers for curve 2 are read directly from the lens markings and are subject to a variety of errors that will be discussed later in the paper. As a result of these random and systematic errors, the points for curve 2 sometimes do not fall as close to the straight line drawn as could be desired. This is especially noticeable at the small apertures associated with the large *f*-numbers. However, these variations in no way interfere with validity of the final results, but are in fact helpful in tracking down errors in the *f*-numbers.

The values of the calibrated *f*-numbers for the actual lens may be readily obtained from these curves. The calibrated *f*-number is a term used to designate the *f*-number of an ideal lens (i. e., a lens having 100-percent transmittance) transmitting the same amount of light that is transmitted by the actual lens at a given marked *f*-number. The terms *T*-aperture ratio or *T*-stop [3, 7, 8] and equivalent aperture ratio [1, 2] are other designations of this same quantity. To determine the calibrated *f*-number, the value of the scale deflection for a given marked *f*-number of the actual lens is noted, and the value of the *f*-number of the ideal lens, for which the same scale deflection is obtained, is read from curve 1. This has been done for 20 lenses covering a wide range of focal lengths and *f*-numbers. The results are listed in table 1.

The unusual values of marked *f*-numbers, which are listed in the first column, result from assigning a calibrated *f*-number to the maximum stop opening for each lens. The maximum stop

TABLE 1. *Measured value of the calibrated f-number for each value of the marked f-number for each of 20 lenses having focal lengths that range from 0.5 to 47.5 inches*

Lens number	1	2	3	4	5	6	7	8	9	10
Nominal focal length (in.)	0.5	0.5	1.0	1.4	1.6	2.0	2.0	3.0	3.0	3.0
Marked *f*-number	CALIBRATED *f*-NUMBER									
1.9	2.40		2.09							
2.2							2.23			
2.3									2.45	
2.5		2.82								
2.7				3.14	3.14	3.09				
2.8	3.25	3.13	2.86				2.79	3.20	2.96	
3.0										3.68
3.5										4.26
4.0	4.42	4.45	3.92	4.33	4.10	4.36	3.95	4.48	4.07	4.85
4.5										
5.6	5.32	6.32	5.52	5.82	5.46	6.00	5.29	6.22	5.78	6.74
6.8										8.68
7.5										
8.0	7.80	8.78	7.50	8.48	7.37	8.37	7.26	8.72	8.33	10.4
9.5										
11.0	11.0	11.8	9.94	12.5	9.66	11.6	11.2	12.3	11.4	14.4
12.5										
15.0										
16.0	15.4	17.2	13.6	16.8	12.3	16.0	15.7	17.4	17.4	21.5
22.0	21.3			24.2	16.0	21.9	20.4	24.5		33.6
32										
45										
64										
90										
128										

Lens number	11	12	13	14	15	16	17	18	19	20
Nominal focal length (in.)	4.0	7.0	7.5	11.0	13.5	16.5	19.0	24.0	30.0	47.5
Marked *f*-number	CALIBRATED *f*-NUMBER									
1.9										
2.2										
2.3										
2.5	2.79									
2.7										
2.8	3.00									
3.0										
3.5										
4.0	4.24									
4.5			5.60							
5.6	5.76		6.86							
6.8		8.00								
7.5					9.72					
8.0	8.33	9.32	9.75	10.1						
9.5						12.3				
11.0	11.1	13.1	13.6	13.9	14.1	13.4	13.6	14.3		
12.5									15.6	
15.0										16.0
16.0	15.4	18.7	18.3	19.7	19.8	19.5	19.2	19.8	19.3	17.3
22.0		25.2	24.0	28.0	28.4	26.8	25.8	28.2	26.7	23.3
32	27.6	36.7	29.5	37.0	40.0	38.0	37.6	40.9	39.2	34.7
45		49.0			56.9	52.8	50.8	59.9	53.4	48.6
64					76.0	71.8	69.6	86.8	79.0	71.1
90						100.0	98.0	117.0	99.0	97.6
128										143.0

opening of a lens quite frequently does not fall in the commonly accepted series of marked *f*-numbers, although the remaining marked *f*-numbers of the lens usually do. The calibrated *f*-numbers, in most instances, are larger than the marked *f*-numbers. This is as expected, because it is known that some of the light incident on the front surface of a lens is lost as a result of reflection back in the object space or by absorption in the glass. The considerable differences in the calibrated *f*-numbers for a given marked *f*-number indicate appreciable differences in the light-transmitting qualities of the various lenses. This is illustrated in figure 3 where the calibrated *f*-numbers are plotted on semilogarithmic paper for 10 lenses. The values are given for the marked

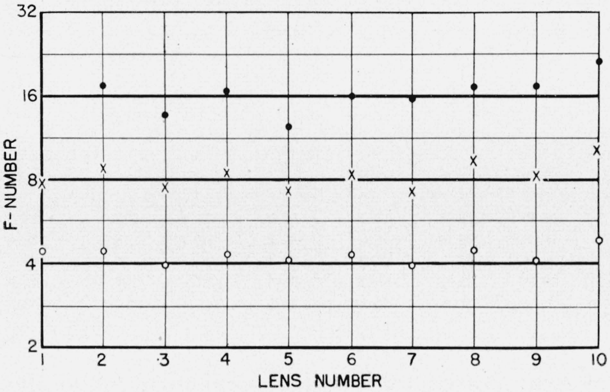

FIGURE 3. *Departure of the calibrated f-number from the marked f-number at f/4, f/8, and 5/16 for 10 lenses.*

The line separations shown are equal to one stop-opening.

f-numbers, 4, 8, and 16. Departures as great as one-third stop-opening are indicated in many instances. As the departures may be in either direction from the marked stop-opening, it is possible to select two lenses such that, on using each for the same scene at the same marked stop-opening, the effective difference in exposure is equal to that produced by a change in excess of one full stop-opening. The fact that some lenses have calibrated *f*-numbers less than the marked stop-opening may seem anomalous in that it indicates a transmittance greater than unity. This is, however, for the most part, an indication of errors in the marked stop-opening and will be discussed in more detail in a later section.

Lens 7 is of especial interest in that the indicated stop-openings are marked in *T*-stops, consequently the values of the calibrated *f*-numbers are quite close to the marked *f*-numbers. Lenses 2, 3, 7, 9, 11, and 20 have coated surfaces to reduce reflection losses. The gain in transmittance is definitely present but is somewhat obscured in table 1, because the marked aperture ratios frequently differ from the true geometric aperture ratio.

The fact that the calibrated *f*-number varies so much from lens to lens for the same nominal *f*-number gives support to the proposition that all lenses should be so marked that differences in light-transmitting properties are negligible for a given *f*-number. This can be done from the curves shown in figure 2 by reversing the procedure used in deriving the information reported in table 1. The deflection of the light meter for a given *f*-number of the ideal lens is noted on curve 1, and the *f*-number of the actual lens, which will yield the same deflection, is read from curve 2. This can also be done by plotting the calibrated *f*-number for a lens listed in table 1 against the marked *f*-number on logarithmic paper. The marked *f*-number for a given calibrated *f*-number can then be read directly from the graph. This has been done for the same 20 lenses, and the results are listed in table 2. This table shows the proper settings in terms of the marked *f*-number, so that each of these lenses will yield uniform performance for each of a series of calibrated *f*-numbers.

TABLE 2. *Settings of the stop-openings in terms of the marked f-number to yield a series of calibrated f-numbers corresponding to 100-percent transmittance for each of 20 lenses having focal lengths that range from 0.5 to 47.5 inches*

Lens number	1	2	3	4	5	6	7	8	9	10
Nominal focal length (in.)	0.5	0.5	1.0	1.4	1.6	2.0	2.0	3.0	3.0	3.0
Calibrated *f*-number	SETTINGS IN TERMS OF MARKED *f*-NUMBER									
2.8	2.33	2.48	2.74	2.38	2.27	2.42	2.81	2.42	2.62	------
4.0	3.58	3.60	4.08	3.63	3.83	3.63	4.05	3.56	3.91	3.27
5.7	5.92	5.10	5.80	5.47	5.78	5.33	6.02	5.10	5.50	4.67
8.0	8.10	7.24	8.57	7.56	8.86	7.75	8.63	7.32	7.75	6.26
11.3	11.3	10.5	12.7	10.2	13.8	10.7	11.3	10.3	10.8	8.90
16	16.4	14.9	19.1	15.1	22.0	16.0	16.5	14.6	14.9	12.2
22.6	23.2	------	------	20.6	35.3	22.7	24.8	20.5	------	16.6
32	------	------	------	------	------	------	------	------	------	------
45	------	------	------	------	------	------	------	------	------	------
64	------	------	------	------	------	------	------	------	------	------

Lens number	11	12	13	14	15	16	17	18	19	20
Nominal focal length (in.)	4.0	7.0	7.5	11.0	13.5	16.5	19.0	24.0	30.0	47.5
Calibrated *f*-number	SETTINGS IN TERMS OF MARKED *f*-NUMBER—Continued									
2.8	2.51	------	------	------	------	------	------	------	------	------
4.0	3.76	------	------	------	------	------	------	------	------	------
5.7	5.55	------	4.62	------	------	------	------	------	------	------
8.0	7.72	6.80	6.60	------	------	------	------	------	------	------
11.3	11.2	9.60	9.23	9.04	8.80	8.60	------	------	------	------
16	16.7	13.6	13.4	12.8	12.7	13.1	13.2	12.4	12.8	14.6
22.6	24.7	19.3	20.6	18.2	18.0	18.6	19.2	18.2	18.8	20.6
32	38.1	27.9	36.4	26.2	25.3	26.9	27.4	25.2	26.2	29.0
45	------	40.5	------	39.8	35.6	38.2	39.3	35.1	37.3	41.0
64	------	------	------	------	51.8	56.3	58.6	47.8	53.0	58.2

IV. Sources of Error in the Nominal *f*-Number

In addition to the light losses in the lens arising from absorption and reflection, there are several sources of error that affect the reproducibility in the amount of light reaching the focal plane at a given stop-opening. The first of these is back lash in the iris-diaphragm-stop and results in differences in light transmission, dependent upon the manner in which the diaphragm is set at a given stop-opening. The second error is an actual error in the markings themselves and may arise from errors in aperture, errors in equivalent focal length, or errors in both at the same time. The back lash error varies for each lens, whereas the error in *f*-markings contributes to variations in performance when several different lenses are in use for the same type of work.

1. Error in Setting the Lens at a Given *f*-Number

When the diaphragm is set at a given *f*-number, there is an appreciable difference in the amount of light passed by the lens, dependent upon the direction of movement of the diaphragm control. The error arising from this source has been investigated, and the results are listed in table 3 for several lenses. This backlash error is determined by two methods. In the first method, the lens is mounted on a stand, and the edges of the diaphragm are illuminated from the rear of the lens by a fixed source. Photographs of the stop-opening are made with an auxiliary camera placed in front of the lens. Each stop-opening is photographed for the condition of the setting being made with the diaphragm closing and with the diaphragm opening. Prints are made of these negatives, and the area of each image is measured with a planimeter. Let the area of the image, taken for the condition when the setting is made by closing the diaphragm, be A_c; and the area of the image for the same stop opening, taken for the condition when the setting is made by opening the diaphragm, be A_o. Then the ratio A_c/A_o is accepted as the ratio of the relative illuminations in the axial region of the focal plane when the lens is used under identical lighting conditions for these two processes of setting the lens at a given *f*-number.

TABLE 3. *Ratios of relative illumination in the axial region of the focal plane for lenses used under identical lighting conditions, settings being made with the diaphragm control moving to close and with the diaphragm control moving to open the lens*

Equivalent focal length	Nominal *f*-number	Ratio of light transmissions diaphragm closing to diaphragm opening		
		Planimeter A_c/A_o	Light meter L_c/L_o	Weighted average
In.				
16.5	9.5	1.01	1.04	1.03
	11	1.01	1.02	1.02
	16	1.02	1.04	1.03
	22	1.02	1.07	1.06
	32	1.05	1.11	1.10
	45	1.13	1.08	1.09
	64	1.11	1.08	1.09
19.0	11	1.00	1.00	1.00
	16	1.06	1.02	1.03
	22	1.05	1.04	1.04
	32	1.07	1.06	1.06
	45	1.10	1.09	1.10
	64	1.24	1.26	1.26
24	11	1.00	1.00	1.00
	16	1.00	1.03	1.02
	22	1.05	1.05	1.05
	32	1.02	1.11	1.09
	45	1.09	1.14	1.13
	64	1.06	1.18	1.16
30	12.5	0.99	1.01	1.00
	16	1.04	1.03	1.03
	22	1.02	1.02	1.02
	32	1.04	1.06	1.05
	45	1.08	1.02	1.03
	64	1.08	1.07	1.07

In the second method, the data taken in section II is treated in such manner as to separate the light meter readings L_c, taken for the condition of the setting being made with the diaphragm closing, and the light meter readings for the same stop opening L_o, taken for the condition of the setting being made with the diaphragm opening. Then the ratio L_c/L_o is accepted as the ratio of the amounts of light passing through the lens for these two conditions and is comparable to A_c/A_o obtained by the first method.

The values of these ratios are tabulated in table 3 for a series of stop-openings for four lenses. The differences by the two methods result mainly from the fact that a greater number of sets of data is used in the determination of L_c/L_o. The third column gives the weighted average with a weight of 4 given to L_c/L_o and a weight of 1 given to A_c/A_o It is noteworthy that this error arising from backlash varies for 1 to 2 percent at the larger stop-openings to as high as 10 to 26 percent for the smaller stop-openings. It is clear that error from this cause can be avoided by always making the diaphragm setting in the same manner, and preferably in the direction of closing the diaphragm.

There still remains the random error of making the setting, even if care is taken to move the control always in the same direction. This error is, however, small in comparison to backlash error, and it is believed that it should be negligible for the careful worker at the larger stop-openings and perhaps rising to approximately one-fourth of the backlash error for the smaller stop openings.

2. Errors in the Existing Geometrical *f*-Number

(a) At full aperture

The true geometrical *f*-number is obtained by dividing the equivalent focal length of the lens by the diameter of the effective aperture. It is therefore obvious that errors in the value of the equivalent focal length and the effective aperture will be reflected by errors in the *f*-number. Table 4 lists the nominal and measured values of equiv-

TABLE 4. *Comparison of nominal and measured values of equivalent focal length and effective aperture for a representative group of lenses*

Lens number	Equivalent focal length		Difference in equivalent focal length	Effective aperture		Difference in aperture
	Nominal	Measured		Nominal	Measured	
	Mm	*Mm*	*Percent*	*Mm*	*Mm*	*Percent*
1	12.5	12.35	−1.2	6.58	7.07	7.4
2	12.5	12.99	3.5	5.00	5.07	1.4
3	25.4	25.56	1.0	13.37	13.65	2.1
4	35.0	37.50	7.1	12.96	14.06	8.5
5	40.0	42.08	5.2	14.81	14.94	+0.9
6	50.0	51.39	+2.8	18.52	19.62	+5.9
7	50.8	50.62	−0.4	25.40	24.40	−3.9
8	75.0	75.31	.4	26.78	27.36	2.2
9	75.0	75.02	.0	32.61	32.58	−0.1
10	76.2	74.71	−2.0	25.40	24.60	−3.2
11	101.6	99.42	−2.1	39.53	40.64	2.8
12	177.8	180.81	1.8	26.15	26.15	0.0
13	190.5	190.53	0.0	42.34	40.17	−5.1
14	279.4	284.85	2.0	34.92	35.74	2.3
15	342.9	351.60	2.5	45.72	42.21	−7.7
16	419.1	418.14	−0.2	44.12	41.30	−6.4
17	482.6	481.97	−.1	43.87	43.29	−1.3
18	609.6	605.55	−.7	55.42	51.40	−7.2
19	762.0	756.54	−.7	60.96	59.14	−3.0
20	1,206.5	1,207.60	.1			

alent focal length and effective aperture. In those instances, where the nominal focal length was given in inches, conversion has been made to millimeters. The nominal values of effective aperture are computed from the values of nominal focal length and nominal *f*-number. Examination of this table shows that the measured value of the equivalent focal length is within ±2 percent of the nominal focal length for 15 of the 20 lenses. The average departure for the entire 20 lenses is ±1.7 percent. The errors in effective aperture are as high as ±8 percent, with an average for 19 lenses of ±4 percent. Nine of the nineteen lenses show errors in effective aperture in excess of ±3 percent. It is doubtful if the errors in focal length can be brought below ±2 percent during the process of manufacture, but it does seem that the error in aperture at the maximum aperture could also be reduced to ±2 percent.

As a result of these departures of the measured values of the equivalent focal length and effective aperture from their nominal values, appreciable errors in the *f*-number are produced. This is shown in table 5, which lists the nominal and measured *f*-numbers for the same group of lenses. The errors in the *f*-numbers range from −6.8 to +11.1 percent. The effect of these errors in terms of relative transmittance is shown in the last column.

TABLE 5. *Nominal and measured values of the f-number for a representative group of lenses*

Lens number	Nominal focal length	*f*-number		Error in *f*-number	Relative transmittance
		Nominal	Measured		
	mm			*Percent*	
1	12.5	1.9	1.77	−6.8	1.15
2	12.5	2.5	2.62	4.8	0.91
3	25.4	1.9	1.87	−1.6	1.03
4	35.0	2.7	2.67	−1.1	1.02
5	40.0	2.7	2.82	4.4	0.92
6	50.0	2.7	2.62	−3.0	1.06
7	50.8	2.2	2.07	−5.9	1.13
8	75.0	2.8	2.75	−1.8	1.04
9	75.0	2.3	2.30	0.0	1.00
10	76.2	3.0	3.04	1.3	0.97
11	101.6	2.5	2.51	0.4	0.99
12	177.8	6.8	6.91	1.6	97
13	190.5	4.5	4.74	5.3	.90
14	279.4	8.0	7.97	−0.4	1.01
15	342.9	7.5	8.33	11.1	0 81
16	419.1	9.5	10.12	6.5	.88
17	482.6	11.0	11.13	1.2	.98
18	609.6	11.0	11.78	7.1	.87
19	762.0	12.5	12.79	2.3	.96

These values of relative transmittance show that, neglecting losses in the lens, the difference between nominal *f*-number and true geometric *f*-number may alone produce deviations of as much as 19 percent between the expected and actual values of the amount of light passed by the lens. It must be emphasized that these differences are present at maximum stop-opening where the effective aperture is that of a true circular opening and not that of a many-sided opening, which is operative when the aperture is determined by the iris diaphragm. In 6 out of 19 cases, the relative transmittance deviates from unity by 10 percent or more, which may produce significant differences in exposure time in some instances of use.

(b) Errors in the marked *f*-numbers at reduced apertures

It is clear that errors of the type described in the preceding section are also present for all of the marked *f*-numbers. Because the aperture formed by the usual many-leaved iris diaphragm is a polygon, the accuracy of determining the diameter of the effective aperture is somewhat less than that for the full aperture, where the limiting opening is circular. Where the number of leaves is greater than six, two diameters at right angles to one another are measured, and the average is considered to be the diameter of a circular opening of the same area. For those diaphragms having four to six leaves, the area is computed from two or three diameters, and the diameter of the equivalent circle is used in computing the *f*-number. It is believed that the *f*-number obtained in this manner is correct within ±2 percent for the small *f*-numbers and rising to ±5 percent on the average for *f*-numbers greater than 22.

The errors in the *f*-number markings for twelve lenses are shown graphically in figures 4, 5, and 6, where the marked *f*-numbers are plotted as ordinates and the true (measured) *f*-numbers are plotted as abscissae. The dotted line with slope of unity passing through the origin is the line upon which the marked *f*-numbers would lie if there were no error in the markings. The points are plotted on logarithmic paper, so that one may see at a glance what the magnitude of the error is in terms of fractions of a stop-opening. For example, in the case of lens 3, figure 4, the true *f*-number corresponding to the *f*-number marked 16 is 12.9. This error of marking is clearly shown on the graph to exceed one-half stop. For lens 10, figure 5, at

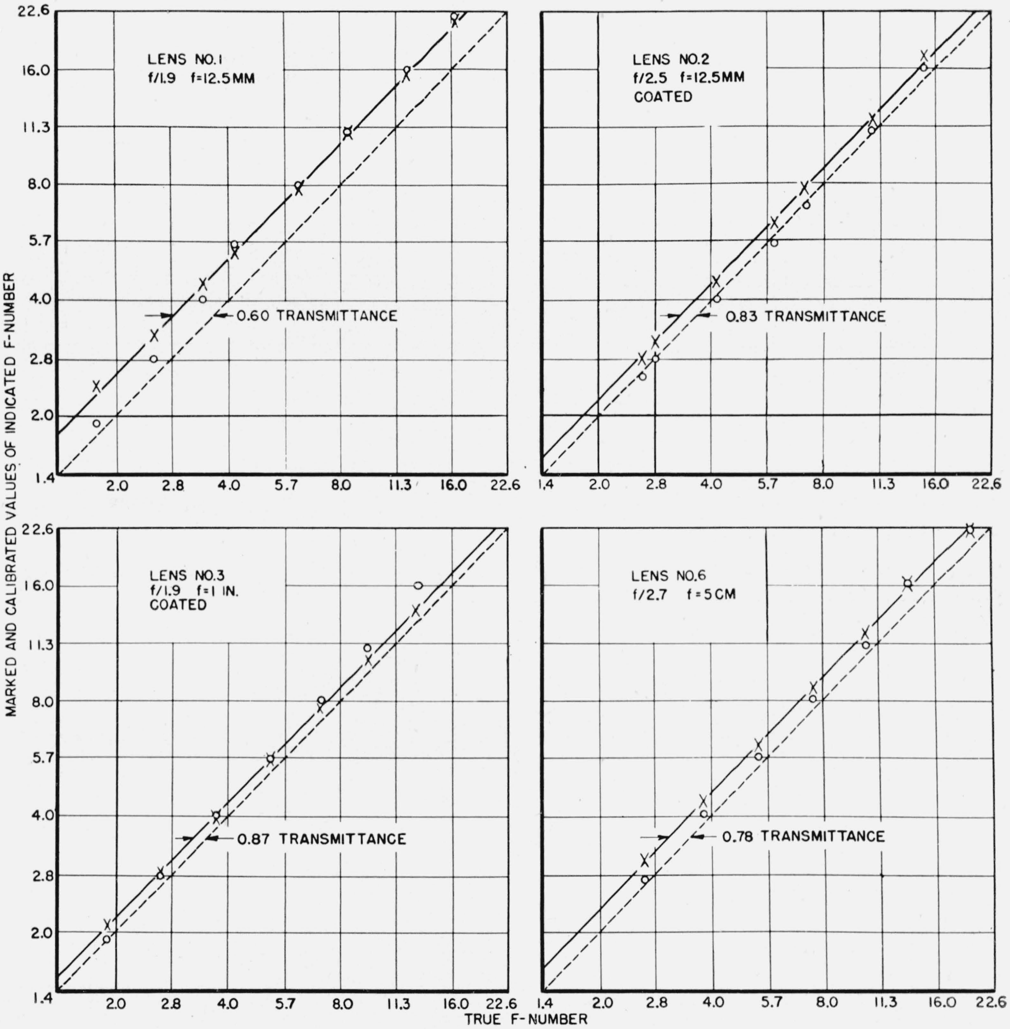

FIGURE 4. *Marked and calibrated values of f-number versus true geometric f-number.*

The circles indicate the marked *f*-numbers, and the crosses indicate the calibrated *f*-numbers. The circles would fall upon the dotted diagonal line if marked and true *f*-numbers were equal. The crosses would fall upon the dotted line if the transmittance were 100 percent. The separation of the dotted- and solid-line curves gives a measure of the transmittance of the lens. The steps in the net equal one stop-opening for ready appraisal of differences in fractions of a stop-opening.

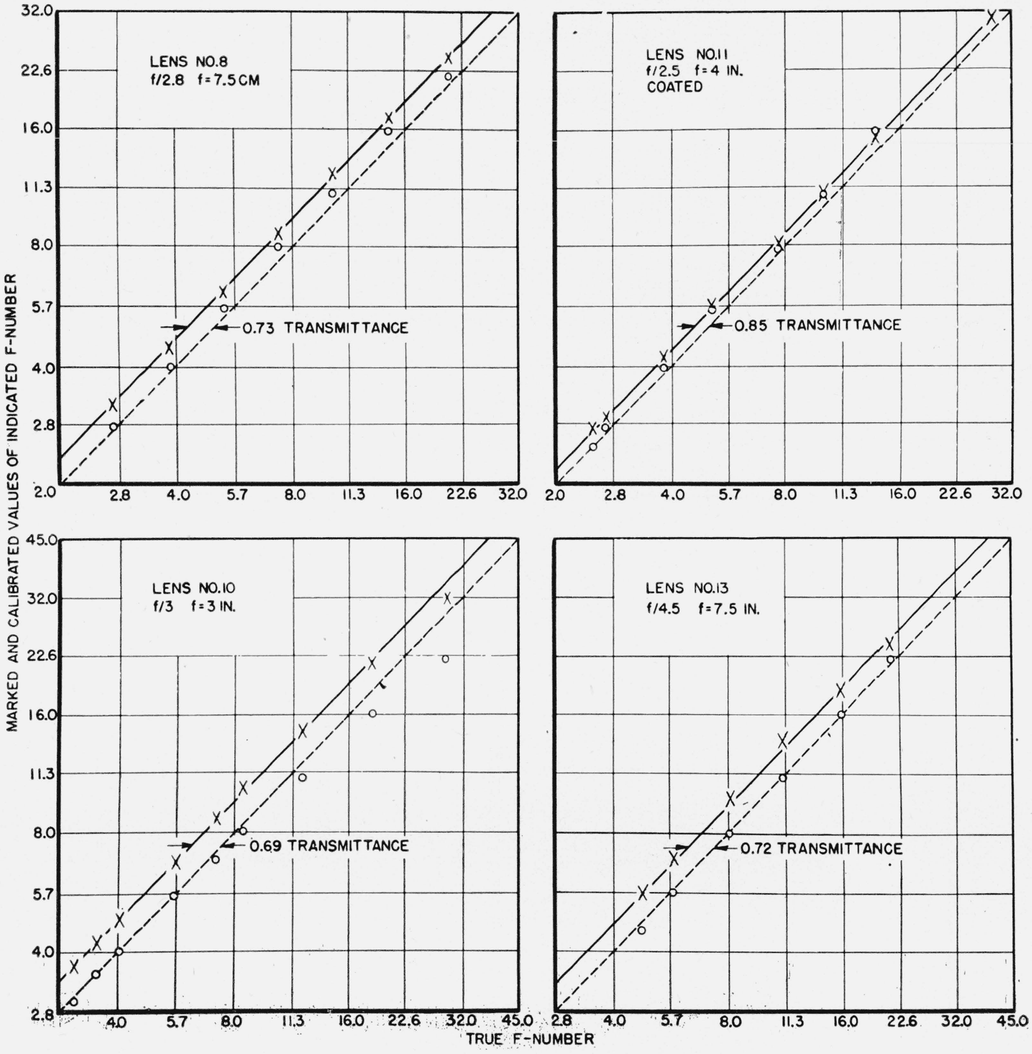

FIGURE 5. *Marked and calibrated values of f-number versus true geometric f-number.*

The circles indicate the marked *f*-numbers, and the crosses indicate the calibrated *f*-numbers. The circles would fall upon the dotted diagonal line if marked and true *f*-numbers were equal. The crosses would fall upon the dotted line if the transmittance were 100 percent. The separation of the dotted- and solid-line curves gives a measure of the transmittance of the lens. The steps in the net equal one stop-opening for ready appraisal of differences in fractions of a stop-opening.

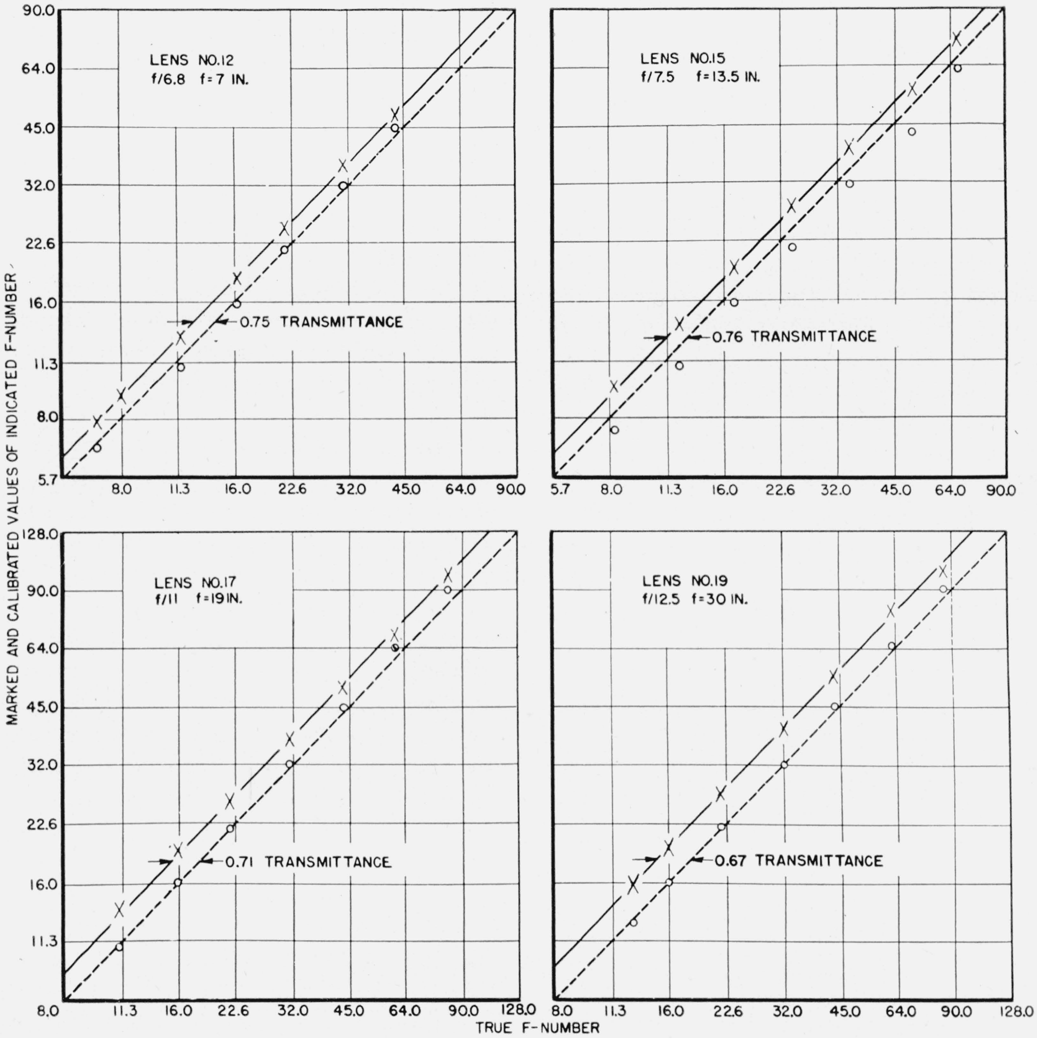

FIGURE 6. *Marked and calibrated values of f-number versus true geometric f-number.*

The circles indicate the marked *f*-numbers, and the crosses indicate the calibrated *f*-numbers. The circles would fall upon the dotted diagonal line if marked and true *f*-numbers were equal. The crosses would fall upon the dotted line if the transmittance were 100 percent. The separation of the dotted- and solid-line curves gives a measure of the transmittance of the lens. The steps in the net equal one stop-opening for ready appraisal of differences in fractions of a stop-opening.

$f/16$, the true f-number is 18.4, or more than one-half stop in the opposite direction. For lens 12, figure 6, the values of marked and true f-number are very close together throughout the range of the markings.

V. Measurement of Transmittance

1. Transmittance at Full Aperture

It is possible, on the basis of the information obtained in the course of this experiment, to determine the light transmittance of the lens itself. It must be emphasized, however, that the transmittance so determined is the ratio of the amount of light passing through the lens to the amount of light incident on the front surface of the lens, and does not differentiate between image-forming and non-image-forming light. There are two ways of making this determination. The first method yields the nominal transmittance, and is simply the square of the ratio of the nominal f-number and the ideal f-number that gives the same deflection on the light meter. Values obtained by this method are listed in table 6, under the heading of nominal transmittance. Since no cognizance is taken of the errors in the nominal f-number, the nominal transmittance is affected by the error in f-number, as well as by reflection and absorption losses in the lens.

TABLE 6. *Nominal and actual values of the transmittance at full aperture for a representative group of lenses*

Lens number	Equivalent focal length	f-number			Transmittance	
		Marked	True	Calibrated	Nominal	Actual
	in.					
1	0.5	1.9	1.77	2.40	0.63	0.54
2	.5	2.5	2.62	2.82	.79	.86
3	1.0	1.9	1.87	2.09	.83	.80
4	1.4	2.7	2.67	3.14	.74	.72
5	1.6	2.7	2.82	3.14	.74	.81
6	2.0	2.7	2.62	3.09	.76	.72
7	2.0	2.2	2.07	2.23	.97	.86
8	3.0	2.8	2.75	3.20	.77	.74
9	3.0	2.3	2.30	2.45	.88	.88
10	3.0	3.0	3.04	3.68	.67	.68
11	4.0	2.5	2.51	2.79	.80	.81
12	7.0	6.8	6.91	8.00	.72	.75
13	7.5	4.5	4.74	5.60	.65	.72
14	11.0	8.0	7.97	10.10	.63	.62
15	13.5	7.5	8.33	9.72	.59	.73
16	16.5	9.5	10.12	12.30	.60	.68
17	19.0	11.0	11.13	13.60	.65	.67
18	24.0	11.0	11.78	14.30	.59	.68
19	30.0	12.5	12.79	15.60	.64	.67

The second method yields the actual transmittance and is the square of the ratio of the measured and calibrated f-numbers. Since this method rules out the error in f-number, the actual transmittance is affected only by reflection and absorption losses in the lens.

It is interesting to consider lenses 16, 17, 18, and 19. These are all of the same type, having 8 glass-air surfaces, but ranging in focal length from 16.5 to 30 ins. The nominal transmittance for these four lenses varies from 0.59 to 0.65, whereas the actual transmittance is almost invariant, changing from 0.67 to 0.68.

The effect of antireflecting coatings on the lens surfaces can be seen in this table. Lenses 2, 3, 7, 9, and 11 are coated, and all have transmittances that exceed 80 percent. Only one, 5, of the uncoated lenses has a transmittance above 80 percent, and the remaining 13 lenses have transmittances ranging from 62 to 75 percent, with one lens (1) falling as low as 54 percent. The antireflecting coatings increase the transmittance by 25 percent or more. Even so, consideration of the actual values of the transmittance shows that 10 percent or more of the incident light is still lost by the coated lens. This is not surprising when it is remembered that antireflecting films usually yield close to 100 percent transmittance for only one wavelength of light. Accordingly, when a broad region of the spectrum is covered, as is the case for white light, the transmittance measured is the average for the whole region.

The fact that the values of transmittance obtained by this procedure are affected in some small amount by the presence of nonimage-forming or scattered light cannot be considered as important. It is improbable that markedly different values would be obtained by the use of collimated light incident on the front surface of the lens during the experiment. In any comparison between the broad source method of measuring transmittance or calibrating a lens and the collimated light method, it is unlikely that light scattered by the lens will produce appreciable difference in the end result. The broad source fills the lens with light, giving rise to a greater amount of scattered light. However, the diaphragm in the focal plane rigidly restricts the measured scattered light to that falling within a small area. The collimator system, at least for the larger aperture, illuminates the inner surface of the barrel with light at small angles of incidence favorable for reflection. All the light that is scattered and emerges from the lens is evaluated by the detector. It is difficult to say which will give the most weight to scattered light. Certainly for a well-constructed lens, the differences in results obtained by the two methods will be small. For a lens purposely made to reflect the light from the mount, the result is open to question. However such lenses do not constitute a threat, because they would not make satisfactory photographs. The extended source does give a measure of the light (some of which is scattered), which will be incident on a central area of the film when photographing a subject with a reasonably average illumination over the entire field. The collimator method gives a measure of the light available over a central area of the film, plus all scattered light, when photographing a relatively small bright source on a dark ground.

2. Average Transmittance for All Apertures

The value of transmittance obtained in the preceding section is a reliable one for full aperture, but, since a lens is frequently used at reduced stop-opening, it is advantageous to consider a method of determining average transmittance throughout the entire range of stops. This is done by plotting the calibrated *f*-number against the true *f*-numbers as has been done for 12 lenses in figures 4, 5, and 6. The crosses show the relation thus obtained. It is clear that these crosses lie on a straight line, shown as a solid line, parallel to the dotted diagonal line. If the crosses fell on the dotted line, it would indicate a transmittance of 100 percent. As it is, the displacement of the solid line from the dotted line gives at once a measure of the average transmittance for all apertures. This has been computed from the curves, and the value of the average transmittance for all apertures is shown for each of the 12 lenses in the proper figure.

It is worthy of mention that this method of plotting the results of measurement serves the dual purpose of showing the consistency of the method of calibration and the reliability of the measured values of true *f*-number. Errors in either operation would cause the crosses to fall away from the solid-line curve. The fact that these deviations are small indicates that both calibrated and true *f*-numbers have been quite accurately assigned.

VI. Summary

The present system of marking the diaphragms stops, in terms of the geometric *f*-number, is subject to serious deficiencies so far as uniform performance for lenses set at the same marked stop-opening is concerned. Decisions regarding the proper exposure time to use at a selected stop-opening may be in error by ± 10 percent for a lens whose surfaces do not have antireflection coatings, and by even greater amounts for a lens whose surfaces do have antireflection coatings. These errors arise from differences in the reflection and absorption losses in the lens elements themselves, departures of the measured from the nominal focal length, and departures of the measured diaphragm openings from the nominal diaphragm openings.

A method is described whereby a lens can be calibrated by a light meter in terms of an ideal lens, so that the variation in axial illumination in the focal plane need not exceed ± 2 percent in using different lenses set to the same calibrated stop-opening.

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