Magnification and Depth of Detail in Photomacrography

H. Lou Gibson, FPSA

Medical Division, Eastman Kodak Company

In the field of photomacrography, where prints of small subjects are made at over-all magnifications varying from 1 to about 30, a compromise constantly has to be made between magnification, definition and depth of field. These factors have been discussed and their effects illustrated in previous parts of this investigation.[1,2] Such compromises can be made judiciously after considerable experience. Yet one is never sure that the best adjustments have been made in camera aperture, negative magnification and enlargement for the numerous combinations possible with varied subjects. Therefore, formulas or curves that indicate practical values to employ would be quite useful for arriving at the best compromise.

The image-producing capabilities of camera lens, negative, enlarger lens and paper limit the resultant detail separation—the distinguishability, in the print, of small elements from the subject. Hence, there is a final print scale beyond which further magnification becomes "empty." Also, there is a certain aspect of depth-of-field considerations that is affected by these capabilities in photomacrography, although it is of no practical importance in ordinary photography.

For two-dimensional subjects it would be useful to have curves that show how to select relative apertures and negative magnifications attainable with the camera lenses at hand to secure optimum print magnification. This is particularly true when photographing flat surfaces for which depth of field is a problem only so far as the facility for accurate alignment and focusing is concerned. The degradation introduced by the enlarger ought to be known too, when the photography of such flat subjects is to entail enlargement. It would then be possible to judge whether a setup involving only contact printing should be worth considering. Or, the proportion of camera to enlarger magnification is a worthwhile ratio. An approximation of the corresponding resolution of, or degree of separation between, detail elements in the focused subject plane would also be a valuable figure in all cases.

For three-dimensional subjects an expression that would indicate depth of field on the basis of the required definition at the near and far limits would be extremely useful. It would provide more realistic depth figures than existing formulas offer photomacrographers. It would also ensure that the desired detail separation be present throughout the field when such a goal can be achieved, and indicate when it cannot.

In all these considerations it is the size of the smallest details that are to be separated which should be kept uppermost in the mind. For example, in Figure 1, the spots on the flower are relatively large in comparison with the dots on the wing of the moth—both have been photographed to the same scale. In both subjects, the *desired* detail has been recorded. However, there are smaller detail elements on the flower, such as fine hairs and pores, that could have been depicted had the definition, or degree of "sharpness" as it is often rather loosely called, been the same as that achieved for the moth. What is the reason for having to sacrifice such detail in the flower?

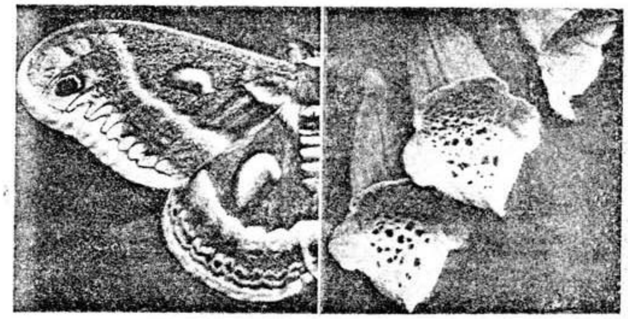

Figure 1—Cecropia moth and foxglove photographed and reproduced to the same scale. The size limit of the desired detail is represented by the dark spots on the flower and the peppery dots on the wing. Detail as small as the latter has not been recorded on the flower, even though it exists. Yet both photographs appear to have satisfactory definition. It is thus apparent that acceptable quality depends on the nature of the specimen. This paper deals with the establishment of optimum technical conditions for depicting various photomacrographic subjects.

The foxglove presents a depth problem that does not pertain to the moth. And it is physically impossible to obtain both great depth and definition. Therefore, technical conditions were selected for photographing the flower that would separate the spots and also provide acceptable overall or "general" definition throughout the depth in the field—there was no need to separate the finer elements. The major concern of the photomacrographer is the selection of such optimum technical conditions.

The approach to the above problem will be toward evaluating the effects of unavoidable physical imperfections in the image on the print. These involve limitations in optical and photographic components and tend to blur the photograph. They are aberration and diffraction patterns, which combine to prevent the lens from imaging a point as a point, and graininess and turbidity in the emulsion, which prevent the film from recording a point as a point. These blurs can be calculated or measured separately. A method for approximating their effect in combination will be worked out in the analytical section of this paper.

Table 1 lists the blurs involved. Since no single one of them is very large, it is their sum with which we are concerned. Nevertheless, every effort to keep each blur small is worthwhile. This, of course, is well known for the avoidable manipulative imperfections also indicated on Table 1.

TABLE I (5A)

Factors that degrade the crisp rendition of photomacrographic detail

	Location of Blurs				
	Subject	Camera Lens	Negative	Enlarger Lens	Print
PHYSCIAL BLURS:			Camera lens, diffraction pattern (Airy disc)		Enlarger lens, Airy disc
			Camera lens,		Enlarger lens, aberrations
			geometric aberrations		Emulsion factors
			Emulsion factors		Depth circle of confusion
MANIPULATIVE BLURS:	Subject motion	Illumination flare	Poor focus	Dust and dirt	Poor focus
	Diffuse illumination	Dirt	Camera motion		Enlarger vibration
					Safelight fog
					Curtailed development

The physical blurs—called circles of definition herein—cannot be eliminated but their sizes can be juggled for best results. This paper develops considerations for doing this.

The manipulative blurs can be controlled by means of careful parallax focusing; clean equipment; firm and anti-vibration supports; fast electronic-flash exposures for living specimens; time exposures made with the light switch rather than the camera shutter; "raw," collimated, or point-source, lighting; and correct positioning of the subject. Handling these measures effectively depends on the technical skill of the photographer. Suggestions have been given elsewhere.[2,3,4]

The first application of analyzing the consequences arising out of the physical blurs in photomacrography is that of obtaining working curves for two-dimensional subjects. These are shown in Figure 2 and enable the photomacrographer to select technical conditions for obtaining optimum detail. To give the curves further meaning, Figure 3 relates the data to actual examples and includes a demonstration of the effects of lighting. These illustrations will be discussed in the following text. Then, as the second application, Figures 4 and 5 will be presented in a subsequent section. They indicate how to additionally take depth factors into account when photographing three-dimensional objects.

Reading Useful Magnification Curves

Before going on to the significance of these curves, the materials and equipment employed in their production must be specified. The data are based on the use of a low-graininess film like Kodak Panatomic-X; a high-definition lens, like the f/4.5, 2-inch Kodak Enlarging Ektar Lens; and enlarging at an effective* aperture of fe/50 (whenever possible) with the same lens in the Kodak Precision Enlarger. The photomacrographer will be able to work out similar data from the discussion in the analytic section to suit conditions that vary appreciably from these. The prints were made on a glossy paper and the conditions apply to a viewing distance of 12 inches. The desired print-detail separation has been set at 6 elements (lines)/millimeter.

*Effective aperture is $E+1$ times relative aperture, and is the ratio of the lens-paper distance to the diameter of the exit pupil. E is the enlarger magnification.

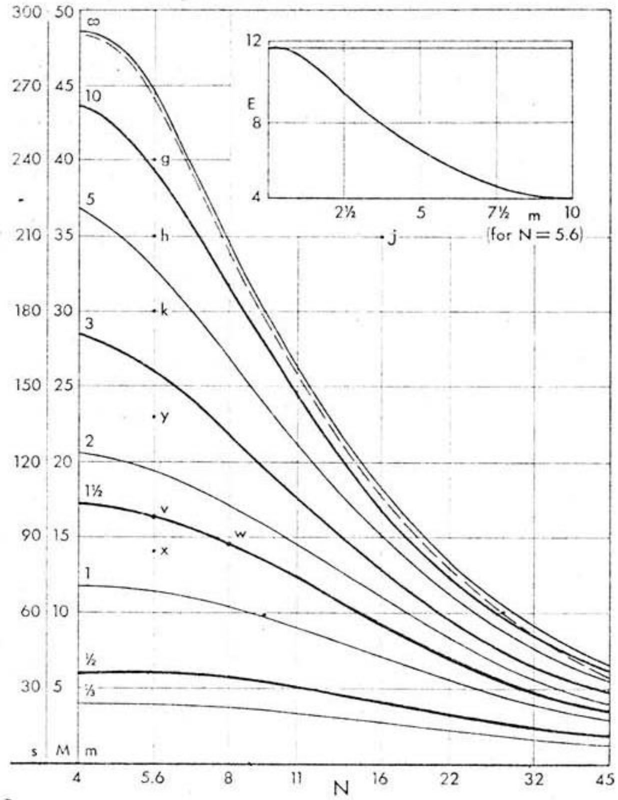

Figure 2—Useful magnification and enlargement curves. **Key:** "s" is detail separation in elements/millimeter. "M" is over-all magnification; "m" is camera magnification. "E" is degree of enlargement from the negative. "N" is marked camera aperture. The small letters mark specific technical conditions that were adopted for making the negatives for Figure 3. The broken line indicates the results from good contact printing.

The method of utilizing the curves for finding optimum magnification is outlined in the text.

Figure 2 gives the desired detail separation, *s*, as the quantity known by the photographer, and the *f*-number of the camera, *N*, as the independent technical variable. It then shows how to record the desired detail by selecting a suitable final print scale, *M*, and the camera magnifications, *m*, that must be adopted at the available relative apertures, *N*.

While *s* is given rather specifically in elements/millimeter, it should be realized that the actual resolution is dependent upon the nature of the surface texture of the subject. Ordinary resolving-power values are based on bar charts and the like, but photomacrographic detail does not always resemble such patterns. Hence the concept of detail separation, even though of practical use, approximates rather than corresponds to the concept of resolution. The separation values are rated in the same way as resolution figures would be when the latter are based on a column and a space constituting one "line" in a bar chart. To give a numerical example: an entity 0.1 millimeter wide plus an adjacent equal space constitutes an element 0.2 millimeter wide, representing a detail separation of 5 elements/millimeter. Detail separation is discussed further in the analytic section.

The positions of the small letters on Figure 2 indicate the technical conditions employed to make the test exposures for Figure 3. The inset curve gives information on useful enlargement, E. It was plotted from the enlargements called for at the intersections of the m curves with the $N=5.6$ co-ordinate in order to attain the permissible values of M indicated by these intersections. The way to utilize this curve is contained in the suggestions of the next section.

The significance of the curves in Figure 2 can be gained by studying one of them–say the $m=5$ line. This shows the conditions arising out of utilizing a camera magnification of $\times$ 5. When the photograph is made at f/4, a detail separation of about 220 elements/millimeter is obtainable–provided a final print scale of 37 is adopted. This would necessitate a $\times$ 7.4 enlargement (M/m E) to be made in order to attain $M=37$. It will be seen that by picking off other points from the $m=5$ curve, new conditions arise which are governed by the camera aperture that might have to be employed. Examples are:

m	N	s	M	E
5	5.6	198	33	6.6
5	16	90	15	3

The logical question that now arises concerns the significance of points outside the curves. If we take an $m=5$ - $N=5.6$ negative and enlarge it to $M=40$, will we have $s=240$? The answer is no. The effect of empty magnification has crept in. That is to say, a detailed separation of about 200 (198) has merely been enlarged to a greater extent. But no new detail has been opened up.

As stated before, and explained in the analytic section, the curves are based on a detail separation of 6 elements (or lines)/millimeter in the final print. Thus, an $\times$33 over-all magnification of $s=198$ results in a print separation of 6. The $m=5$ - $N=5.6$ negative records only a detail separation of about 200 and, of course, this appears as 40 on the negative and is enlarged to 6 elements/millimeter through the agency of $E=6.6$.

When this negative is enlarged further to $M=40$ ($E=8$) this same detail now appears at 5 elements/millimeter on the print–but $s=240$ detail has not been concomitantly enlarged to 6 elements/millimeter. Such detail has not been separated at the negative in the first place, because that would have required the impossible resolving ability of lens and film of 48 elements/millimeter.

The curves show that to record $s=240$ at $N=5.6$, m must be about 10 and M should be 40. This calls for a resolving capability at the negative of 24 in contrast to 40 required at $m=5$. This is not a contradiction because it is the camera lens as well as the emulsion that governs the detail separation at the negative–the effective aperture of the lens governs the size of the Airy disc blur component. The equations for deriving the curves take this into account.

To examine the significance of selecting factors below a given curve, we can first consider the empty magnification discussed above. That is, trying to achieve the $s=240$ of the $m=10$ curve with an $m=5$ negative instead of $m=10$ was unsuccessful. The other circumstance would be that of making a negative at say, $N=5.6$ - $m=10$, but only enlarging it to $M=33$. The lens-film system would record 24 elements/millimeter as before; an enlargement of 3.3 would result in a print that bore the separable detail at about 7.3 elements/millimeter. This could be observed but the print would be more difficult to study and would not attain the capabilities of the system. Furthermore, should M be reduced still more–e.g., to 10 by contact printing, yielding a print separation of 24–the detail

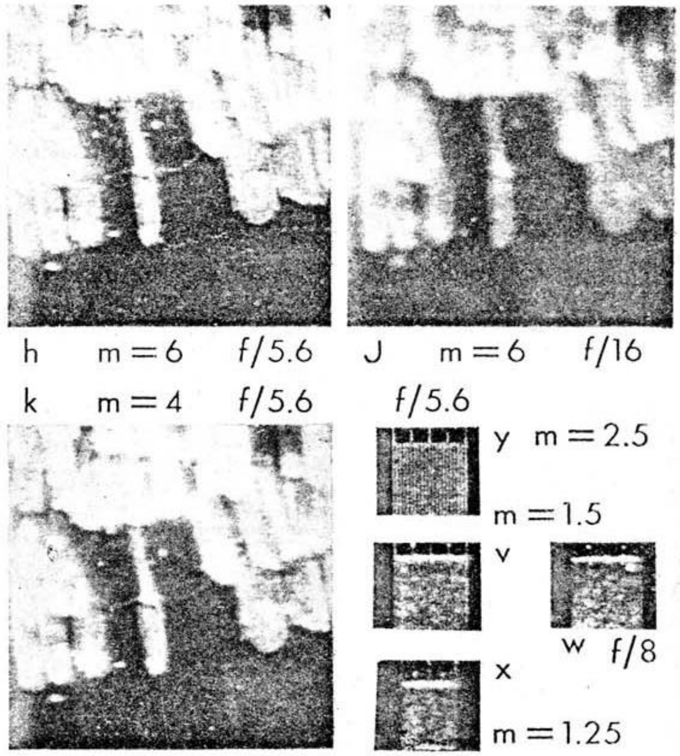

Figure 3—Test photographs made under conditions indicated by Figure 2, except that, to offset losses from reproduction, they appear here at 2½ additional magnification over the magnification that would be useful for prints from negatives "h" or "v." Wing scales, low-contrast subject; reading from left to right, subject was photographed at conditions "h," "j" and "k" on Figure 2—**h:** curve calls for a separation of 210 elements/millimeter; finest teeth on actual black scales measure an average of 200 elements/millimeter under the microscope; they are adequately separated here, indicating a recorded **s** of just over 200—**j:** made outside the useful limit indicated by the curves; definition is entirely inadequate.—**k:** curve limits separation to 180 elements/millimeter; teeth on actual white scales measure 93 elements/millimeter; these are well separated but the finer black teeth begin to merge; the photograph was not made at a high enough negative magnification to meet the criterion represented by "h"; yet the print is enlarged more than is necessary to record the white teeth. The wing scales for "g" were lit at a contrasty ratio with a spotlight for comparison with "h", which was illuminated with a floodlight to reduce contrast for checking the curves.

Resolution pattern; micrometer slide ruled with 100 lines/millimeter; photographed at conditions "v," "w," "x," "y".—**v:** the lines are just defined.—**w** and **x:** made a little outside the conditions for **s** = 100; lines are not defined. (Note it was not possible for the author to enlarge print "x" up to quite the same scale as "v", "w", "y" for reproduction; but smaller prints for conclusive checking at 12 inches were made to equal final scales.)—**y:** since curves represent threshold conditions, it may be necessary to employ a safety factor when a given detail is to be boldly shown; to do this, here, technical conditions for 1/3 higher separation than that yielded by the "v" conditions were selected.

of interest would have to be observed with a loupe. In extreme "under magnification" the resolving capabilities of the paper may not be sufficient to record the desired detail.

When considering lower print scales on Figure 2, several sets of conditions are apparent. Thus for $M=10$, combination from $m=1$ and f/8 to $m=3$ and f/22, are indicated. However, smaller values of N will lead to greater definition than that on which the curves were based. For example, s is 30 at: $M=5$, f/22, $m=1$ and $E=5$, and this is the best that can be obtained at f/22; yet s would equal

65 at f/5.6 with the other factors remaining the same.

(Note: This figure can be obtained by utilizing these factors and finding for the diameter of the final print blur, I, a value of 0.153 millimeter in Equation (2) of the analytic section. It should be observed that this expedient could not be employed for determining suitable higher magnifications. When $I=0.153$, M max for $m \rightarrow \infty$ is only 17.8 at f/5.6; the separation is then 230, with 13 elements/millimeter on the print. The separation of 65 at $M=5$ at f/5.6 given above would also be printed at 13 elements/millimeter under the conditions above. This is more stringent than necessary and the finest detail could not be seen with the unaided eye.)

The broken curve represents conditions for contact printing; here $m=M$. It lies above the corresponding points for enlarging. The dot marks the $\times$ 10 scale, for example, and is above rather than at the intersection of the $m=10$ curve at the $M=10$ ordinate. The reason for the better definition, of course, is that enlarging losses for $E=1$ are not involved and that those from an excellent contact printer are not as great. Nevertheless, when E becomes fractional the negative blurs are recorded as a reduction and this could more than offset enlarger losses.

g

Hence, with a good enlarger, reduction could lead to better definition than contact printing. This is why the contact-printing curve lies below the upper limit of the solid curves, which represent a system that includes an enlarger. Since the differences are so slight and since it is practically very difficult to focus an enlarger sharply for a reduction, or even at 1:1, the gains from reducing over contact printing are chiefly of academic interest.

Figure 3 was prepared to show how to find the useful magnification in practice and to indicate how well the experimental and predicted results agree. Wing scales of a morpho butterfly were photographed under conditions "h," "j" and "k" from Figure 2. The prints were all enlarged to the magnification indicated by "h"–$M=35$–for visual study. (For the illustration here other prints were made at $M=35 \times 3\frac{1}{8}$, and this is explained in the section dealing with prints for journal reproduction.) At $M=35$ the enlargement from a negative made at a camera magnification of $m=6$ should separate 210 elements/millimeter. From a measurement under a microscope the finest teeth on the black scales averaged 200/millimeter. These are separated under conditions "h." However, an $m=6$ negative made at $N=16$, instead of $N=5.6$, does not provide a print that separates these teeth, because the size of the Airy disc of the camera lens is too great. Similarly, an $m=4$ - $N=5.6$ negative when over-enlarged to $M=35$ does not separate the black teeth adequately, because the lens-film combination has not resolved them. This is to be expected because condition "k" should only yield 180 elements/millimeter. It can be seen that the "k" print does separate the white teeth to a wide degree. These measure 93/millimeter and are over-enlarged for "k" conditions; yet these factors produce empty magnification, for the black teeth have not been separated as they have been on the "h" print.

The micrometer slide was photographed under conditions "v," "w," "x" and "y." It carried 100 lines/millimeter. The curves predict that they should be just separated on an $m=1\frac{1}{2}$, $N=5.6$, $M=17$ print; they are. Conditions "w" and "x" are analogous to positions "j" and "k." Similar results obtain.

Inasmuch as the curves represent a threshold separation (because they plot the lower boundaries of useful magnification), the "v" print has only just resolved 100 lines/millimeter. Whenever a photograph is intended for boldly recording desired detail elements rather than to present acceptable general definition, conditions should be selected that incorporate a safety factor. This can be done by adopting technical conditions that would just separate elements finer than the desired detail. For example, conditions "y" would just record 130 lines/millimeter; but they delineate 100 lines with good emphasis. This represents an increase in s of about 1/3.

A check was made with a slide having 200 lines/millimeter around the $m=5$ - $N=5.6$ point; the results were similar. The slides were back- and cross-lit to simulate crisp photomacrographic detail, but not the high contrast of the usual resolution chart. The results show how well the curves agree with practice. It should be noted that for the "v" conditions the theoretical resolution of the camera lens alone is 330 and of the film about 80; the negative image represented 66 lines/millimeter and these are just defined, as the curve predicts.

To demonstrate that the selection of the optimum camera and enlarger conditions alone do not guarantee best results, print "g" was made to the same final scale. Part of the improvement in sharpness over that of the "h" print is due to a higher camera magnification (used here because this particular comparison was unforeseen at the time of making the negatives), but most of it can be credited to the increase in lighting contrast. Print "h" was made with a floodlight for critically checking the curves with a low-contrast subject, whereas print "g" was made with a spotlight. The reproductions show how important it is to provide suitable illumination for a crisp rendition of photomacrographic subjects.

Utilizing Useful Magnification Curves

It will first be noticed that at the higher camera magnifications m, the final print magnification, M and the detail separation, s, start to drop appreciably at about a relative camera aperture N of f/5.6. As the opening is made larger there is some gain, of course, and certainly f/4 is a valuable aperture for use with good photomacrographic lenses. However, most lenses are subject to losses from aberration when they are opened up beyond f/5.6. Such losses would depress the curves. Errors in focusing are more likely when the lens is only stopped down to f/4 rather than f/5.6. Hence the first suggestion:

(1) Utilize f/5.6 unless it is known that the lens and photographer perform well when a wider opening is adopted.

Each curve shows the camera technique conditions that will just separate the desired detail. The second suggestion is:

(2) Select the detail separation required and final print scale needed; then find a relative aperture for the camera lens and a negative scale that will yield the results.

It should not be overlooked that the curves represent threshold conditions, because the definition indicated by any point on one of them will be just apparent. The reason for this is that the curves represent the lower boundary of the resolving ability of the system producing the photographs. A safety factor, based on individual experience, can be applied for the bold delineation of specific detail rather than for a given degree of general sharpness if desired. The effects of using such a safety factor are shown in Figure 3.

(3) A suggested safety factor for obtaining an emphasized detail separation is the selection of a value for s that is 1/3 greater than the actual separation of the desired detail elements, see Figure 3. The technical conditions for this increased value should be utilized instead of the ones that would ordinarily be adopted.

The topmost curve is the academic limit of the capabilities of the system. It shows what could be obtained with an infinitely high camera magnification.

(4) Should the required separation be greater than that for the topmost curve, a *photomicrographic* technic will have to be adopted. In practice there is little to be gained beyond a photomacrographic camera magnification of 50.

As m is increased, s increases, with other factors remaining constant. The $m \rightarrow \infty$ curve shows the limit of useful magnification with an enlarger; the contact-printing curve is almost coincident with it.

(5) For any two-dimensional subject m should be made as large as possible. From a practical standpoint, good contact printing is sharper than enlarging when m can equal M.

So far we have been dealing with relatively high print magnifications. Upon examining the lower range of the curves, it will be noticed that the choice of lens aperture is not so critical.

(6) For print scales of about $\times$ 5 or under, and for 1:1 negative scale, the camera lens can be stopped down to about f/22 to minimize aberrations when the lens is not as good as the one employed for these experiments and to offset focusing errors. However, it should not be overlooked that better definition will result when wider apertures and good lenses are adopted.

The inset curve on Figure 2 shows the useful enlargement, E, as a function of negative scale and for a camera aperture of f/5.6. It is thereby indicated that an enlargement of $\times$ 12 marks a point where losses in definition caused by the enlarger become quite influential. The curves are based on an effective enlarging aperture of fe/50 and the Airy disc at this opening. The usefulness of enlarging at about $E=9$ and beyond is less than the curves indicate. The reason is that effective apertures greater than fe/50 will result at the higher enlargement with the f/5.6 enlarger lens. Also, the curve indicates that the efficiency of enlarging starts to fall off rapidly beyond $E=10$.

(7) Enlargements of 8 times or less should be planned for a photomacrograph to be viewed at 12 inches.

It should be understood clearly that Figure 2 represents average conditions and that photographs made below the curve limits may often be acceptable. The important determining factor is the order of the detail that is required. This has been discussed in connection with Figure 1 and more extensively elsewhere.[2] The author has seen 14 x 17-inch exhibition prints upon which the finest distinguishable elements were separated by almost a millimeter, yet they were adequate for their purpose. When an individual application indicates that fine detail is not needed, a set of curves can be calculated with a larger value for the print definition circle than used for Figure 2.

Prints for Journal Reproduction

It is generally accepted that for a very good photomechanical reproduction (120-line screen or finer) in a journal, the reproduced image size should be 2½ times that of the corresponding glossy print intended for visual study at 12 inches, if about the same detail is to appear. The engraver can also produce sharper plates when at least a slight reduction of the copy is permissible.

Suppose a subject is to be reproduced that has detail of interest requiring a separation of 90 elements/millimeter. Figure 2 shows that M should be 15. This can be achieved through any means discussed previously. Then the area of interest should be cropped to the minimum and a reproduced size of 2½ times the visual print planned. Also, it is best to submit a print to the engraver that is at least 1¼ times as large as the *reproduction*. Both extra enlarging factors, of course, produce empty magnification in the submitted copy but ensure that most of the required detail appears in the journal. The procedures also guard against wastefully making the illustration too large. Another sample set of factors would be:

s	=	150
M	=	25
m	=	3 (at f/5.6)
E	=	8 1/3
E extra	=	3⅛ (2½ × 1¼)
E total	=	26

The prints to be submitted should be viewed at 3⅛ feet and the detail observable should persist in the illustration when reproduced at 62½ times (2½ $\times$ $M=25$) the subject scale. These procedures were followed exactly for Figure 3.

(8) Copy sent to a printer should be 3⅛ times as large as the corresponding prints for visual study at 12 inches. The submitted illustration should be linearly reduced in the journal to 4/5 of its size.

Depth of Detail

A distinction is made in this paper between depth of field and depth of detail in three-dimensional subjects. The former can connote a wide range having poor but

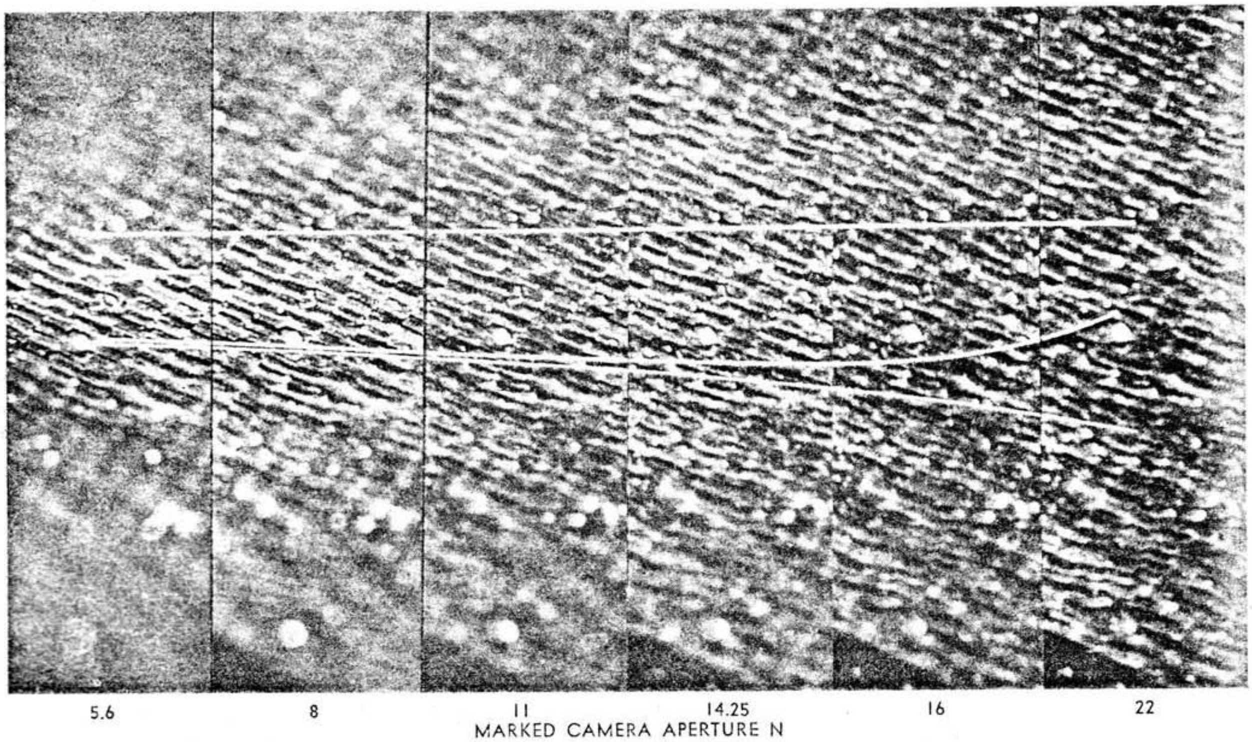

Figure 4—A photographic demonstration of depth of detail made at m = 4, M = 12. The upper curved line marks one of the limits; the lower, a limit from ordinary depth-of-field formulas. The straight lines mark the other depth-of-detail limits for f/14.25 and f/5.6, respectively. The single wing scale that is turned broadside-on in the plane of sharpest focus, "x," (instead of at 45° like the others) has "teeth" that reproduce at 6 elements/millimeter on a print intended for viewing at 12 inches. At f/22 these are not separated and this is the condition for no depth of detail nor useful magnification adopted in this investigation. Here, f/14.25 yields the optimum depth—0.57 millimeter.

homogeneous definition. The latter, on the other hand, is intended to define a region whose *limits still render the useful detail separation desired.* As will be seen from an actual example in Figure 4 and from the derivation of Figure 5 later, depth of detail does not increase indefinitely as the camera lens is stopped down.[2] It increases until it reaches a maximum and then, one stop further, it becomes zero; then not even the plane of sharpest focus exhibits the desired definition. It is thus important to know the optimum aperture for a given set of conditions. In this way the photomacrographer can ascertain the maximum depths available for various subjects and also find the factors that will yield them.

Another interesting point that is not often realized about depth phenomena is that, for a given final print magnification, the greater the proportion of this contributed by the camera magnification, the greater the depth of detail. The reason for this will be made apparent in the analytic section. Briefly, the over-all print magnification dominates the amount of depth and the depth does decrease as this goes up. Yet the photomacrographer should know that the total depth of detail will be greater as the camera magnification approaches the final magnification. Therefore, he should utilize the highest negative scale he can set with his equipment.

The total depth is of more interest in photomacrography than the near and far limits themselves. Subjects are so small that it would be difficult to measure to the plane of sharpest focus. For practical purposes the total depth can be approximately divided in half by the plane of sharpest focus. One of the reasons is that the near detail is enlarged to a slightly greater extent than the far parts; also, longitudinal aberrations tend to add to the ordinarily shallow near depth. However, the author usually focuses about ⅜ of the way from the front limit of fairly large subjects, because when depth is scanty it is psychologically more satisfying to have the farthest detail a trifle more blurred than the nearest. Depth can be studied with the lens stopped down and the plane of sharpest focus adjusted accordingly. Such a procedure is also necessary with a lens that changes focus as it is stopped down. Photographic tests can be made to check the allocation of the depth.

The concept of total depth of detail can be gained from Figure 4, upper curve, and the way in which it diverges from the depth of field, lower curve, of ordinary photography seen. For the counterpart of this illustration, made for visual study, the camera magnification was X 4 and the enlargement X 3, yielding a final scale of X 12. Had the negative been made at X 12, more depth would have resulted, of course, and the effects of such variations are dealt with in the discussion of the depth-of-detail curves, Figure 5.

The lower curve in Figure 4 shows a limit of the classical depth of field when a circle of confusion equal to the criterion for tolerable definition of this paper is employed. This is 6 elements/millimeter and a specific example of exactly this deatil separation is exhibited by the single wing scale that is turned perpendicularly to the camera axis instead of at 45° like the rest. Teeth on this scale measure 6 to the millimeter on the visual print. As to be expected, there is not much difference in the two curves at the wider apertures. However, at the optimum aperture of f/14.25 the divergence is obvious. This shows how well the curves agree with practice.

The straight line marks the other limit at f/14.25. Comparing detail near this line at the other apertures will reveal the changes in definition involved. The short stroke indicates depth of detail at f/5.6.

It is also interesting to note that white spots near the region of sharpest focus increase in size as the lens is stopped down, due to diffraction and other blur effects. On the other hand, in the plane near the bottom, where the circle of confusion dominate the results, there is a bright white spot whose image diminishes in size with stopping down. These two opposing factors produce an optimum balance point where the maximum tolerable depth of detail can be obtained—here, f/14.25, for a depth of 0.57 millimeter.

Depth-of-Detail Curves

The curves in Figure 5 plot the most practical data obtainable from the expressions worked out in the analytic section. There are four sets of data involved: The basic (heavy) curve; the parametric depth curves for $m=1$, 2, and 5; the optimal aperture curves for f/8 to f/32; and the "defining power" curve (inset). These will be described in turn and their uses given.

It should be recalled that the depth data are based on a detail separation of 6 elements/millimeter in the final print. At the subject, then, detail separation is $6M$.

Basic Curve

The basic, heavy curve is the one that will most often be used. It is divided into two parts. The lower part to the right is made up from optimized depth-of-detail figures for prints from negatives made at high camera magnification ($m \longrightarrow \infty$). The upper part is the practical depth of detail at a fixed camera aperture of f/22 and was calculated for prints made at the same scale as the negatives ($m=M$). Since the author's lens does not stop down beyond f/22, the upper part is "optimum" in a practical sense. The full import of this selection of data is academic and can be gained from the analytic section. Here, it need only be understood that the most common conditions, and particluarly contact printing, are met thereby.

It will be apparent that an extension of the heavy portion of the $m \longrightarrow \infty$ curve would demand f-numbers beyond the f/22 of the lens used—the dotted extension of this curve (and of the other parametric curves) was included up to the f/32 point for the benefit of those who may have a suitable lens bearing this aperture.

For most applications the photographer will know the final print scale, M; he can then read the depth of detail in millimeters, T, from the heavy curve. Sample figures are:

M:	2.5	5	8	10	15
T:	8.5	3.2	1.6	1.1	0.5mm

The selection of M in relationship to the desired detail separation, s, has been explained already in connection with the useful magnification curves.

The depth of detail given by the basic curve is intended mainly for moderate enlargements and for a camera aperture of f/22. It will be less when: (1), the negative magnification is much less than the final print scale and when; (2), f/22 is employed for negatives to be printed to final scales of over $M=10$. The first of these two considerations is now taken up.

Parametric Curves

In the region where the proportions of camera and enlarger magnification are critical, curves have been plotted essentially parallel to the lower portion of the basic curve. They indicate factors for $m=1$, $m=2$, and $m=5$ —and the lower portion itself represents those for $m \longrightarrow \infty$.

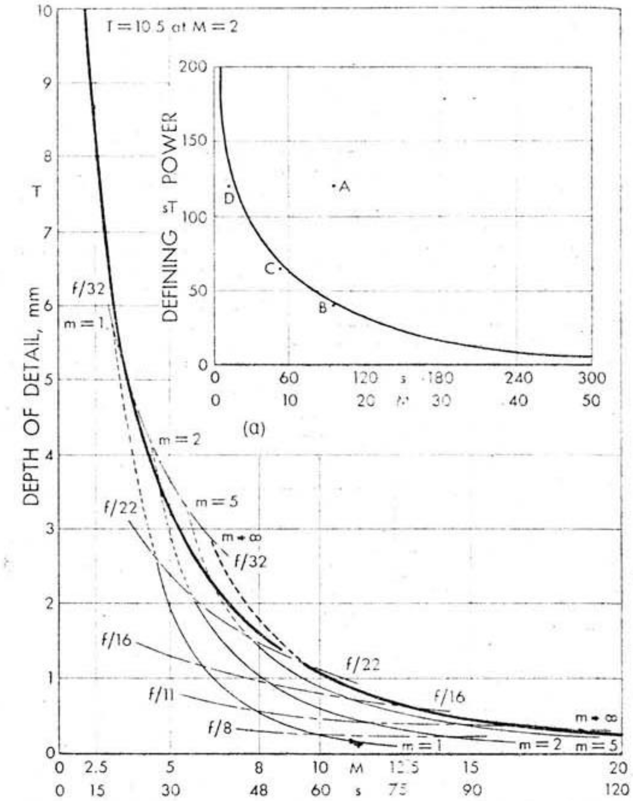

Figure 5—Working curves for determining optimum depth of detail. The inset curve, 5a, indicates the defining power, "sT," of the system. The method of using these curves is outlined in the text.

Key: "M" is over-all magnification; "m" is camera magnification; "s" is detail separation in elements/millimeter; "T" is partly optimum and partly practical (see text) depth of detail in millimeters. The letters "A," "B," "C," "D," on 5a refer to conditions discussed in the text.

When a $\times 10$ print is to be made from an $m=10$ negative, the depth will be practically that shown by the basic curve ($T=1.1$ millimeters), because a parametric $m=10$ curve would be very close to the $m \longrightarrow \infty$ curve. This depth would not be obtained however, with say, an $m=2$ negative. The way that depth varies with camera magnification in this region can be noted from the following figures obtained from the parametric curves at the $M=10$ and $M=8$ absissae:

M = 10	m:	1	2	5	∞
	T:	.2	.6	.9	1.1
M = 8	m:	1	2	5	∞
	T:	.6	1	1.4	1.6

Obviously, the camera magnification should be made as great as possible.

In finding these figures, the photomacrographer has by now encountered the optimal aperture curves (dashed lines). These are explained next.

Optimal Aperture Curves

It should be remembered that the parametric curves just described are calculated from the aperture for optimum depth (see Figure 4); they show this optimum depth, but not the aperture at which it is obtained. To indicate optimal apertures the dashed curves have been drawn across the parametric curves at values for the marked f-stops on the camera lens. To obtain the depth shown by a point on a parametric curve, the camera f-number, N, must be set in accordance with the stops indicated. For example, when $m = 1$ and $M = 5$ there is a depth of detail, T, of 2 millimeters—provided $N = 20$. This can be seen by noting that the point for $m = 1$, $M = 5$, $T = 2$, lies about 4/6 of the distance along the $m = 1$ curve between f/16 and f/22. In practice, setting the aperture pointer at a given stop or halfway between stops, is close enough.

For practice, the optimum point for Figure 4 can be found by interpolating between $m = 2$ and $m = 5$. First though, the following sets of factors could well be located for a good understanding of the optimal aperture curves.

s:	36	36	48	48	54	90	120
M:	6	6	8	8	9	15	20
m:	2	5	1	5	5	5	20
T:	1.9	2.6	0.5	1.4	1.1	0.4	0.25
N:	22	22-32	11	22	16-22	11	11

In an actual photomacrographic problem, as the above table suggests, detail separation needs probably would first establish M. Then the depth requirements would lead to the selection of an appropriate camera magnification. And finally, the camera aperture would be found. Should one or more of the values for these factors demanded on Figure 5 not be attainable, compromises would have to be made. In general, detail separation is usually sacrificed for depth by making prints at smaller final magnifications, but within the other conditions of Figure 5. Thereby more of the subject is included and photographed at a good general sharpness. In contrast, it may alternatively be necessary to work outside these conditions; optimal apertures, and hence the sharpness criterion of this paper, are then foregone.

Sometimes it is possible to arrange or cut the subject in such a way as to reduce depth requirements. This is a desirable approach. In any event, Figure 5 will be of great help in juggling factors. It will also be of value in determining the practicality of a proposed photomacrographic project and thus aid in planning the program.

Defining Power

There is size-limitation effect encountered in photomacrography that is bound up with depth of detail. It can best be described through an example: A final print size of, say, ten inches can be readily achieved when the subject is a Galapagos tortoise. Yet a ten-inch print of a ladybug, which has about the same shape, would be very disappointing from a sharpness standpoint. Satisfactory detail could be obtained in a shallow depth zone, but not throughout the beetle form, as would be the case with the tortoise form. The beetle depth zone could be "increased" by stopping down the camera lens for homogeneous definition over the entire body, but the detail separation would be unacceptable.

This effect arises because, as subjects become very small, detail elements approach the size of various physical limits in the recording system. A common experience will help to clarify this.

A mountain viewed through the wrong end of a telescope could appear to have the same final size as a molehill on its slope that is observed through the right end. Large boulders could provide the limiting detail elements in the former case and small balls of earth in the latter.

Yet the mountain and the boulders would look sharper than the molehill. The introduction of magnification for imaging the lumps of earth has reduced what is going to be called "defining power" in this paper. This is not resolving power; the telescope actually resolves smaller elements when used the right way around.

Defining power is associated with the final image; however, figures both for specifying it and for applying the concept to practice, can be obtained from the subject.

Defining power is to be the ratio of the optimal or practical total depth of detail, T, over the width of the detail elements at the depth limits. This width is the reciprocal of the detail separation s. Again, s has been defined as $6M$. Therefore:

$$sT = 6MT$$

In order to find the defining power for the camera lens used in this investigation (and for similar lenses), Figure 5a has been plotted from the basic curve in Figure 5. Other defining-power curves can be plotted from any depth-of-detail or depth-of-field data to suit individual needs.

The defining power, in Figure 5a, is plotted against the detail separation and overall magnification. The photomacrographer usually knows s and the depth of his subject. He can multiply these together and find out whether the defining power curve permits his value at a given s absissa. Should his value fall on or below the curve, his subject can be photographed satisfactorily and he can refer to Figure 5 for technical factors. Should his value lie above the curve, the subject will have to be changed, rearranged or discarded.

The concept of defining power can be further illustrated by considering a common subject from ordinary photography and then photomacrographic subjects will be compared in connection with Figure 5a.

First consider a medium-sized pet cat. A half-scale "portrait" is to be made. The depth of the subject is about 65 millimeters. The guard hairs in the fur are the desired finest detail to be separated; they measure 0.16 millimeter in diameter. Accordingly, the subject calls for a detail separation of $1/(2 \times 0.16)$, or 3, (see p. 42 and Appendix). To determine whether the proposed photograph is feasible, note that M is going to ½ and that $6M = 3$; therefore the scale is suitable for reducing the subject detail to the limit of six elements/millimeter at the print. The defining power needed by the subject is 3×65, which equals 195, at $M = ½$. A classical depth-of-field curve would be almost the same as the basic curve of Figure 5 in the $M = 1$ region; hence a similar defining-power curve would be obtained. And from 5a it can be noted that a defining-power of 195 is possible at $s = 3$; this point is below (i.e. to the left of) the curve.

Checking ordinary depth-of-field figures shows that at f/32 a depth of 64 millimeters can be obtained for the circle of confusion adopted in this paper—0.33 millimeters. Therefore, from subject calculations, from 5a and from depth-of-field-calculation standpoints, the depth and the defining power needed are shown to be provided. That is, the defining power called for by the subject is closely met by the proposed photographic factors, and this is predicted by the point falling below the curve.

Apart from yielding some easy practice in the type of arithmatic the photomacrographer needs to do, the above example merely demonstrates what is already well-known—a satisfactory portrait of a cat *can* be made. But what if a full-length photographic record of a fruit fly with eye setae (hairs) sharp is to be made—can it be done? Average dimensions of Drosophila melanogaster in millimeters are:

Length	2.8
Width of face	0.74
Width across wings	1.2
Depth of eye	0.18
Median diameter of eye setae	0.005
Approximate diameter of eye facets	0.009

By arranging the fly so that a line along the near eye and the edge of the near wing is perpendicular to the lens axis, the depth requirement could be confined to the width across the wings, 1.2. The detail separation has to be $1/(2 \times 0.005)$ or 100, if we are to record the eye setae as tapered hairs rather than blobs. The defining power is thus 100×1.2, or 120, at the $s = 100$ ordinate. This is point "A" on Figure 5a—obviously the picture cannot be made.

However, the requirements for a profile "portrait," with the eyes and setae sharp, are not so stringent. (T would be about ½ the width of the face, say 0.4 millimeters.) Here the defining power is 100×0.4, resulting in a practical proximity to the curve at point "B."

Other factors for picture "B" can now be obtained from Figure 5. Note that $s = 100$, $M = 16.6$, $T = 0.4$ and the optimum aperture is $N = 12$. The defining power—$sT = 40$—from the data is seen to agree with that calculated from the subject. (To correspond with these figures, the camera magnification should be as close to 16.6 as possible.)

To find out what type of record can be made of the entire fly body, find by trial a value for s on Figure 5 that will make $s \times 1.2$ (for the width across the wings $T = 1.2$) fall on or below the curve of Figure 5a. Such a point is "C" and the technical factors are: $s = 54$, $M = 9$, $T = 1.3$, $N = 22$. It should be noted that the defining power calculated from the subject is 54×1.2 equals 65; since the factors yield slightly more than enough depth, 1.3, "C" falls below the curve and the potential defining power of the system is 54×1.3, or 70, which is adequate.

Working the expression for s in reverse yields, when x represents the width of the detail separated upon utilizing the above factors:

$$\frac{1}{2x} = 54$$

$$x = 0.009$$

Then x corresponds closely to an eye facet on the fruit fly. Of course, the setae will not be more than blobs in this photograph.

To summarize conditions "A," "B," and "C": The entire body of the fruit fly can be photographed at ×9 with reasonable sharpness and the eye facets should be resolved. The profile head of the fly can be photographed at about ×17 and most setae should be resolved into tapered hairs. This corresponds very closely with practice.

There is another well-known fact that can be explained through Figure 5a. The photograph of an accurate scale model of an insect is technically (if not scientifically) more satisfactory than the image of the actual insect, both to the same final scale. We can apply this to the fruit fly. Point "A" leads to an unsuccessful result when $M = 16.6$; but with an ×8.3 scale model, M need only be 2 for images of the same size. The following requirements then appear:

	s	M	T	N	sT
At model:	12	2	10	..	120 (point "D")
From curves:	12	2	10.5	22	126

Point "D" is just below the curve, indicating a feasible record can be made. The model would be about the size of a bee, and it is well known that the latter can be photographed much more easily than a fruit fly. In practice, the model would probably be large enough for ordinary photography in the size-range of a small cat. This would make its recording even more simple.

This paper has explained why it is not possible to photograph very small objects at high magnifications with good overall sharpness. It has shown how to minimize, and sometimes eliminate, the imperfections arising out of low defining powers. Withall, it should not be overlooked that many useful technical photographs can be and are made which have to show unsharp limits.

Those who use and view photographs should realize that the shortcomings are not the fault of the photographers. The latter also should appreciate the limitations of the process, so that they will not expect too much nor fail or get the most quality possible from a given situation. By knowing the factors involved, both groups will be able to approach problems and results with discernment.

At first glance many photomacrographs may appear dissapointing. It should be remembered that they are made for imparting information, not for looks. Therefore, the better the lens and the finer the resolution of the film, the more useful the result. These factors will produce a photograph that may not look as good as one made with other less exact lenses and films. The reason is that the optimum factors will produce a more obvious difference between the sharpness of the plane of sharpest focus and the limits of depth of detail. Nevertheless, they will concomitantly extend the *useful* range of these limits. This does not mean that the esthetic aspect should be neglected, because the avoidance of distracting elements in the photographs, through suitable selection and arrangement of the subjects, also enhances clarity.

ANALYTIC SECTION

Several surprising and valuable findings arise out of the analyses that support and provide the practical working information in Figures 2 and 5. The photographer will gain a better understanding and appreciation of photomacrographic problems if he merely reads through the following material. Of course, should he wish to plot curves for special applications, he can study the discussion more thoroughly.

The physical blur circles listed in Table I are here called "circles of definition," because they affect the image-producing capabilities—called "detail separation" in this paper—of the camera-enlarger system in a manner similar to the circles of confusion of depth-of-field considerations. The capacity of the system for separating and recording fine subject detail will depend upon the size of the cumulative blur in the print, just as the circle of confusion poses limits of tolerable definition. In photomacrography this cumulative blur should be taken into account; the usual depth formulas, satisfactory for ordinary photography, do not do this.

A Modified Circle of Confusion

Depth-of-field values, classically, are calculated from purely geometric assumptions concerning the object space. The formulas are based on a tolerable blur circle—the circle of confusion—which can be referred to the image in the final print. To obtain realistic depth figures for photomacrography, a blur circle made up of the aggregated circles of definition in the photographic system must be convoluted with the geometric confusion blur.

It is then possible to determine an effective circle of definition in the subject or in the final photograph.

If these two blurs are considered as Gaussian spread functions, then the sigma value of their convolution is equal to the square root of the sum of the individual squared sigma values. It has been found that the effective diameters of such blur circles are closely proportional to these sigma values.[5] Conceptually then, it is convenient to find a blur whose area is the combined area of the component blurs; this can be done to within 5 per cent accuracy.[6] Such a blur, referred back to the subject, is indicated by *i* in the equation below.

In other words, if the diameter of the physical blur from diffraction, aberration and diffusion in the photographic system, referred to the subject plane, is *d*; and if the diameter of a realistic blur from geometric depth-of-field considerations, also referred to the subject, is *c*; then their convoluted diameter is:

$$i = \sqrt{c^2 + d^2}$$

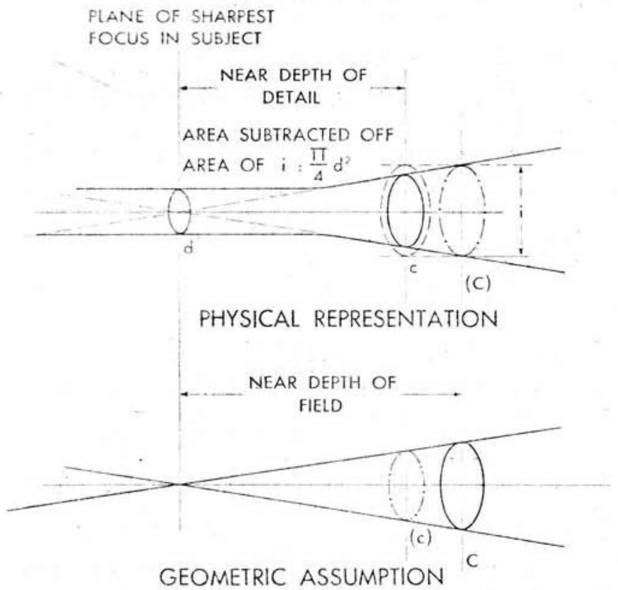

Figure 6—Comparison between depth-of-detail and depth-of-field relationships. *Key:* diameters indicated by letters as follows— "d" is physical blur, referred to subject—"C" is ordinary (geometric) circle of confusion at subject—"c" is modified (geometric) circle of confusion at subject—"i" is image circle of definition referred to subject.

Figure 6 shows the geometry of this modified circle of confusion *c*. It also shows how *i* can be set to correspond to any suitable classical geometric circle of confusion, *C*.

The diagram makes a distinction between depth of field and depth of detail. The reason for this is that depth-of-field formulas indicate a region of tolerable sharpness; yet there is no provision in them for determining when the lack of detail separation within the range becomes intolerable, because there is no allowance for the physical blurs. From the formulas to be developed for "depth of detail," on the other hand, it will be possible to find a range possessing the desired detail separation out to the limits. And the physical blurs will be taken into account.

Figure 6 also implies that there is a homogeneous tunnel-like focal region that can be referred to the negative, rather than a geometric crossover. This will be justified in the last section of the paper.

In the discussion now to be presented, the way in which *i* is obtained from studying practical photomacrographs will be shown. Also, an expression for evaluating *d* will be developed. Then the diameter of the geometric component, or modified circle of confusion *c*, of the convoluted blur circle *i* can be determined, for:

$$c = \sqrt{i^2 - d^2}$$

Values for the total depth of detail, *T*, will be obtained from *c* and compared with the depth of field from *C*—both as functions of *N*, the marked f-number of the camera. It will also be shown that for a given set of technical parameters there is a predictable aperture $N_{T\,max}$ that yields a maximum value for *T*. Early in the development it will be enlightening to examine the special case of the above expression: when *c* equals zero, for this is the condition of no depth. Thereby the factors for photographing 2-dimensional subjects at the most useful magnification are going to be revealed.

Subject Circle of Definition

To find a tolerable value for *i*, it is most practical to examine its diameter referred to the final photograph through the agency of the over-all magnification *M*. Thus if *I* is the diameter of the image circle of definition in the final print:

$$I = Mi \text{ and } i = \frac{I}{M}$$

There are two reasons for this referral. First, from a philosophical standpoint, the circle exists as an actual disc in the photograph—it is only a mathematical convenience at the subject. Second, it can be estimated from measurements made on actual photomacrographs. Once this has been done it can be projected back to the subject for the familiar depth-formula manipulations.

While the image-circle diameter referred to the subject, *i*, will be employed for considering depth of detail and useful magnification, and *C* will be adopted for finding the depth of field, comparable *limit values* can be set, of course, for both circles.

Then:

$$C = \frac{I}{M} = i$$

Their basic difference lies in the fact that for 2-dimensional subjects *C* becomes zero, whereas *i* reduces only to *d*.

A VALUE FOR *i*

The detail separations on many good photomacrographs were measured and judged to be 6 elements (or "lines")/millimeter. Further justification for selecting this criterion to find a fixed circle at the print will be given under "Values for Computation." In this analysis the detail-separating capabilities of individual or of summated blurs is held analogous to the resolving power of two Airy discs. This has been found to yield sufficient practical accuracy, especially for line detail.

When photomacrographic detail elements comprise setae or ridges that are as wide as the spaces between them, they resemble the photographic, low-contrast, bar chart. The concept of detail separation then parallels that of resolution. Detail separations, in elements/millimeter at the print (and sometimese the negative), and at the subjects are indicated by *S* and *s* respectively. A "bar" and a space is considered as one "line." It is not possible to truly specify *S* as an objective quantity; however, its practical status will be described in connection with the evaluation of *r* in the computation section.

From Airy disc considerations, the following relationships will be adopted:

$$S = \frac{2}{I} = \frac{2}{Mi} \text{ and } s = \frac{2}{i}$$

Hence:

$$I = \frac{2}{S} \text{ and } i = \frac{2}{s} = \frac{2}{MS}$$

This yields the diameter of the final tolerable print blur projected back to the subject.

Summation of Physical Blurs

The next factor to be examined is *d*, the effective diameter of the physical blurs in the photographic system. By means of the previously established method of convoluting circles, the summation of the various component diameters can be made by the formula:

$$d = \sqrt{d_1^2 + d_2^2 + d_3^2 - - - - - - d_n^2}$$

It should be noted that the factor $\pi/4$ cancels out, and that $d_1 - d_n$ are individual blurs.

SPECIFICATION OF PHYSICAL BLURS

It is necessary to specify certain conditions under which the sizes of the blurs are considered so that they can be summated for deriving working equations. They are first all referred back to the subject to form a subject circle. Hence, with one exception ("r," below), their actual diameters have to be divided by either the camera magnification *m*, or the over-all magnification *M*, depending on whether they are regarded at the negative or the print, see Figure 7. Since the symbols to be adopted will designate the *actual* diameters *squared*, the *referred* diameters squared, below, involve the appropriate magnifications squared.

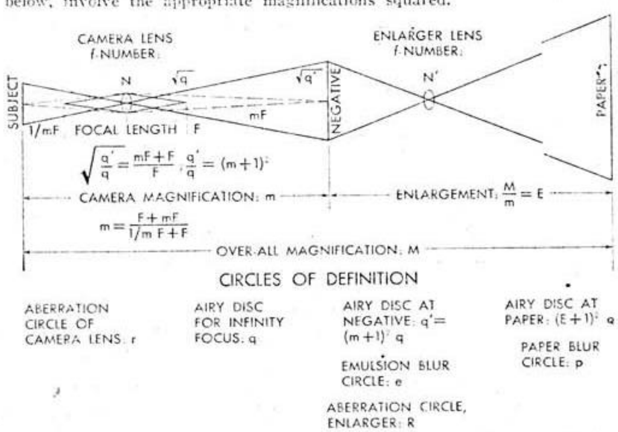

Figure 7—Diagram showing where the circles of definition will be evaluated and the symbols adopted for their diameters squared.

For geometric aberrations of camera lens .... r

While this degradation of the image occurs at the negative, it cannot be divorced from the diffraction circle of the Airy disc there. However, a method of segregation and measurement at the subject is worked out in the section on computation. Hence this blur is to be located and evaluated at the subject. It is also assumed that, for applications in photomacrography, the size of this blur at the subject does not vary to any practical extent with longitudinal aberration, camera aperture or magnification. This hypothesis will be justified further on.

For Airy disc of camera lens .... $\frac{z(m+1)^2N^2}{m^2}$

The usual calculation for the Airy disc at infinity focus contains a constant factor based on the wavelength of the light and a variable depending on the angle subtended by the exit pupil. To simplify Figure 7, the symbol *q* has been entered; but it is necessary to take this angle into account, because it will vary with camera magnification at the negative and with the f-number, *N*. By inspection of the diagram, the way to allow for the former will be apparent. To free *N* for subsequent operations, the square of the constant factor is called *z*.

For emulsion blur circle .... $\frac{e}{m^2}$

This blur results from the graininess and turbidity of the negative emulsion.

For aberrations of enlarger lens .... $\frac{R}{m^2}$

The author uses the same lens for both camera and enlarger. Hence, the aberration circle here is treated like r, and is considered at the negative.

For Airy disc of enlarger lens .... $\frac{n}{M^2}$

The size of this circle will vary with the enlargement $E(M/m)$ and with N'. However, the computations are much simpler when M/m is not permitted to produce such variability. It is desirable, and practical, to hold the *effective* enlarging aperture, $N'(E+1)$, constant at the enlarger—fe/50. The diameter squared of the Airy disc at this effective aperture is called n. It equals $(E+1)^2 zN'^2$.

For paper blur circle .... $\frac{p}{M^2}$

This circle is similar to the one at the negative. When contact printing is considered, the factor can include an allowance for diffusion caused by the printer.

Obviously, the areas of the above blurs will depend on the lenses and materials used. The author utilizes for most photomacrographic work the 2-inch, f/4.5, Kodak Enlarging Ektar Lens, Kodak Panatomic-X Film and glossy Kodak Medalist Paper.

The methods of this paper can be applied to other equipment, and they also allow the insertion of refinements like acutance and spread functions and factors like unavoidable manipulative blurring or a television raster.

Utilizing the Modified Circle

It is now possible to determine the expression for c, starting from the set value I and the relations:

$$i = \frac{I}{M} \text{ and } i^2 = c^2 + d^2$$

$$\frac{I^2}{M^2} = c^2 + r + \frac{z(m+1)^2N^2}{m^2} + \frac{e}{m^2} + \frac{R}{m^2} + \frac{n}{M^2} + \frac{p}{M^2}$$

$$c = \sqrt{\frac{1}{M^2}\left[I^2 - (n+p)\right] - \frac{1}{m^2}\left[z(m+1)^2N^2 + (e+R)\right] - r}$$

Since c is a modified but geometric circle of confusion at the subject, the usual formula for depth of field can be applied for depth of detail, provided this circle is adopted. Again, because c is determined from a fixed circle in the print, M is the magnification involved in the formula. The total depth can be expressed in the usual way:

$$T = \frac{vc}{D-c} + \frac{uc}{D+c}$$

Now, even in the photomacrography, c^2 is relatively small compared with D^2. Hence the following common transformation can be made:

$$T = \frac{2N(M+1)}{M} \cdot c$$

and this is the formula that will be utilized for computing depth of detail.

Before the formula can be usefully applied, it will be necessary to know a reasonable value for M to employ with a given subject having detail elements of a specific separation. This can be obtained by first examining the concept of useful magnification as applied to two-dimensional subjects.

Useful Magnification

The purpose of finding an expression for M is to provide a means for indicating all the enlargement capabilities of the system and to determine when empty magnification will begin. A given system has the capacity for separating $2/i$ elements/millimeter in the subject. The over-all magnification expands this separation and when the degree is M, s has been expanded to S, which is 6 elements/millimeter. Now the capabilities s and i are inherent in the system. Hence:

$$M = \frac{I}{i} = \frac{s}{S} \text{ and } SM \text{ or } 6M = s$$

A print having a greater over-all enlargement than M exhibits empty magnification, because s is merely expanded beyond S; no new detail is disclosed, for the system is not capable of separating finer detail.

On the other hand, an over-all magnification of less than M records M-s finer than $S=6$. The desired detail could be observed with a loupe, provided the capabilities of film, enlarger and paper have not been exceeded. Yet the print is "sharper" than it need be.

This concept has great practical value. It has been discussed more fully from that standpoint in the section on reading useful magnification curves. The same considerations hold for considering the separation at the limits of the depth of detail. A value s can be read off Figure 2 and the corresponding value M can be compared with magnifications attainable from Figure 5.

The expression for useful magnification can be obtained by noting that for two-dimensional subjects T equals zero, as does c. Formulas for plotting curves for both useful magnification and optimized depth of detail will now be worked out.

Formulas

First, the equations that were utilized for plotting Figure 2 can be derived by setting c equal to zero.

LIMITS OF USEFUL MAGNIFICATION

$$I^2 = M^2\left[r + \frac{1}{m^2}\left\{z(m+1)^2N^2 + (e+R)\right\} + \frac{1}{m^2}(n+p)\right] \quad (1)$$

It is now possible to solve for M as functions of m and N.

$$I^2 = (n+p) + M^2\left[r + \frac{1}{m^2}\left\{z(m+1)^2N^2 + (e+R)\right\}\right]$$

$$M = \sqrt{\frac{\left[I^2 - (n+p)\right]}{\left[r + \frac{1}{m^2}\left\{z(m+1)^2N^2 + (e+R)\right\}\right]}} \quad (2)$$

It will be noted that for contact printing m equals M and that n and R are not involved. Equation (1) can then be transformed to:

$$m = \sqrt{\frac{\left[I^2 - (p+e)\right](r + zN^2) - rzN^2 - zN^2}{(r + zN^2)}} \quad (3)$$

An interesting feature of Figure 2 is that it shows contact printing does not necessarily produce the best definition in the print. It will be seen that when m is made very large and the negative is reduced instead of being enlarged, M can sometimes be greater than the scale for contact printing. The difference is more academic than practical, largely because of the difficulty in focusing a reduction "needle" sharp. The defining equation is:

$$\underset{m \to \infty}{M} = \sqrt{\frac{\left[I^2 - (n+p)\right]}{(r + zN^2)}} \quad (4)$$

Here the blurs in the negative disappear (e and R), because the enlargement approaches zero. Further, practical use can be made of Equation (4) in determining r, as described subsequently.

There may be occasions when a variable such as $(E+1)^2Q$ in the basic specification of blurs cannot be reduced to a simple term like n. With the resulting expression it is useful to utilize E as a parameter. Equation (2) then expands into the following, which has been arranged for ease in computation:

$$M = \sqrt{\frac{(r + zN^2)K - E^2rzN^2 - EzN^2}{(r + zN^2)}} \quad (5)$$

where

$$K = \left[(I^2 - Q - p) - 2EQ - E^2(Q + e + R)\right] \text{ and } Q = zN'^2$$

DEPTH AS A FUNCTION OF CAMERA APERTURE

Utilizing the expression for c, the formula for the total depth of detail becomes:

$$T = \frac{2(M+1)}{M} \times N\sqrt{\frac{I^2}{M^2} - r - \frac{I}{m^2}\left[z(m+1)^2N^2 + (e+R)\right] - \frac{I}{M^2}(n+p)} \quad (6)$$

This can be simplified to:

$$T = aN\sqrt{b - N^2} \quad (6a)$$

where $$a = \frac{2z^{0.5}(M+1)(m+1)}{Mm}$$

and $$b = \frac{m^2}{z(m+1)^2}\left[\frac{I^2 - (n+p)}{M^2} - \frac{(e+R)}{m^2} - r\right]$$

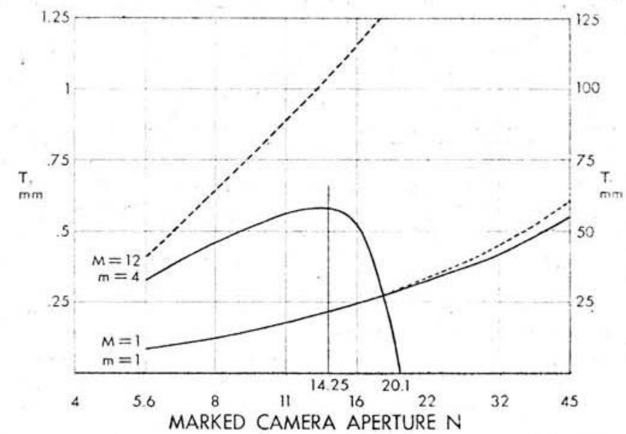

Figure 8—Curves comparing the depth of field of geometric optics with the depth of detail of photomacrography. Key: "T_d" is depth of detail, "T_f" is depth of field (both in millimeters) and "N" is camera lens aperture. Upper curves—dotted line indicates the geometric depth of field specified for a print at X 12 magnification; solid line shows depth of detail when a X 4 negative is enlarged to a X 12 print. Lower curves—dotted line indicates the geometric depth of field for 1:1 photography; solid line shows the depth of detail in a print from a 1:1 negative.

Equation (6) gives us a means for calculating T_M as a function of N when M is known and m is made a parameter. Figure 8 compares the depth of detail calculated from this equation with the depth of field of geometric optics.

From the derivative of Equation (6a) with respect to N we can find the aperture that yields the maximum depth for a desired M at any negative magnification:

$$T' = \sqrt{\frac{(b - 2N^2)}{b - N^2}}$$

By setting T' equal to zero and testing the result over the range in which we are interested, we get:

$$N_{T_{max}} = \sqrt{\frac{b}{2}} \tag{7}$$

Substituting this value in Equation (6a) we find that the maximum depth is:

$$T_{max} = \frac{ab}{2} \tag{8}$$

It should also be observed that T is zero when $N^2 = b$, which is one stop smaller than the optimal aperture. Beyond that, T, mathematically, becomes imaginary, and the definition, practically, becomes intolerable throughout.

Equation (7) will yield the optimal aperture for a desired final print scale for any combination of negative and print scale. Figure 9 shows a plot of the equation with m as a parameter. However, the curves do not yield the magnitude of the depth. This can be done by translation to the curves in Figure 10, which were plotted from Equation (8). Combining data from Figures 9 and 10 yields the working curves of Figure 5.

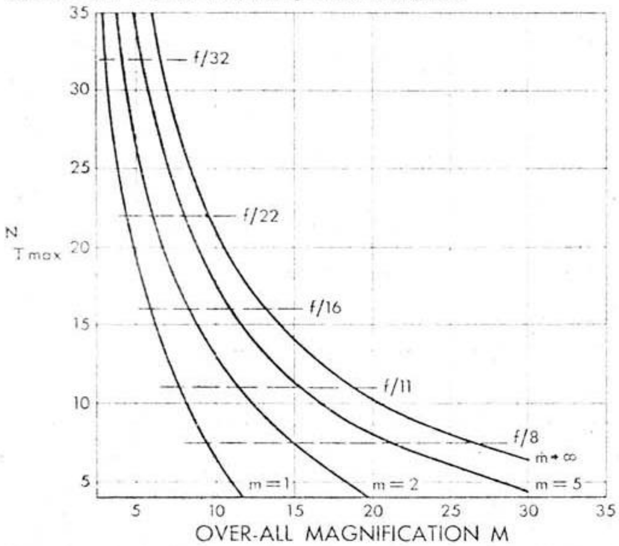

Figure 9—The f-numbers "NT_{max}," for achieving optimum depth of detail, at various overall magnifications, "M," for a range of camera magnifications, "m."

Equation (8) gives us the value for $Tmax$, the optimum depth of detail, as a function of m and M but it does not tell us at what f-number the value occurs. The latter figure can be obtained from (7), but this is also a function of m and M. It is, therefore, going to be necessary to attempt to find an efficient value for m, and this problem is now examined. From Equation (6) in can be seen that when $m \to \infty$, T approaches a maximum. However, (6) shows that a very great negative scale, coupled with reduction in the enlarger to arrive at the desired M, is hardly worthwhile for the slight benefits obtained. From the expression for b it will be seen that the factor: $-(e + R)/m^2$, reduces to zero and that only this lowest value for it is subtracted from the other figures for the image degradation.

On the other hand, when m is fractional, a relatively large quantity has to be deducted from the value of the surd, which reduces the value of T greatly. Hence, m must enter into calculations of depth of detail. The practical implication of this is that m should be made as large as possible with the equipment at hand, with good contact printing as the desirable limit. The surprise at this realization will be allayed when it is noted that M plays the dominant role in the depth change.

For the convenience of those who wish to compute curves for their own applications, the depth-of-detail equations are analyzed further.

The long form of Equation (7) is:

$$N_{T_{max}} = \sqrt{\frac{m^2}{2z(m+1)^2}\left[\frac{I^2-(n+p)}{M^2} - \frac{(e+R)}{m^2} - r\right]} \tag{7a}$$

To find the limiting curve for Figure 9, let $m \to \infty$. This yields:

$$N_{T_{max}}\Big|_{m \to \infty} = \sqrt{\frac{1}{2z}\left[\frac{I^2-(n+p)}{M^2} - r\right]} \tag{9}$$

Equation (8) can be expressed:

$$T_{max} = \frac{(M+1)m}{z^{0.5}M(m+1)}\left[\frac{I^2-(n+p)}{M^2} - \frac{(e+R)}{m^2} - r\right] \tag{8a}$$

To find the limiting curve for Figure 10 we can again let $m \to \infty$:

$$T_{max}\Big|_{m \to \infty} = \frac{(M+1)}{z^{0.5}M}\left[\frac{I^2-(n+p)}{M^2} - r\right] \tag{10}$$

When $Tmax$ is zero we have:

$$M\Big|_{m \to \infty,\ T = 0} = \sqrt{\frac{I^2-(n+p)}{r}} \tag{11}$$

We could also plot the conditions for contact printing on Figure 9. From Equation (7a) the following can be derived (n and R are not involved):

$$M\Big|_{M = m,\ N_{Tmax}} = \sqrt{\frac{(r+2zN^2)\,[I^2-(e+p)] - 2zrN^2 - 2zN^2}{(r+2zN^2)}} \tag{12}$$

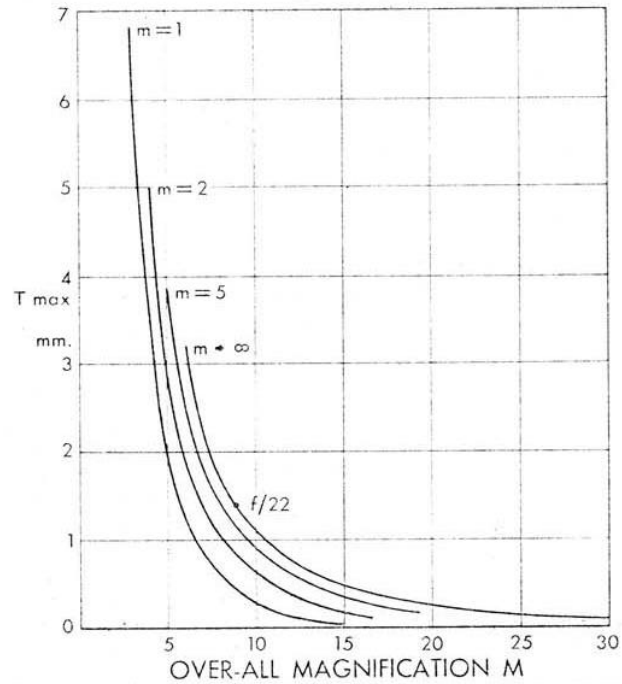

Figure 10—The relationships between over-all magnification, "M", camera magnification, "m", and optimum depth of detail, "Tmax." The curves have been terminated at N = 35, on the left.

Values for Computation

The curves plotted from the equations depend on the values entered for the various blurs. These were defined earlier. Also, certain qualifications were placed on the aberration and final image circles. The justification for restricting r is bound up with finding a figure for it. The reason for setting the value for I where it is also warrants further discussion.

It should be recalled that the equations deal with the diameters *squared* of the various blurs.

Another important point is that the factor 10^{-4} cancels out through all the equations except in the expression for a in the depth formulas. Accordingly, this factor is *not* given below in the values listed, but it should be remembered when a is computed.

For r; Camera lens geometric aberration circle:

The value for r must be quite accurate because the effect is multiplied by M in the print. It is, of course, impossible to actually separate the geometric aberration from the Airy disc. However, in the subject, when $m \to \infty$ in the empression for I^2, Equation (1):

$$i = \sqrt{r + zN^2} \tag{13}$$

Then i becomes the effective diameter of the star image at the short conjugate of the lens (The negative blur drops out because it is relatively small, and does not have to be referred to the subject.) When r is zero, we have the expression for the theoretical resolving power of a lens with no aberrations. This resolution is plotted in terms of s to provide the upper curve in Figure 11.

Negatives at 30 and 50 magnifications were made with a 2-inch, f/4.5 Kodak Enlarging Ektar Lens. The subjects were micrometer slides and natural objects in photomacrographic setups. The slides were illuminated from both the side and the rear to reduce contrast to a photomacrographic range. The crosses in Figure 11 represent values of S/m, (s), obtained from actual measurements or estimated on the negatives and averaged over several examples. (For the conditions of Equation (13), S is considered at the negative and $m = M$.)

The values were inserted in Equation (4), noting that M equals $sI/2$, because:

$$s = \frac{2}{i} \text{ and } \frac{s}{2} = \frac{1}{i} = \frac{M}{I}$$

(Since negatives were studied rather than prints, n and p were not involved as they are in other applications of Equation (4).) Upon solving for r, it was found to be higher at f/4.5 than the almost equal values obtained at f/5.6 and f/8. From there on it was erratic (see inset on Figure 11), because zN became relatively large—necessitating impossibly accurate practical estimates of s. The lower curve and its dotted extension were plotted with the f/5.6 value. It corresponds to the locus of the crosses within experimental accuracy. The higher f/4.5 value was extrapolated to f/4 to adjust the lower curve.

The basis for relegating r to the subject lies in Equation (13). The star image appears on the short-conjugate side of the lens on a lens bench when the other conjugate is very long and carries the small source. Then the area associated with r can be treated as a reduced image of an imaginary blur at the long-conjugate plane. Now, if a negative is placed in the long-conjugate plane, the actual aberration blur can be hypothetically projected to it at the over-all magnification M. Conversely, when the point source exists in the short-conjugate plane, the real blur appears in the distant plane, but it can be translated to the source plane by the reduction $1/M$.

This is the operation implied in Equation (1). The expedient is necessary because r cannot be evaluated at the usual photomacrographic negative. But it can be considered at the subject, which is always in the short-conjugate plane.

In the derivations from Figure 11, the value for r was actually made from measurements in the long-conjugate plane and then referred back to

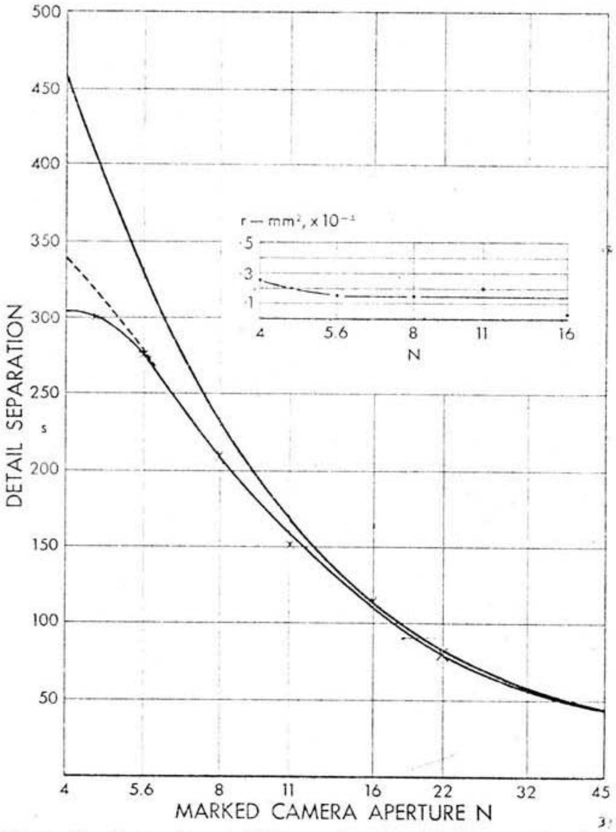

Figure 11—Curves for establishing values for detail separation, "s," and the size of the aberration circle, "r," for various camera apertures, "N."

the short-conjugate plane for separation at the subject via Equation (4). This emphasizes the subjective nature, based on practical results, of both s and r. The procedure is also mathematically convenient, because the aberration circle is not permitted to continuously vary with m and N like the Airy disc.

To facilitate work with other lenses, the star image of the lens under investigation was measured on a lens bench. It was found to be $(r + zN^2)^{1/2}$ when the central spot was focused as the smallest sharp disc obtainable. The first dark ring and the first light one were sharp and distinct, but the latter was narrow and not measured. In this way other lenses could be appraised and r found without going through the above steps.

Not permitting r to vary without restriction in the equations, assumes that the geometrical aberrations do not diminish enough to be detectable relative to the Airy disc as the lens is stopped down beyond f/5.6. This is a safe practical assumption, as evidenced by the contiguity of the curves in Figure 11. Another hypothesis is that the aberrations do not increase unduly, laterally nor longitudinally, at the smaller camera magnifications; this is reasonable for photomacrographic and good enlarging lenses, because they are corrected for finite conjugates. Practice supports this assumption.

At f/4 .... $r = 0.254$

At f/5.6 .... $r = 0.160$

For z; Factor (squared) for camera lens diffraction circle:

$(2 \times 5460 \times 10^{-7})^2$ ...... $z = 0.0119$

For e; Negative emulsion circle:

A fine-grain emulsion, like that on Kodak Panatomic-X Film, has a resolution of about 100 lines/millimeter, when developed in Kodak Microdol Developer, with a high subject contrast. Raw photomacrographic illumination produces the effect of about a 4:1 lighting ratio on larger subjects. There are tone differences involved also, so that 8:1 was taken as an average subject contrast. When a negative density of 0.6 is considered as useful for shadow detail, the resolution can be placed at about 80 lines/millimeter.[7]

$(2/80)^2$ .... $e = 6.25$

For R; Enlarger lens aberration circle:

It is assumed that the enlarging lens is as good as the camera lens. The author uses the lens mentioned for photography.

$R = 0.160$

For n; Constant enlarger lens diffraction circle:

The use of this simplification by employing fe/50 has been discussed.

$(50)^2 \times 0.0119 \times 10^{-4}$ .... $n = 30.0$

For p; Paper emulsion circle:

The resolution of a glossy enlarging paper is about 130 lines/millimeter. However, halation confuses any relationship between resolution and spread function. Here an arbitrary factor of 5 is used to allow for paper diffusion. Since p is divided by M^2 in Equation (1), a more accurate figure is scarcely worthwhile. In contact-printing investigations, p should possibly be increased further when the effects of the printer are great enough to take into account.

$(2/130)^2 \times 5$ .... $p = 12.0$

For I²; Final image circle:

Both for two-dimensional subjects and for depth-of-detail considerations, a viewing condition for the prints must be selected. Photomacrographic subjects themselves are usually observed through a loupe, therefore a center of perspective is somewhat indefinable. Accordingly, a comfortable fixed viewing distance is assumed here, 12 inches.

Good definition with sufficient depth of field is difficult to achieve in photomacrography; hence, too stringent a print circle should not be demanded. The diameter of the circle of confusion usually stated for miniature negatives is 0.051 millimeter at the negative.[8] For an average enlargement, say $\times$ 7, this becomes 7.357. To that should be added the losses of enlargement. The resulting 8 $\times$ 10-inch print renders about 5½ elements/millimeter at the depth limits. Hence I will be based on 6 elements/millimeter for quite critical photomacrographs.

$(0.333)^2$ .... $I^2 = 1110$

Photomacrographic Conditions in the Focal Region

In adding the blur and confusion circles for deriving a formula for total depth of detail, it was necessary to make certain hypotheses about the nature of the image in the focal region. The validity of the assumptions is now examined and demonstrated.

Herzberger[9] has shown that the distribution pattern of light from a point source in the focal region is extremely complex. He has reproduced this at high magnification and shown how it varies through the region. It is also well known that there exist regions of greatest resolution and of maximum contrast in the vicinity of the focal plane. These can be demonstrated by photographing the aerial image of a point focus at high magnification, or their effects can be noted in specialized fields.

For ordinary three-dimensional photographic and photomacrographic subjects, the effects do not appear to an appreciable extent. These subjects are not point sources and their contiguous component images do not come to a given focal condition in the same plane. Hence, a theoretical point in one part of the subject would have its contribution to the focal effects masked by the spread of the adjacent points and diffused by the emulsion grains and turbidity. This is demonstrated in Figure 12, where very tiny, but finite, holes in a screen have been photographed at an angle. Depth-of-field effects are quite noticeable but there are no appreciable size irregularities near the focal region.

It is apparent that the energy in the overlapping Herzberger patterns is concentrated into a small and effectively homogeneous area. When the "point" focus of the camera lens is on an emulsion instead of at the focus of an optical magnifying system, it is too small to be resolved into a pattern by the emulsion. Therefore, it is safe to assume here that

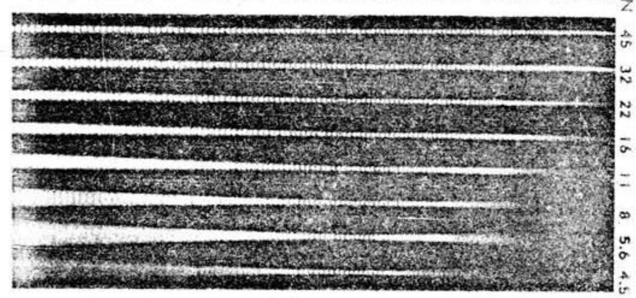

Figure 12—Holes in an accurate, fine screen photographed at an angle. Depth of field effects are evident but no perturbations in image size appear near the focal plane.

the referred image circle exists throughout the focal region and that only the out-of-focus circles of confusion tend to increase the size of this image circle on either side of the focal point from any practical element in the subject. Another factor that helps this concept for photomacrography is the relatively narrow angle of view—the spread of the Herzberger patterns increases with the angle between the lens axis and the image.

Appendix

Those wishing to draw working curves for depth of detail in their own field may want to know the details of combining Figures 9 and 10 to obtain Figures 5 and 5a. The lower part of the basic curve is from the $m \rightarrow \infty$ parametric curve (Figure 10) plotted to f/22. This point (f/22) was found on the $N_{T max}$ ordinate of Figure 9 and it will be seen that the corresponding value for M is 9.5. At the $M = 9.5$ absissa on Figure 10, the value for T is 1.2, and this value marks the f/22 point on the $m \rightarrow \infty$ curve. All the other f-stop levels were found in the same way in order to yield the optimal aperture curves.

This lower portion of the basic curve provides a good general depth curve, because in this region the depth obtainable with any reasonably high camera magnification is practically the same as the theoretical optimum depth indicated by the $m \rightarrow \infty$ curve.

Since the author's lens can only be stopped down to f/22, it was necessary to use a modification in the $m \rightarrow \infty$ curve for M less than 9.5 (although a dotted extension to f/32 has been included for the convenience of others). Hence equation (6a) was computed with $M = m$ and $N = 22$. This yields the upper part of the basic curve. It indicates a fair average depth, for most conditions, with the lens stopped all the way down. It is also close to the optimum depth locii and to the results obtainable with a practical proportion between camera and print scales. The curve swings across the parametric curves, from $m \rightarrow \infty$ to $m = 1$, at points readily attainable in practice and avoids reductions during enlarging.

The defining power is derived from the ratio of the depth of detail (or it can be obtained from depth of field in many applications) to the width of the smallest element satisfactorily rendered at the depth limits. Detail separation, s, is given in elements/millimeter where an "element" is an entity (such as a hair) plus a space, just as a bar plus a space constitutes a "line" on a resolution chart. The width of an element is $1/s$; hence, defining power is sT. When a definite entity is involved, rather than an estimated or known figure for s, it should be noted that $1/s$ is twice the width of the entity.

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